

# Some aspects of Physics beyond the Standard Model at LHC

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**Abstract.** The LHC is constraining BSM physics at an impressive efficiency, but no sign of new physics has been found yet. SUSY (and other BSM scenarios) are starting to be in trouble, though there is still room for new physics able to solve the Hierarchy Problem. This situation poses new challenges to optimize the LHC discovery potential using smarter strategies for analysis. In this sense, direct and indirect searches of new physics can play complementary roles.

## 1. Introduction

The two main purposes of the LHC are to probe the Higgs mechanism and to look for physics beyond the Standard Model (BSM). In both goals the LHC performance has been impressively good, although of course the outputs are so far very different.

Concerning the Higgs mechanism, in only one year the LHC has been able, first, to exclude most of the mass range of the Higgs boson; second, find possible signals for a Higgs boson in the 120 GeV - 130 GeV region (this was the situation at the time of this PASCOS conference in June-2012); and finally give  $> 5 \sigma$  evidence of a Higgs-like particle at 125 – 126 GeV [1, 2].

On the other hand, the job of the LHC probing paradigmatic BSM scenarios has been equally impressive. However nature has not been as friendly to us as in the Higgs case, and all we have at the moment are strong exclusion limits for supersymmetric models and other scenarios of new physics (and maybe weak hints coming from the Higgs-boson properties). In spite of this, the LHC results have already profound implications in BSM physics.

Under the title "Physics beyond the Standard Model" there are many different scenarios. On the one hand, we have those related to a solution of the Hierarchy Problem (stability of the electroweak scale). The paradigmatic one is Supersymmetry (SUSY), especially the Minimal Supersymmetric Standard Model (MSSM), which is the minimalistic supersymmetric extension of the SM without assuming new degrees of freedom, except those obliged by SUSY. But there are many MSSM scenarios depending on the assumptions about the unknown parameters (typically the soft terms). The most popular and extensively studied one is the Constrained MSSM (i.e. CMSSM, sometimes called mSUGRA) [3], in which one starts with universal soft terms at the gauge unification scale,  $M_X \sim 10^{16}$  GeV. This scenario is in part motivated by the strong constraints in flavour-changing neutral-currents and the empirical and theoretical hints of a unification scale close to  $M_P$ . Moreover it takes place in some well-motivated theoretical scenarios, like gravity-mediated ones. But there are other MSSMs, like NUHM, gauge-mediated MSSM, string-inspired MSSMs, etc. All of them represent particular (and quite constrained)



possibilities of the full MSSM. Besides, we have supersymmetric models beyond the MSSM, like the NMSSM (characterized by the presence of an extra singlet) and the BMSSM (characterized by SUSY breaking at low-scale). Apart from SUSY, there are other frameworks of new physics, like the different versions of Extra-Dimensions scenarios: ADD, RS, ...; Composite and Little Higgs models; etc.

On the other hand, we have additional scenarios or chances for new physics, motivated by other phenomenological and theoretical facts or possibilities: dark matter candidates, flavour violation, extra massive-gauge-bosons, 4th generation, etc.

Roughly speaking there are two main strategies to constrain new physics: direct searches, i.e. production and detection of BSM particles; and indirect searches, i.e. search of fingerprints of the new physics in the effective (SM-like) theory. In this note we will concentrate on direct searches, but we will address indirect ones in sect. 5. We will focus mostly (but not only) on SUSY scenarios, although many strategies and results reviewed here are essentially valid for other frameworks of new physics.

SUSY has been the paradigmatic scenario of physics BSM, and for good theoretical and phenomenological reasons. SUSY is a beautiful symmetry, strongly suggested by string theories. It provides an elegant solution to the Hierarchy Problem since the dangerous quadratic divergences contributing to the Higgs mass (and thus to the electroweak scale) cancel. In addition, SUSY presents nice features which was not designed for. Namely, the supersymmetric running of the gauge couplings makes them unify at a high scale,  $M_X$ , with great precision. Also, the electroweak (EW) breaking occurs in a quite natural way since the square-mass of one of the two Higgs doublets is driven towards negative values along the renormalization group (RG) running from the high scale. This is called radiative EW breaking. Let us also mention that SUSY models offer a natural WIMP candidate for dark matter (usually the lightest neutralino). SUSY is indeed beautiful... but maybe false! Now it is the time for SUSY to be probed by the experiment (LHC).

## 2. The search of SUSY

### 2.1. Typical SUSY signals

The highest cross sections of SUSY production are normally gluino and/or squark pair-production. By squark we mean here a squark state of the first or second generation since the production of stops and sbottoms is very suppressed. In a typical SUSY process the gluinos ( $\tilde{g}$ ) and squarks ( $\tilde{q}$ ) decay along cascades with diverse topology. In models with some kind of R-parity (desirable though not mandatory to avoid proton decay and other baryon/lepton number violating processes), each cascade always produces one lightest supersymmetric particle (LSP), typically a neutralino  $\chi_1^0$ , among the final states. In addition, one or more jets, with or without leptons, are created in each cascade. Therefore the most direct search of SUSY is to look for events with

- jets with high  $p_T$
- $E_T^{\text{miss}}$
- 0-N leptons

Normally, multijet events with large  $E_T^{\text{miss}}$  and 0-leptons are the most efficient channel, but channels with leptons may play an important (sometimes capital) role, especially for particularly elusive types of SUSY spectrum (see subsect. 3.2 below).

