Grand Unification with Gauge Mediated Supersymmetry Breaking

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Abstract

We consider constraints on gauge mediated supersymmetry breaking models imposed by the requirement of grand unification. In particular, we demonstrate several ways to reduce the number of parameters coming from the dynamical supersymmetry breaking sector. One of approaches exploits nonperturbative unification of gauge couplings in multi-messenger models.

1. *Introduction.* Almost all existing experimental particle physics data fit well the Standard Model predicitons, so every reason to invent new physics beyond this theory is purely aesthetical. From the particle theory point of view, more beautiful models are obviously those which have more symmetries, and those which are predictive, i.e. have less free parameters. Two of the most popular extensions of the Standard Model deal with supersymmetry and with Grand Unification, respectively. The latter concept shares both pleasant features, namely, larger symmetries in gauge interactions and in matter content together with restrictions on the existing parameters of the Standard Model. On the other hand, supersymmetry requires much more symmetries restricting particle dynamics but often fails to be predictive in realistic models — it introduces quite a few new parameters instead of constraining the existing ones. Merging the two concepts, however, can lead to really aesthetically appealing models – Supersymmetric Grand Unified Theories (GUTs).

The main purpose of this talk is to demonstrate how the concept of Grand Unification helps to constrain the parameters in one particular class of supersymmetric models – models with gauge mediated supersymmetry breaking

(GMSB). The latter models are known to be rather predictive by themselves; we show here that in some cases the number of free parameters may be even more reduced once a particular model is specified. We begin with a brief sketch of GMSB models, then discuss possible general constraints coming from the Grand Unification postulates. We turn then to particular examples and consider the ways the models of direct gauge mediation may be constrained.

2. *Sketch of GMSB.* In most realistic supersymmetric models, supersymmetry is broken in the sector of fields different from the Standard Model and its minimal supersymmetric extension (MSSM). The (rather weak) interaction between the two sectors transfers supersymmetry breaking to the visible fields, and so determines the parameters of the MSSM. In the most general case, there are of order 10^2 of these parameters, and to start comparing the model with experiments, one first needs to constrain the parameter space. The most attractive way is to specify the interaction between the two sectors and to calculate the values of the parameters, but in practice several relations between them are often conjectured.

It is the kind of interaction between the dynamical supersymmetry breaking (DSB) sector and the observable world which distinguishes between different classes of supersymmetric models. This interaction should be suppressed at low energies, and two conventional choices are gravitational (which operates at energies of order Planck scale) and Yukawa or/and gauge (operating somewhere between the electroweak and Planck scales) interactions. The latter case corresponds to the GMSB theories, and makes it possible to calculate the supersymmetry breaking parameters of the MSSM by means of the field theoretical methods, without invoking less understood theories of quantum gravity. In the former case, some simple constraints on the MSSM parameters are often postulated (see, e.g., Ref. [1] for a review of gravity mediated supersymmetry breaking).

The key ingredient of the GMSB scenario is a set of messenger fields which fall in the vectorlike multiplets of the Standard Model gauge symmetry. They are the only fields from the visible sector which directly interact with the DSB sector. By means of this interaction (either pure Yukawa in the minimal models or both Yukawa and gauge in the so-called direct mediation models) the messengers obtain supersymmetry breaking masses of their component fields. The parameters of the MSSM – soft gaugino and scalar masses and trilinear couplings — are generated via loop effects by MSSM gauge interactions between messengers and ordinary particles. Thus, the masses of the superpartners are determined by their $SU(3) \times SU(2) \times U(1)$ quantum numbers and the parameters describing the spectrum of messengers (typically, there are two such parameters, the mass of the fermionic component, and the mass splitting between bosonic messengers). The gauge mediation mechanism naturally suppresses flavour violating processes and is highly predictive — all MSSM parameters (not counting 17 parameters of the non-supersymmetric Standard Model) are calculated in terms of four — two in the messenger sector and two in the Higgs sector. The GMSB phenomenology and model building are widely discussed, e.g., in the review Ref. [2]; here we will concentrate on ways to further reduce the number of free parameters by making use of Grand Unification constraints.

3. *Simple GUT constraints.*

Let us list the well known constraints which are characteristic to Grand Unified theories and enable one to restrict parameters of the low-energy theory. These constraints are

1. unification of gauge couplings;
2. unification of Yukawa couplings;
3. matter content in full GUT multiplets (or explanation of splitting, as in the case of Higgs doublets and triplets);
4. interactions which may be written in terms of GUT multiplets.

