The MSSM After Two Years of LHC Running

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The Minimal Supersymmetric Standard Model is increasingly getting constrained by the null results from squark and gluino searches at the LHC, and by the indications for a Higgs around 125 GeV. This talk presents a theorist's (biased) view of the impact of these constraints, with a focus on recent work.

1 Introduction

The Minimal Supersymmetric Standard Model (MSSM) is obtained by promoting all Standard Model (SM) fields to superfields, *i.e.* by adding adding scalar *squark* and *slepton* superpartners for all SM fermions and fermionic *gaugino* superpartners for all SM gauge bosons. Moreover, the scalar Higgs doublet of the SM is replaced by two Higgs doublets H_u and H_d and their fermionic *higgsino* superpartners. If the superparticle masses are close to the electroweak scale, this model can solve the electroweak hierarchy problem, lead to gauge coupling unification at high energies, and (if the lightest superparticle is stable) provide a dark matter candidate.

The MSSM has around 100 free parameters more than the SM. They should be fixed by augmenting it with a predictive mechanism for supersymmetry breaking and its mediation. However, many such mechanisms have been proposed (and many more might be conceivable), and it is difficult to assess which of them should be preferred. To study the MSSM phenomenology with a manageable number of parameters, the following approaches are common:

- Appealing to more or less motivated universality principles, one can just reduce the independent UV-scale parameters *ad hoc* to a small subset which still gives a viable phenomenology. The most common example is the CMSSM with parameters m_0, $M_{1/2}$, A_0, $\tan\beta$, and $\mathrm{sgn}(\mu)$. This gives a self-consistent particle spectrum which is useful for phenomenological benchmarks, but is hard to justify theoretically.

- In so-called simplified models, the spectrum is truncated to a few states relevant for a particular collider signature. Bounds *e.g.* on superparticle masses can then be obtained relatively easily, although they are usually stronger than they would be in realistic models. A related approach, the pMSSM, retains the full MSSM spectrum but prescribes the 19 most relevant parameters at the electroweak scale without referring to their UV-scale origins. It is often not clear if such a simplified spectrum can resemble an actual model.

- It is also worthwile to study full realistic models, but as mentioned there is a multitude of models on the market, and insights gained in one specific framework often cannot easily be carried over to another.

2 Constraints

In the R-parity conserving MSSM, supersymmetric particles are pair-produced at the LHC. The production channels with the largest cross-sections are $pp \rightarrow \tilde{g}\tilde{g}, \tilde{g}\tilde{q}, \tilde{q}\tilde{q}^*, \tilde{q}\tilde{q}$; here $\tilde{g}$ is the gluino and $\tilde{q}$ is any first-generation squark. Squarks and gluinos decay via cascade decays into Standard Model particles and the lightest supersymmetric particle, which escapes the detector as missing transverse energy (MET). This gives rise to the characteristic jets + MET (+ possibly leptons) signatures at ATLAS and CMS. The null results with the first 4.7 fb^{-1} of data at $\sqrt{s} = 7$ TeV allow to set stringent exclusion bounds on the superparticle masses [1, 2]. For instance, in the CMSSM with $\tan\beta = 10$, $A_0 = 0$, at the point where the squark and gluino masses are equal, masses below 1.4 TeV are excluded [1]. For $m_{\tilde{q}} \gtrsim 1500$ GeV, the gluino mass bound is somewhat weaker, $m_{\tilde{g}} \gtrsim 900$ GeV. These bounds do not necessarily carry over to less restrictive models; *e.g.* they become significantly weaker if the mass ratio $m_{\tilde{g}} : m_{\tilde{B}}$ between the gluino and the bino, which is about $6 : 1$ in the CMSSM, is reduced.