It is not straightforward to translate LHC data about these types of events into concrete limits on SUSY (MSSM) parameters. Let us recall that the MSSM has  $\sim 100$  independent parameters, mainly soft terms related to the unknown mechanism of SUSY breaking and its transmission to

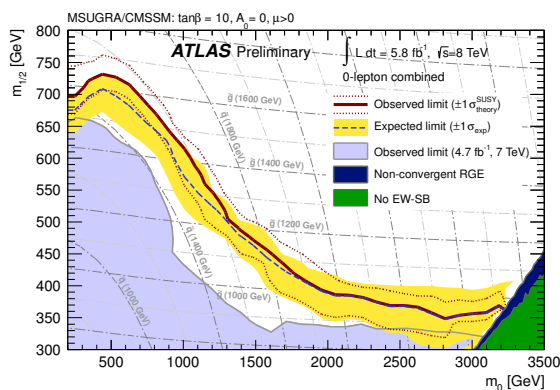
the observable sector:  $\{m_{ij}^2, M_a, A_{ij}, B, \mu\}$ . Here  $m$ ,  $M$  and  $A$  are scalar masses, gaugino masses and trilinear scalar couplings;  $i, j$  and  $a$  are family and gauge group indices respectively;  $B$  is the bilinear scalar coupling and  $\mu$  is the usual Higgs mass term in the superpotential. Requiring no flavour or CP violation in the first and second generations reduces the number of parameters to  $\sim 20$  (plus those already present in the SM), still a huge number. It is certainly cumbersome to translate the LHC data into constraints on such complex parameter-space. A usual strategy is to present the LHC data as constraints in a simplified version of the MSSM, typically the CMSSM. Then the previous parameters are reduced to  $\{m, M, A, B, \mu\}$ , i.e. the universal scalar mass, gaugino mass and trilinear scalar coupling; plus the  $B$  and  $\mu$  parameters. All quantities are to be understood at the high scale  $M_X$ . Using the EW breaking conditions, coming from the minimization of the Higgs potential, one can eliminate  $\mu$  (except for the sign) and trade  $B$  by  $\tan \beta = \langle H_u \rangle / \langle H_d \rangle$  (the ratio of the expectation values of the two Higgs doublets). So the usual set of CMSSM parameters is

$$\{m, M, A, B, \tan \beta, \text{sign} \mu\}$$

Due to the remarkable growth of the gluino and squark masses along the RG running, the typical CMSSM spectrum is

$$\begin{aligned} M_{\tilde{g}} &\sim m_{\tilde{q}} > m_{\tilde{t}} \\ M_{\tilde{g}} &> M_{\chi^\pm} \gtrsim M_{\chi_1^0} \\ \chi_1^0 &\equiv \text{LSP} \end{aligned}$$

where  $\chi^\pm$  and  $\chi_1^0$  denote the lightest chargino and neutralino states (the squark can be much heavier than the gluino if  $m \gg M$ ). The values of  $A$  and  $\tan \beta$  are not very important for the multijet signal, as they play almost no role in the gluino and squark production. Because of that, the impact of the LHC results on the CMSSM are usually presented as exclusion limits in the  $m - M$  plane (or in the  $m_{\tilde{q}} - M_{\tilde{g}}$  plane) for  $A$  and  $\tan \beta$  fixed (often  $A = 0$ ,  $\tan \beta = 10$ ). Fig. 1 shows the ATLAS limits with an integrated luminosity of  $\sim 5.8 \text{ fb}^{-1}$  at  $\sqrt{s} = 8 \text{ TeV}$  [4]. The results for CMS are similar.



**Figure 1.** ATLAS constraints on the  $m - M$  plane of the CMSSM.

## 2.2. The MSSM in trouble

Roughly speaking, the above-mentioned ATLAS and CMS results imply that for  $M_{\tilde{g}} \sim m_{\tilde{q}}$ , then  $M_{\tilde{g}}, m_{\tilde{q}} \gtrsim 1100 \text{ GeV}$  (recall that  $M_{\tilde{g}} \sim 2.5M$ ). And this means that the CMSSM is *in trouble*. The reason is that with such large masses the EW breaking is rather fine-tuned. We cannot just

“forget” about the fine-tuning problem, since the main reason to consider low-scale SUSY was to avoid the Hierarchy Problem, i.e. the big fine-tuning problem of the EW breaking in the SM.