All these types of constraints may be used to rule out some models, and the first and the second constraints may provide quantitative bounds on parameters of a given model. Consider, as an example, the minimal gauge mediated model with one $(5+\bar{5})$ set of messengers. Perturbative gauge unification in the visible sector is unchanged by construction (at least in one loop). One may, however, impose an additional constraint (which seems very plausible) that the Grand Unified Theory, if exists, should contain the secluded (DSB) sector as well. With this assumption, one can exploit the unification of gauge couplings of the DSB and visible sectors to gain information about the values of the coupling constant in the secluded sector and, notably, about the scale where it becomes strongly coupled. The latter scale Λ_s determines the value of one of the supersymmetry breaking parameters for a given model.

Phenomenological and cosmological constraints on this parameter allow us to extract "unifiable" models from a plethora of known DSB schemes. Only three of them (the "3-2" model [3], its extension with extra matter, and the model with $SU(2)$ group and vector-like matter content [4]) were found to satisfy these criteria [4, 5] without introducing additional matter thresholds. Another example concerns the restrictions on the minimal $SU(5)$ GUT with GMSB that come from the analysis of gauge and b–τ Yukawa coupling unification [6]. These restrictions in fact have shown the inconsistency of the minimal model with unification.

One should note, however, that a unified theory containing both DSB and visible sectors is still missing. Nevertheless, as we will see in the next section, even the requirement of unification in the visible sector may be sometimes very restrictive.

4. *Constraining multi-messenger direct gauge mediation scenarios.* Let us turn to the models with direct gauge mediation where the messenger fields themselves are part of the DSB sector, namely, they carry charges under the secluded gauge group. From the visible sector viewpoint, the latter gauge group plays a role of a flavour group, so several copies of messenger fields should appear in the spectrum – the number of copies being equal to the dimensionality of the corresponding representation of the secluded gauge group. Since the messengers are charged under the Standard Model too, their contribution to the gauge beta functions of the Standard Model may lead to the loss of the asymptotic freedom. For example, if the number of $5+\bar{5}$ multiplets exceeds four, the gauge coupling constants become large below $M_{\rm GUT}\sim 10^{16}$ GeV which contradicts the idea of perturbative unification. On the other hand, it is often that the DSB group is not very small, so it has no representation with dimension 4 or less[1]. The most common approach to the question of saving gauge unification in this case is to make the messengers heavy [8, 9]. For high enough thresholds of the messengers, Landau poles might be "pushed" away to energies higher than $M_{\rm GUT}$. Though particle phenomenology does not suffer from messengers being heavy, they often are problematic for cosmology [9, 10]. This fact suggests to look for other ways of solving the gauge unification problem in multi-messenger mod-

[1]Recently, a model of direct mediation with the DSB group $SU(2)$ and two sets of $5+\bar{5}$ messengers has been constructed [7]. We will not discuss this model here since analysis in this section is valid for multi-messenger models only.

els. One of the ways is to invoke completely new physics at intermediate scales between $M_{\rm SUSY}$ and $M_{\rm GUT}$. If the Standard model fields and/or messengers are composite states made of a few fundamental preons, the latter transforming as complete GUT multiplets, then at high energies only preons contribute to the beta functions of $SU(3) \times SU(2) \times U(1)$. Generally, their contribution is smaller than the contribution of the composite fields, and the coupling constants at $M_{\rm GUT}$ can remain small. A few examples of gauge mediated supersymmetry breaking models with direct gauge mediation and compositeness were constructed, but they are either toy models [11] or too complicated to be realistic [12]. All models require dynamical assumptions about uncalculable dynamics at strong coupling.

Let us turn now to the last, and the least explored possibility. Its main idea is to replace the perturbative unification of couplings by a controllable and phenomenologically acceptable unification at the strong coupling.

The possibility of gauge coupling unification in the strong coupling regime has been considered in the framework of both the Standard Model and its supersymmetric extensions [13]. Recently, this problem attracted some interest again [14] after more precise measurements of the gauge coupling constants at M_Z have been carried out. The latter results differ from the two-loop unification predictions by more than one standard deviation (see, e.g., Ref. [15]).

Note that running gauge couplings of the MSSM α_1 and α_2 increase with energy, so $SU(2) \times U(1)$ is not asymptotically free. These couplings, however, run relatively slow, so Landau poles of these two groups appear at energies higher than the unification scale. Together with the asymptotic freedom of QCD this means that below M_{GUT} all gauge couplings are small, and perturbative analysis is valid. This picture impies the existence of the "desert", i.e. absence of particles huge region of masses between superparticle and unification scales. When new particles, like several multiplets of messengers, are introduced, the first coefficients of the β functions increase, so gauge couplings may become large at the unification scale.