Further constraints come from the recent indications for a 124–126 GeV Higgs boson [3, 4]. Should these be confirmed, the Higgs mass would be rather high for the MSSM. More precisely, at large $\tan\beta$ and in the decoupling limit $m_{A^0} \gg m_Z$, including the dominant one-loop corrections, the Higgs mass is

$$m_{h^0}^2 = m_Z^2 + \frac{3}{4\pi^2} y_t^4 v^2 \left(\log \frac{m_{\tilde{t}}^2}{m_t^2} + \frac{A_t^2}{m_{\tilde{t}}^2} \left(1 - \frac{A_t^2}{12\, m_{\tilde{t}}^2} \right) \right) + \ldots \tag{1}$$

where $m_{\tilde{t}}$ is the average stop mass and A_t is the stop trilinear coupling. To increase m_{h^0} above m_Z, the terms in parentheses should be large, which requires either $m_{\tilde{t}} \gg m_t$ or $|A_t/m_{\tilde{t}}| \approx 2$ (see *e.g.* [5, 6] and Fig. 1). The former implies a large fine-tuning of parameters, whereas the latter, the *maximal stop mixing scenario*, is nontrivial to realize in UV-scale models [7, 8, 9].

In addition, there are constraints from flavour physics and from cosmology. For instance, one often asserts that the lightest supersymmetric particle should be the lightest neutralino and that its thermal relic density should reproduce the WMAP measurement for the dark matter abundance [10]. This is increasingly difficult to realize in constrained scenarios such as the CMSSM [11]. However, dark matter might also consist of other particles such as gravitinos, axions, or axinos, whose abundance cannot readily be computed without further model assumptions.

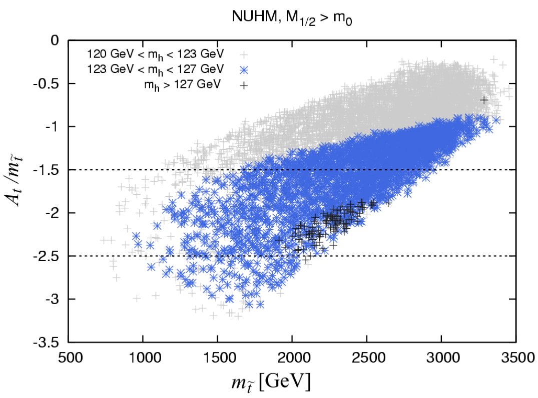

Figure 1: Higgs masses around 125 GeV (blue points) require $|A_t|/m_{\tilde{t}}$ around 2–2.5, or very large $m_{\tilde{t}}$ (from scans over non-universal Higgs mass models with large GUT-scale $M_{1/2}$ [9]).

3 Light stops

While the first-generation squarks and gluinos must be heavy to evade the direct search bounds, the stops could still be relatively light, $m_{\tilde{t}} < 1$ TeV. This is favoured by naturalness: The stops couple to H_u with a large Yukawa coupling, and consequently the stop masses and Higgs mass parameters are naturally of similar order of magnitude. However, the parameters of the Higgs potential also set the electroweak scale, which therefore cannot be much smaller without considerable fine-tuning. Explicitly, for large $\tan\beta$ one obtains

$$m_Z^2 = -2(m_{H_u}^2 + |\mu|^2)\,, \tag{2}$$

so $|m_{H_u}^2| \gg m_Z^2$ requires a large cancellation between the two terms on the right-hand side. Furthermore, also the higgsino mass μ cannot be too large. A minimal spectrum, in which only those states are light that are required to be light by naturalness [12, 13], is sketched in Fig. 2.

The stops and the left-handed sbottom, as well as two higgsino-like neutralinos and a higgsino-like chargino, are below a TeV. The gluino should not be much heavier. All other superparticles can be heavy enough to be of LHC reach. The Higgs mass should be accounted for by large stop mixing. Several models have recently been proposed in order to obtain a superparticle spectrum of this kind [14].

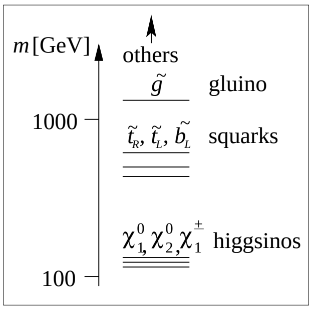

Figure 2: A “natural” mass spectrum with light stops.