Let us briefly review how the fine-tuning appears. The minimization of the tree-level Higgs potential leads to expectation values for the Higgses, which must be of the right size to reproduce the  $Z$ – and  $W$ –boson masses. More precisely, working with the Higgs potential at tree-level, the  $Z$ –mass can be expressed as

$$M_Z^2 = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2 \beta}{\tan^2 \beta - 1} - 2\mu^2 \quad (1)$$

where  $m_{H_u}^2, m_{H_d}^2$  are the mass parameters of the two Higgses. Clearly, the correct value of  $M_Z$  requires an unnatural cancellation of the various terms unless  $m_{H_u}, m_{H_d} \lesssim \mathcal{O}(1\text{TeV})$ . One cannot just take  $m_{H_u}^2, m_{H_d}^2$  small while  $M_{\tilde{g}}, m_{\tilde{q}}$ , etc. are large, since the Higgs mass parameters receive large radiative contributions from the latter along the RG running from  $M_X$  to  $M_{EW}$  [3]. In other words, large  $M_{\tilde{g}}, m_{\tilde{q}}, \dots$  imply large  $m_{H_u}, m_{H_d}$  (in absolute value). Thus the EW breaking is fine-tuned unless the typical soft masses are  $\mathcal{O}(1\text{TeV})$  or less.

It has been often observed that, since the RG running of  $m_{H_u}^2$  (the most relevant term in eq.(1) for non-small  $\tan \beta$ ) is mostly driven by stop masses, which in turn are mostly driven by the gluino mass, then if  $M_{\tilde{g}}, m_{\tilde{t}}$  are small (less than 1 TeV) and the first and second generations are heavy, the EW breaking can still be natural while SUSY remains undetected at LHC. However, this scenario, sometimes called “natural-SUSY” [5], is also in trouble. First, the direct LHC constraints, though still not very constraining for the stops (more about this later), are already severe for the gluino, implying  $M_{\tilde{g}} \gtrsim 1$  TeV. Second, the observation of the Higgs mass around 125 – 126 GeV makes natural-SUSY very hard to implement and, more generally, makes the fine-tuning problem more severe, as we discuss next.

### 2.3. The impact of the Higgs discovery

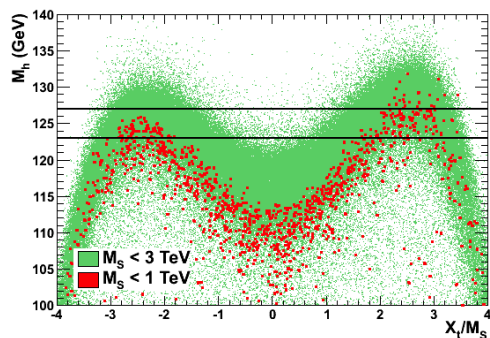
In the effective theory coming from the MSSM, the quartic coupling of the Higgs field has (at tree-level) a purely gauge origin, namely  $\lambda_{\text{tree}} = \frac{1}{4}(g^2 + g'^2) \cos^2 2\beta$ , where  $g, g'$  are the  $SU(2) \times U(1)$  gauge couplings. This relation means, in particular, that at tree-level the mass of the Higgs in the MSSM is bounded by the mass of the  $Z$ -boson (91.1 GeV). As it is well-known, radiative corrections increase  $m_h$ , which can then get compatible with the experimental observation, at the expense of requiring a relatively heavy spectrum ( $\gtrsim 1$  TeV) of superpartners. An approximate analytic formula for  $m_h$  [6, 7, 8, 9] reads

$$m_h^2 \simeq M_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2} \frac{m_t^4}{v^2} \left[ \log \frac{M_{\text{SUSY}}^2}{m_t^2} + \frac{X_t^2}{M_{\text{SUSY}}^2} \left( 1 - \frac{X_t^2}{12M_{\text{SUSY}}^2} \right) \right] + \dots \quad (2)$$

where  $m_t$  is the top running mass,  $M_{\text{SUSY}}$  represents a certain average of the stop masses and  $X_t = A_t - \mu \cot \beta$  [7, 8, 9]. The first term of (2) is the tree-level Higgs-mass and the second are the dominant radiative and threshold contributions. Note that the radiative corrections grow logarithmically with the stop masses while the threshold correction has a maximum for  $X_t = \pm \sqrt{6} M_{\text{SUSY}}$ .

The important point is that, in order to achieve  $m_h = 125 - 126$  GeV, one typically needs (besides non-small  $\tan \beta$ ) stop masses  $\gtrsim 3$  TeV, unless  $X_t$  happens to be close to the above-mentioned maximizing value. Then the stop masses could be around 1 TeV, but not less than that. This is also well illustrated in the scatter-plot shown in Fig.2 (from ref.[10]). Recalling now the discussion of the previous subsection, the obvious consequence is that the EW breaking in *any* MSSM is fine-tuned unless  $X_t$  is close to its maximizing value. The latter possibility represents itself another kind of fine-tuning unless one has some theoretical reason to expect

$X_t$  in the favorable range. Incidentally, note that for moderately large  $\tan\beta$  the value of  $X_t$  is essentially given by  $A_t$ , so one would essentially need a value of  $A_t$  in the favorable range. In any case, this amounts to go beyond the MSSM, e.g. invoking a particular SUSY breaking and mediation mechanism that could lead to this result for  $A_t$ ; see ref.[11] for a recent paper arguing that this can actually occur in a class of superstring scenarios.