Despite the fact that unification in this case occurs at the strong coupling, it is unexpectedly controllable from the low energy point of view, especially in the supersymmetric case [16]. Consider one-loop evolution of the coupling constants in an asymptotically non-free unified theory. If M_G is the unification scale and α_G is the value of the unified gauge coupling at that scale, then the renormalisation group equations

$$\frac{d\alpha_i}{dt} = b_i'\alpha_i^2 \tag{1}$$

have a solution

$$\alpha_i^{-1}(Q) = \alpha_G^{-1} + b_i' t,$$

where $t = \frac{1}{2\pi}\ln\frac{Q}{M_G}$ and b_i' are the first coefficients of the beta functions of the gauge couplings in the asymptotically non-free theory. Consider running of the *ratios* of pairs of the gauge couplings,

$$\frac{d}{dt}\ln\frac{\alpha_i}{\alpha_j} = b_i'\alpha_i - b_j'\alpha_j. \tag{2}$$

At one loop, these ratios have infrared fixed points,

$$\frac{\alpha_i}{\alpha_j} = \frac{b_j'}{b_i'}.$$

These fixed points are reached at the energies which are model-dependent and may be read out from the solution to eq.(2),

$$\frac{\alpha_i(Q)}{\alpha_j(Q)} = \frac{\alpha_G^{-1} + b_j' t}{\alpha_G^{-1} + b_i' t}.$$

The condition that the fixed point is almost reached is $|t| \gg \alpha_G^{-1}/b_i'$. In the case of MSSM without additional matter, one has $\alpha_G^{-1} \sim 24$, so that for α_2 the fixed point occurs at $|t| \gg 24$, i.e., at $Q \ll M_G \cdot \exp(-48\pi) \sim 10^{-66} M_G$ which certainly rules out the possibility of the fixed point analysis.However, with new matter added, the situation changes drastically — b_i increase and α_G^{-1} decreases. Suppose that additional (messenger) multiplets fall in the complete vector-like representations of the $SU(5)$ unified gauge group, for example, $(5+\bar{5})$ or $(10+\bar{10})$. Then $b_i' = b_i + n$, where b_i are β function coefficients of the MSSM. Each $(5+\bar{5})$ set adds 1 to n while each $(10+\bar{10})$ adds 3. For $n \geq 5$ the unification occurs at strong coupling. To estimate the energy scale where ratios of couplings get close to the fixed point value, let us take $\alpha_G = 1$. Then even for $n = 5$ the ratios are almost constant at $Q < 0.04 M_G$.

For given n, the threshold corresponding to messenger mass is uniquely determined. Indeed, the low energy running of MSSM couplings is known, and at the threshold the couplings *should* have the ratios equal to b'_i/b'_j. The energy where ratios of MSSM running couplings, determined experimentally at M_Z, get to their fixed point values corresponds to the messenger threshold. Note that at $n \geq 5$ the corresponding thresholds are deep in the region of the attraction of the fixed points. For $n = 5$, for example, the threshold is between 1 and 10 TeV, much lower than $0.04 \cdot M_G$. This means that the fixed-point approach is self-consistent. The values of thresholds can be read out from Ref.[16]; values of $6 \leq n \leq 20$ are consistent with current bounds on the messenger mass [17].

So, from the low energy MSSM point of view we just have new boundary conditions for running of the gauge couplings. Instead of requiring the equality of couplings at M_G (as in the case of perturbative unification), one should fix their ratios at the messenger scale. Details of evolution of the couplings near M_G, where they are large, are unknown; however, they do not affect significantly the low-energy predictions [16, 18].

We conclude that having quite large number of messenger fields at scales between $M_{\rm SUSY}$ and $M_{\rm GUT}$ does not contradict the gauge coupling unification, the latter occuring in the nonperturbative regime.

The most interesting feature of this scenario is that the strong unification constrains significantly the parameter space of multi-messenger gauge mediation models. Namely, the mass scale of the messenger fields – one of the two parameters describing the superpartner masses – is determined for a given effective number of messengers n.

It is worth noting, however, that the superparticle spectrum does not depend significantly on the messenger mass M. Instead, the scale of superpartner masses is set by the product $\Lambda = Mx$, where $0 < x < 1$. In most supersymmetry breaking models, the scale Λ depends on the scale Λ_S where the gauge coupling constant of the secluded sector becomes strong. To determine Λ_S, one has to put some boundary conditions on that gauge coupling. This can be done either at $M_{\rm GUT}$, from the condition of "total" unification, like in Ref.[5], or at some intermediate scale by means of the fixed point formalism. If all contributions to the soft B_μ term come from the gauge mediation, and the supersymmetric μ parameter is tuned so that electroweak symmetry breaking is radiative, then Λ and M determine the superparticle spectrum completely — the model thus has no free parameters. Whether this spectrum is realistic, depends on the choice of model [17].

5. *Conclusion.* We have demonstrated that simple requirements of the Grand Unification of both visible and secluded sectors, and/or (in the multi-messenger case) of non-perturbative Grand Unification in the visible sector can significantly reduce the number of parameters of theories with gauge mediated supersymmetry breaking, thus ruling out some of them or predicting superparticle spectrum for others.

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