4 Heavy stops

A different approach is to try to reconcile heavy stops with naturalness. With $m_{\tilde{t}} \gtrsim 3$ TeV, the Higgs mass in Eq. (1) can be increased to around 125 GeV, even without large mixing contributions. In a generic setting this would require large fine-tuning, as discussed above and as is also evident from Eq. (2) when expressing its RHS in terms of UV-scale boundary values for the soft terms (quoted here for large $\tan\beta \approx 50$ and $m_{\tilde{t}} \approx 1$ TeV [15]):

$$\begin{aligned} m_Z^2 \approx \Big(&2.25\, M_3^2 - 0.45\, M_2^2 - 0.01\, M_1^2 + 0.19\, M_2 M_3 + 0.03\, M_1 M_3 \\ &+ 0.74\, m_{\tilde{t}_R}^2 + 0.65\, m_{\tilde{t}_L}^2 - 0.04\, m_{\tilde{b}_R}^2 - 1.32\, m_{H_u}^2 - 0.09\, m_{H_d}^2 \\ &+ 0.19\, A_0^2 - 0.40\, A_0 M_3 - 0.11\, A_0 M_2 - 0.02\, A_0 M_1 - 1.42\, |\mu|^2 \Big)\Big|_{M_{\mathrm{GUT}}}\,. \end{aligned} \tag{3}$$

Here $M_{1,2,3}$ are the gaugino masses, m_ϕ^2 are the various scalar soft masses, and A_0 is the trilinear coupling (assumed to be universal for simplicity). Clearly, if the typical soft mass scale is $\gg 1$ TeV, large cancellations are required for the RHS to sum up to $m_Z^2 = (91\ \mathrm{GeV})^2$.

In certain models these cancellations are actually enforced by relations between the parameters. For instance, in the original *focus point* scenario [16, 17], the gaugino and higgsino masses M_i and μ as well as A_0 are of the order of the electroweak scale. The GUT-scale scalar masses are universal, $m_{\tilde{t}_R} = m_{\tilde{t}_L} = m_{\tilde{b}_R} = m_{H_u} = m_{H_d} \equiv m_0$. Because the coefficients in the second line of Eq. (3) happen to approximately sum up to zero, m_0 can be several TeV without worsening the fine-tuning.

Focus point supersymmetry is coming under pressure, because it requires relatively small gluino masses which are now in conflict with direct search bounds. However, variations are possible which also involve relations between the gaugino masses [18]. Examples are given by the models of [15, 19], which rely on a combination of high-scale gauge mediation and gravity mediation. The spectrum is largely determined in terms of three integers $N_{1,2,3}$, with Eq. (3) becoming

$$m_Z^2 = \left(2.25\,N_3^2 - 0.45\,N_2^2 - 0.01\,N_1^2 + 0.19\,N_2 N_3 + 0.04\,N_1 N_3 + 3.80\,N_3 - 1.16\,N_2\right) m_{\rm GM}^2 - 1.42\,|\mu|^2\,;$$

here $m_{\rm GM}$ is of the order of the electroweak scale, GUT-scale gaugino masses are given by $M_i = N_i m_{\rm GM}$, and scalar soft masses scale like $m_\phi^2 \sim N m_{\rm GM}^2$. A model with, for instance, $(N_1, N_2, N_3) = (28, 28, 11)$ gives a realistic value for m_Z despite the individual soft masses being multi-TeV.

Should a scenario like this be realized in Nature, all coloured states would probably be too heavy to be produced at the LHC. The only electroweak-scale superparticles would be three almost mass-degenerate higgsinos which are difficult to detect at the LHC [20, 21]. Signals for them might show up in LHC monojet searches or at a future linear collider. This situation is sketched in Fig. 3.

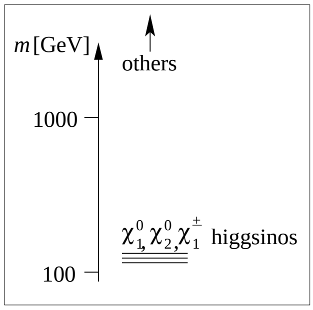

Figure 3: A spectrum where only the higgsinos are light.

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