**Figure 2.** Scatter plot in the  $X_t - m_h$  plane of the CMSSM.

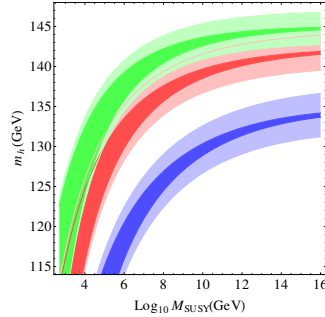
We can go a bit further and evaluate the amount of fine-tuning required for a correct EW breaking when the stop masses are large. A quick and useful estimate of the fine-tuning can be found in ref.[12], namely  $c \simeq 2 \frac{\mu^2}{m_h^2}$ . Then, for  $m_{\tilde{t}} \sim 3$  TeV one gets  $c \sim 100$ , i.e. SUSY is fine-tuned at  $\sim 1\%$  (other alternative estimators of fine-tuning give a similar value). Does this mean that the CMSSM, or even the general MSSM, is dead?

Before addressing this question, let us mention another interesting impact of the Higgs discovery on SUSY theories. The previous discussion reflects the fact that, as it is clear from eq.(2), a measurement of  $m_h$  implies a lower bound on  $M_{\text{SUSY}}$ . But it is also true that a measurement of  $m_h$  (or, more generally, an upper bound on  $m_h$ ) implies an *upper* bound on  $M_{\text{SUSY}}$ . Actually, eq.(2) is only valid for  $M_{\text{SUSY}} \lesssim 1$  TeV. When it is larger (as it happens for the task of evaluating the upper bound) it is necessary to run numerically the effective quartic coupling,  $\lambda$ , from the threshold scale,  $M_{\text{SUSY}}$ , till the EW scale (a nearly optimal choice is  $Q_{\text{EW}} = m_t$  [7]). Then  $m_h \simeq 2\lambda(Q_{\text{EW}})v^2$ . Besides, in order to get the Higgs pole-mass one has to add (pretty small) radiative corrections. The previously-sketched calculation of  $m_h$  using the 2-loop SM RG equation of  $\lambda$  was performed in refs.[13], [14].

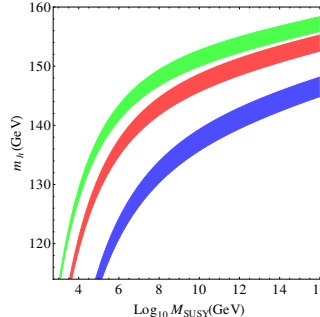
Fig.3 shows  $m_h$  as a function of  $M_{\text{SUSY}}$  for three representative values of  $\tan\beta$ , namely  $\tan\beta = 1, 3, 10$ . Due to the parametric dependence on  $\cos^2 2\beta$  shown in eq.(2), the results remain almost unchanged for larger values of  $\tan\beta$ . From the plots it becomes clear that one cannot reproduce an arbitrary large value of  $m_h$  by just increasing  $M_{\text{SUSY}}$ . Actually, there is an absolute upper bound of  $\sim 145$  GeV, which becomes more stringent as  $\tan\beta$  decreases. It should be kept in mind that  $M_{\text{SUSY}}$  essentially stands for “stop masses”. Indeed, in the usual MSSM scenarios the masses of all supersymmetric particles are of the same order, say within a factor of 10 or less. (A notable exception are split-SUSY models, to be discussed shortly.)

The width of the bands comes from the various sources of uncertainty, including experimental errors and the uncertainty about the value of  $X_t$ , which has been left varying within its range,  $0 \leq X_t \leq 6$ . Clearly a Higgs around 125-126 GeV implies that SUSY (if true) should take place at a scale  $\lesssim 10^{10}$  GeV. Of course, this limit is out of the scope of any realistic experiment. On the other hand, one can take the attitude of *only* considering low  $M_{\text{SUSY}} \lesssim \mathcal{O}(\text{TeV})$  as reasonable, in order to avoid the above-mentioned fine-tuning to get the correct electroweak scale. Still, these results are important from a more philosophical point of view. It has been suggested that in a landscape scenario such fine-tuning can be largely compensated by the overabundance of vacua with SUSY broken at a high scale, in which the anthropic principle would operate, see e.g. ref.

[15]. But, as we have just seen, this kind of framework does not work in the simplest scenario where the typical scale of SUSY breaking is around  $M_P$ .



**Figure 3.**  $m_h$  as a function of  $\log_{10} M_{\text{SUSY}}$  in the MSSM.



**Figure 4.** The same as Fig.3 for split-SUSY

The split-SUSY framework [16] is in fact a popular variant of the above-mentioned landscape scenario. In split-SUSY the masses of scalar superpartners are very high but the gauginos and higgsinos are relatively light (allowing for gauge unification and dark matter candidates). Concerning the calculation of  $m_h$ , the main difference with respect to the MSSM case is that in split-SUSY the gluinos remain active and contribute significantly to the RG equations between the upper and the lower SUSY-thresholds. The results are shown in Fig.4, which is analogous to the previous Fig.3 for the ordinary MSSM. The limits are even more stringent now. Namely, the scale of the heavy SUSY states should be at most at  $10^7$  GeV. I.e. the other side of SUSY cannot remotely be at  $\sim M_P$ .

### 3. Prospects for SUSY

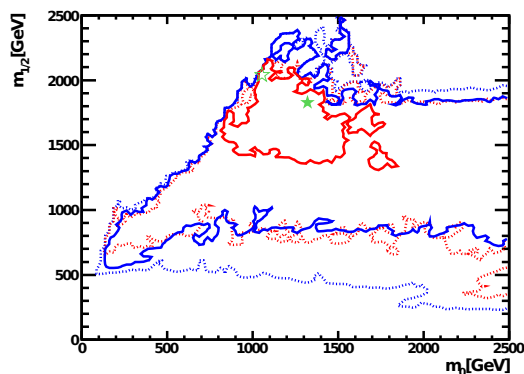
#### 3.1. Global fits and Bayesian forecasts

One can be more precise about the situation and prospects of the CMSSM (or any other MSSM or BSM model) by performing global fits. I.e., one can use all the available experimental information (dominated by LHC data) to show favoured/disfavoured regions in the CMSSM (or the BSM model under consideration) parameter-space. There are two basic approaches to do this task: the frequentist one and the Bayesian one.

In the frequentist approach one scans the parameter-space of the CMSSM evaluating the likelihood (based on the usual  $\chi^2$ ). This leads to zones of estimated probability (inside contours of constant  $\chi^2$ ) around the best fit points in the parameter space. A recent analysis of this kind (which takes the Higgs signal into account) has been performed in ref.[17]. The results are illustrated in Fig.5, which shows 68% and 95% c.l. regions in the  $m - M$  plane. Clearly the favoured region occurs at quite high values of the soft terms,  $m \sim M \sim 1500$  GeV, essentially beyond the actual LHC reach (recall e.g. that the gluino mass is  $\sim 2.5M$ ); though there survive regions at lower scale. On the other hand, in the Bayesian approach, for a model defined by some parameters,  $\theta_i$  and given some experimental data, the goal is to evaluate the probability density (or “posterior”) in the parameter space,  $p(\theta_i|\text{data})$ . This is given by the Bayesian relation

$$p(\theta_i|\text{data}) = \frac{p(\text{data}|\theta_i) p(\theta_i)}{p(\text{data})}$$

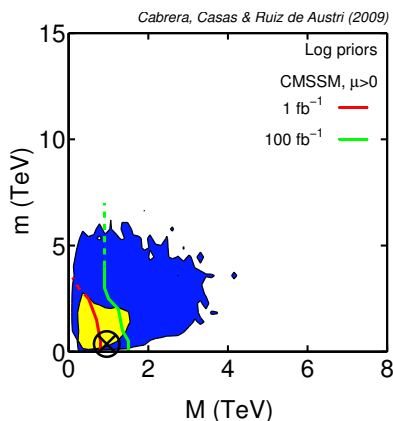
where  $p(\text{data}|\theta_i)$  is the likelihood, i.e. the probability density of measuring the given data for the chosen point in the parameter space (this is exactly the quantity used in frequentist approaches);



**Figure 5.** Likelihood distribution in the  $m - M$  plane of the CMSSM.

$p(\theta_i)$  is the prior, i.e. the “theoretical” probability density that we assign a priori to the point in the parameter space; and finally,  $p(\text{data})$  is a normalization factor which plays no role unless one wishes to compare different classes of models.

Some Bayesian analyses of the CMSSM previous to the Higgs discovery can be found in refs.[18, 19]. The impact of the Higgs discovery has been studied in refs.[20, 21]. Here we present the results of the improved analyses of refs.[19] and [21]<sup>1</sup>.

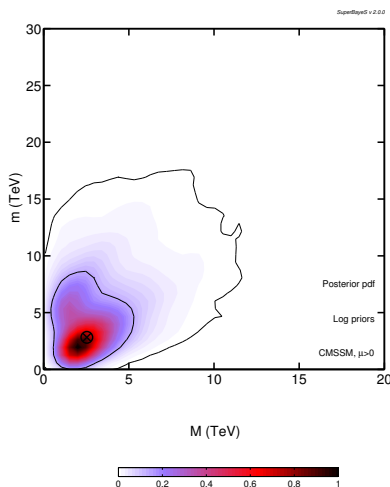


**Figure 6.** Probability density before Higgs discovery.

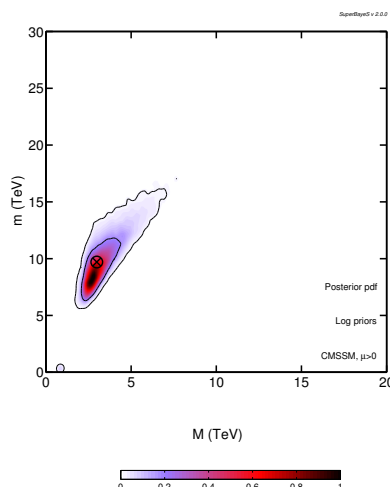
Fig.6 and Fig.7 show the posterior probability in the  $M - m$  plane (the other SUSY and SM parameters have been marginalized) before and after the inclusion of the Higgs discovery respectively. As expected the bulk of the probability has been pushed to higher scales, making problematic (though by no means impossible) the discovery of the CMSSM in the LHC. If one further includes dark matter constraints, then the co-annihilation region is essentially excluded (by the Higgs mass) and one is essentially left with the focus point region (part of it is also excluded by XENON data). This pushes further the probability to high-energy scales, as shown in Fig.8. The pessimistic conclusion is that not only the CMSSM is fine-tuned at  $\sim 1\%$ , but that, even if the CMSSM is true, its chances to be discovered at the LHC have decreased dramatically. Of course, there are some caveats, e.g. supersymmetric dark matter could be unstable due to a tiny amount of R-parity violation (without modifying the rest of the analysis). In that case the

<sup>1</sup> These analyses incorporate automatically (without any ad hoc consideration) a penalization of the fine-tuned regions. This is a logical result in a careful Bayesian study since these regions have little statistical weight. A welcome consequence of this is that the results are quite independent of the ranges chosen for the parameters and even of the choice of prior (e.g. flat or logarithmic).





**Figure 7.** The same as Fig.6 after Higgs discovery.



**Figure 8.** The same as Fig.7 with dark matter constraints.

actual dark matter would have a different origin and dark matter constraints would be irrelevant for SUSY, so Fig.8 would not apply.

### 3.2. And now what? (some present directions)

Let us now re-take the question we made a few pages ago. Do these results mean that SUSY is dead? We can add some complementary questions: To which extent the problems of the CMSSM remain in general MSSMs? Are there natural way-outs to this situation (maybe beyond the MSSM)?

To address these questions let us recall first the original motivations for the CMSSM. These were 1) Minimal Flavour and CP violation, 2) Simplicity, 3) The fact that it arises in some theoretically motivated scenarios (like minimal SUGRA or Dilaton-dominated SUSY breaking). From these motivations only the first one is robust, but the experimental results do not require completely universal soft terms. E.g. the third generation of squarks and sleptons could have very different masses. The degeneracy of gaugino masses at  $M_X$  is not experimentally justified either. Therefore, going beyond the CMSSM is very plausible. Does this solve the problems of the CMSSM?

This question can be explored by promoting the CMSSM to more general MSSMs compatible with the flavour and CP constraints. In this spirit, a pretty general and popular model is the so-called "phenomenological MSSM" (or pMSSM). It is directly defined at low-energy as an MSSM with no additional CP phases (apart from the CKM ones), and flavour-diagonal sfermion mass-matrices and trilinear couplings. Furthermore, the first and second generation are degenerate (with negligible  $A$ -terms) and the lightest neutralino is the LSP. This includes the possibility of a lighter third generation, as invoked in "natural SUSY" models. It also allows certain types of supersymmetric spectrum that can evade the detection at LHC. In particular if the LSP is heavy or the masses of the supersymmetric states are not far from each other ("compressed spectrum" [22]), then the supersymmetric events have small  $p_{Ts}$  and are triggered out in the experimental analyses. Let us briefly comment on all these possibilities.

First of all, as discussed in a previous section, the third generation cannot be too light, since it is needed to be rather heavy in order to reproduce (thanks to the radiative corrections) the experimental mass of the Higgs. This requirement is alleviated if  $A_t$  is close to its maximizing value, but still the required stop masses imply that the EW breaking is quite fine-tuned. The



situation is better if one goes *beyond* the MSSM. Then the tree-level Higgs mass can be larger, so one does not need such important radiative contributions. In consequence the third generation is allowed to be lighter, thus improving the naturalness of the EW breaking. One possibility in this direction is the next-to minimal MSSM (i.e. NMSSM), which has an extra singlet in the spectrum coupled to  $H_u$ ,  $H_d$  in the superpotential, which provides an extra source for the effective quartic coupling of the (scalar components of the) Higgses. Another possibility, keeping the degrees of freedom of the MSSM, is to assume that the scale of SUSY breaking is quite close to the size of the soft terms. This is called low-scale SUSY breaking or BMSSM (“B” stands for “beyond”). Let us recall here that the size of the soft terms typically goes like  $M_{\text{SUSY}} \sim F/\Lambda$ , where  $F$  is the SUSY breaking scale, which corresponds to the dominant VEV among the auxiliary fields in the SUSY breaking sector (it can be an  $F$ -term or a  $D$ -term) and  $\Lambda$  is the messenger scale, associated to the interactions that transmit the breaking to the observable sector. If  $\Lambda$  is close to  $M_{\text{SUSY}}$ , say  $\lesssim \mathcal{O}(10)$  TeV, then beside the usual soft terms there appear extra dimension-4 operators (e.g. quartic couplings between scalars) in the Lagrangian, suppressed by powers of  $F/\Lambda^2$ . Even if they are not very sizeable, they contribute to the tree-level Higgs mass, thus allowing smaller radiative corrections to  $m_h$  and hence smaller stop masses. In addition, since the RG running is much shorter, the “contamination” of the Higgs-mass parameters by the other soft terms is less important. This scenario, however, requires the existence of new physics (beyond SUSY!) at relatively low scales, thus reducing the beauty of SUSY as a solution of the Hierarchy Problem.

Regarding the chance of a compressed SUSY spectrum or a heavy LSP, it is undoubtedly possible to arrange the MSSM spectrum in these ways in order to fool the LHC. But, in the absence of a solid theoretical reason for them, it sounds a rather artificial possibility.

In any case, all this represents new challenges for the data analysis:

- Test more general MSSMs (like the pMSSM)
- Test a light third generation of SUSY particles
- Test a compressed SUSY spectrum or a heavy LSP
- Detect heavy SUSY

Regarding the search of a light third generation, the main problem is of course that the production of stops or sbottoms is very suppressed with respect to the first two generations, and there is nothing one can do about that. The present strategies are to look for direct stop and sbottom pair production or, if kinematically allowed, by their production through gluino decays. Roughly speaking, the present experimental limits imply that stop and sbottom masses can be anything  $\gtrsim 450$  GeV, so there is still a lot of room for a relatively light third generation. These limits will improve much with the future up-gradings in energy of the LHC. They can also improve with the developing of (even) smarter strategies for the data analysis, e.g. exploring new and clever kinematical variables and the like.

Concerning the probe of a compressed SUSY spectrum or a heavy LSP, the study of events with  $E_T^{\text{miss}} + \text{jets} + \text{multileptons}$  may play a crucial role in these scenarios since it is much easier to detect and characterise low- $p_T$  leptons than jets. With respect to heavy SUSY, the only way of improving (beside of course the progress in the luminosity and the energy of the LHC) is to design more efficient strategies of discovery. This includes to look for alternative channels, like chargino-neutralino production, that could be relevant (or even dominant) if the squarks and gluinos are too heavy. Let us recall here that the chargino and neutralino states arise from dimension-two and dimension-four mass matrices, which contain other parameters apart from the gaugino masses (particularly the  $\mu$ -parameter). This makes natural that the lightest states could be much lighter than the typical scalar and gluino masses. As mentioned above, progress can also occur by improving the kinematical variables used in the analyses and

also by performing more complete confrontations of theory vs. experiment (e.g. using the whole richness of the theoretical and experimental histograms).

Concerning the test of more general MSSMs (like the pMSSM), an strategy that is gaining relevance is the use of so-called “simplified models”. A simplified model is defined by an effective Lagrangian describing the interactions of a small number of new particles. They can also be described by a small number of masses and cross-sections. The latter parameters are directly related to collider-physics observables. The idea is to mimic the collider signatures of a particular physical scenario (e.g. the pMSSM) with a dominant simplified model (or a reduced set of them) in each region of the parameter space. This makes more efficient the exploration of such complex models. E.g. squark or gluino decays  $\tilde{q} \rightarrow q\chi_1^0$ ,  $\tilde{g} \rightarrow q\bar{q}\chi_1^0$  are dominant if the other relevant super-particles are heavier. In a simplified model their masses can be just sent to infinity. Of course, additional complexity can be built-in. The strategy is also efficient for non-supersymmetric models of new physics.

#### 4. The Hierarchy Problem under scrutiny

In the previous sections we have focused on SUSY scenarios, but of course there are alternatives to SUSY that may also solve or alleviate the Hierarchy Problem, such as Extra Dimensions or Composite and Little Higgs models. We have no room to review how the LHC has already constrained these scenarios. Roughly speaking, the situation is similar to that of SUSY, i.e. the scale of new physics has been pushed upwards, making them rather fine-tuned. Of course, using more or less ingenuity and cookery this pushing can be more or less dramatic, but it is a rather general fact. The reason is that the Hierarchy Problem requires, on very general grounds, the existence of new physics (with sizeable couplings to the SM states) at energies within the reach of the LHC. The argument is simple and well-known:

In the SM (treated as an effective theory valid below  $\Lambda_{\text{SM}}$ ) the mass parameter  $m^2$  in the Higgs potential

$$V = \frac{1}{2}m^2h^2 + \frac{1}{2}\lambda h^4 \quad (3)$$

receives important quadratically-divergent contributions. At one-loop,

$$\delta_q m^2 = \frac{3}{64\pi^2} \Lambda_{\text{SM}}^2 (3g^2 + g'^2 + 8\lambda - 8\lambda_t^2), \quad (4)$$

where  $g, g', \lambda$  and  $\lambda_t$  are the  $SU(2) \times U(1)_Y$  gauge couplings, the quartic Higgs coupling and the top Yukawa coupling, respectively. The requirement of no fine-tuning between the above contribution and the tree-level value of  $m^2$  sets an upper bound on  $\Lambda_{\text{SM}}$ . Using  $m_h = 125$  GeV,

$$\left| \frac{\delta_q m^2}{m^2} \right| \leq 10 \Rightarrow \Lambda_{\text{SM}} \lesssim 2 \text{ TeV} \quad (5)$$

where we have implicitly used  $v^2 = -m^2/\lambda$ ,  $m_h^2 = 2\lambda v^2$  (with  $v^{\text{exp}} = 246$  GeV). Consequently, we should expect new physics at  $\lesssim 2$  TeV able to cancel the quadratic contributions to the Higgs mass. Since the latter are dominated by the top, one would expect some new states that are somehow related to the top, namely interacting with the strong force and with large Yukawa couplings. This is exactly what happens for the stops in the SUSY scenario, but in general it will occur for other BSM candidates able to solve this Hierarchy Problem.

One of the lessons from the analysis of the CMSSM is that those new states could be quite light ( $\sim 500$  GeV) and still remain so far undetected at LHC. In the case of the CMSSM this possibility does not work very well because one needs heavy stops in order to reproduce the experimental Higgs mass. But this problem may be avoided in other scenarios of BSM physics (and in other SUSY scenarios, as discussed above). So it is still too soon to claim that the LHC

is putting the Hierarchy Problem argument in trouble. Nevertheless, if with higher luminosity and after subsequent upgradings in energy, we continue with no observations of new physics, the Hierarchy Problem should be re-visited.

## 5. Indirect searches

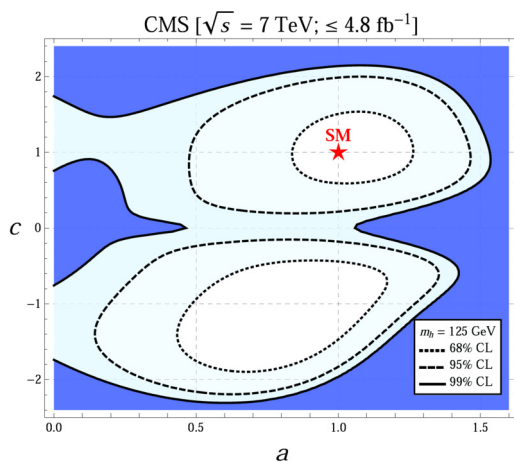
Let us now briefly consider the other way to search for new physics, namely to look for fingerprints in the effective theory. In the past this approach was used to put very important bounds on BSM physics from (LEP) EW precision tests. The procedure is conceptually simple. One starts with a Lagrangian

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \text{Higher - Dim Operators}$$

The second term of the r.h.s. carries the fingerprints of the BSM physics. In the LEP case, all data were consistent with the SM Lagrangian, so we were only capable to put exclusion-limits on the undetected new physics. But, had we been lucky, we could have discovered new physics at LEP. We can repeat now this scheme for the Higgs physics, which is starting to be probed at the LHC. In other words, we can use the information about Higgs-couplings from LHC data on Higgs production and decay, to constrain (or detect) BSM operators involving the Higgs. The approach is less spectacular than performing direct searches of new physics, but it may be more powerful (depending on the nature of the new physics) and it is more model-independent.

So one has to confront the observed rate of Higgs decays in different channels:  $\gamma\gamma$ ,  $ZZ$ ,  $WW$ ,  $b\bar{b}$ ,  $\tau\bar{\tau}$ ,..., with the SM prediction. Actually, at the moment there are discrepancies with the SM predictions, in particular there too many  $\gamma\gamma$  events (and also too few  $b\bar{b}$  events); but of course the error-bars are still too large and the statistics is too low to claim any BSM signal. However, if these deviations persist as the statistics increases, they could be an herald of new physics.

Assuming that in the effective theory there is just one Higgs state (as in the SM) whose couplings keep minimal flavour violation, not inducing flavour-changing-neutral-currents, one can write the effective Lagrangian for the Higgs, which is quite complex, see ref.[24]. A usual simplifying assumption is to take all the fermionic couplings proportional to the Yukawa coupling matrices with a universal factor,  $c$  and neglect higher orders. Similarly the couplings to the gauge bosons are as in the SM times a factor  $a$ . In this way the BSM physics is simply parametrized by the  $\{c, a\}$  parameters and the choice  $c = a = 1$  corresponds to the SM.



**Figure 9.** Favoured regions in the  $a - c$  plane, see text.

Fig.9 (from ref.[24]) shows the favoured regions in the  $a - c$  plane. There is an island around the SM prediction and a second, *more favoured* island around  $c = -1$ . The reason is that, due to the interference of diagrams with fermion and gauge-bosons loops, the branching-ratio to  $\gamma\gamma$

goes like  $BR(h \rightarrow \gamma\gamma) \sim |1.8c - 8.3a|^2$ . Consequently an excess in  $\gamma\gamma$ -events can be reproduced with a negative  $c$ . Keeping  $|c| \sim 1$ , the rest of the predictions are essentially as in the SM. The increase of statistics in the next years will tell us if this possible hint is reinforced or disappears.

## 6. Conclusions

The LHC is constraining BSM physics at an impressive efficiency, but no sign of new physics has been found yet. SUSY (and other BSM scenarios) are starting to be in trouble, though there is still room for new physics able to solve the Hierarchy Problem. This situation poses new challenges to optimize the LHC discovery potential using smarter strategies for analysis (in addition to the increasing LHC luminosity and energy). In this sense, direct and indirect searches of new physics can play complementary roles.

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