Contribution 9

CMSSM mass spectrum at the LHC after the 125 GeV Higgs boson results

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Abstract
We show that if the Higgs boson mass is 125 ± 1 GeV, the CMSSM sparticle spectrum that is testable at the LHC is restricted only to two distinct possibilities – either of the lightest slepton or stop are degenerate in mass with the lightest supersymmetric particle that is the dark matter. This implies that the CMSSM spectrum is now known. However, the two possible options both represent very difficult spectra for the LHC because very soft particles are produced in sparticle decays. We encourage the LHC experiments to perform detailed studies of the two possible CMSSM sparticle spectra.

1 INTRODUCTION

The consistent ATLAS [143] and CMS [144] hints for the existence of a $M_H \approx 125$ GeV Higgs boson have profound implications [177–179, 181, 182, 184, 272] for the sparticle mass spectrum in the context of the minimal supersymmetric standard model (MSSM). In particular, the versions of the MSSM with unification constraints on supersymmetry (SUSY) breaking parameters, such as the CMSSM or mSUGRA, becomes severely fine-tuned [272–276]. The reason is that such a high value of the Higgs boson mass requires unusually large scalar masses to generate the indicated Higgs mass at loop level.

At the same time, a $M_H \approx 125$ GeV Higgs boson mass implies that the possible LHC phenomenology of new CMSSM particles becomes highly predictive. This is because the global fits of the CMSSM parameter space are dominated by two phenomena [277]. The first one is the production of the correct dark matter (DM) relic density via very finely tuned freeze-out processes. The second is explaining the measured value of mthe uon anomalous magnetic moment $(g-2)_\mu$ with extra contributions from sparticles. All other phenomenological constraints, summarized in Table 1, are less constraining and, at present, play a role only in some particular corner of the CMSSM parameter space. As a result, the DM freeze-out processes alone determine the sparticle spectrum that is potentially observable at the LHC.

In this work we point out that the 125 GeV Higgs implies only two possible options for the CMSSM phenomenology at the LHC – the lightest stable SUSY particle, the DM, is (almost) degenerate with either the lightest slepton or stop. This is because for $M_H \approx 125$ GeV only the slepton and stop coannihilation processes can produce the correct DM density and have light sparticles. All other DM freeze-out processes imply unobservable sparticle spectra at the LHC. If, in addition, one also requires generation of the measured $(g-2)_\mu$,, at 3σ level only the slepton coannihilation region of the CMSSM parameter space survives (with a poor fit). This may be testable at the LHC.

quantity	experiment	Standard Model
$\alpha_3(M_Z)$ [282]	0.1184 ± 0.0007	parameter
m_t [283]	173.2 ± 0.9	parameter
m_b [44]	4.19 ± 0.12	parameter
$\Omega_{\rm DM} h^2$ [284]	0.112 ± 0.0056	0
δa_μ [285]	$(2.8 \pm 0.8) \times 10^{-9}$	0
BR($B_d \to X_s \gamma$) [286]	$(3.50 \pm 0.17) \times 10^{-4}$	$(3.15 \pm 0.23)\, 10^{-4}$
BR($B_s \to \mu^+ \mu^-$) [287]	$< 1.1 \times 10^{-8}$ at 95%C.L.	$(0.33 \pm 0.03)\, 10^{-8}$
BR($B_u \to \tau \bar{\nu}$)/SM [288]	1.25 ± 0.40	1

Table 1: *Constraints used for the CMSSM analyses.*

The implications of those results for the LHC are twofold. On the one hand, the CMSSM spectra testable at the LHC are now known and the experiments can concentrate on detailed studies of those spectra. On the other hand, those spectra are really difficult because the transverse momenta of the particles produced in sparticle decays are predicted to be very small due to the sparticle degeneracies. The aim of this work is to encourage the LHC experiments to analyze the slepton and stop degenerate spectra in detail.

2 THE DIFFICULT CMSSM SPECTRA

The CMSSM is one of the most thoroughly studied SUSY models and the CMSSM parameter space was rather fine-tuned already before the 125 GeV Higgs hint [277–281]. Naturally, if the Higgs boson is discovered with mass $M_H = 125 \pm 1$ GeV, one would like to know what the implication of this discovery is for the LHC phenomenology of this model. At the GUT scale the parameter space of the CMSSM is described by five parameters,

$$m_0,\ M_{1/2},\ A_0,\ \tan\beta,\ \mathrm{sign}(\mu), \tag{1}$$

the common scalar mass, the common gaugino mass, the common trilinear coupling, the ratio of the two Higgs vacuum expectation values (vevs) and the sign of the higgsino mass parameter. To scan over the CMSSM parameter space we randomly generate parameters in the following ranges: $300 < m_0,\ M_{1/2} < 10000$ GeV, $|A_0| < 5m_0, 3 < \tan\beta < 60, \mathrm{sign}(\mu) = \pm$. We use the MicrOMEGAs package [206, 208] to compute the electroweak scale sparticle mass spectrum, the Higgs boson masses, the DM relic abundance $\Omega_{\rm DM}$, the spin-independent DM-nucleon direct detection cross section $\sigma_{\rm SI}$ and the other observables in Table 1. In addition, we require $M_H = 125 \pm 1$ GeV. There is a few GeV theoretical uncertainty in the computation of SUSY Higgs masses in the available codes. Therefore, to select the phenomenologically acceptable parameter space we impose 3σ hard cuts for the observables in Table 1. Our approach should be regarded as an example study of the CMSSM parameter space for a heavy Higgs boson; qualitatively similar results should hold if the real Higgs boson mass deviates from 125 GeV by a few GeV. We first study the parameter space that induces correct M_H and $\Omega_{\rm DM}$. We discuss the implications of the $(g-2)_\mu$ constraint later.

In Fig. 1 we present our results in scatter plots without the $(g-2)_\mu$ constraint. In the left panel the results are presented in the $(m_0, M_{1/2})$ plane and in the right panel in the $(M_{\rm DM}, \sigma_{\rm SI})$ plane, where the first 100 days XENON100 constraint [196] is also shown. One can identify five

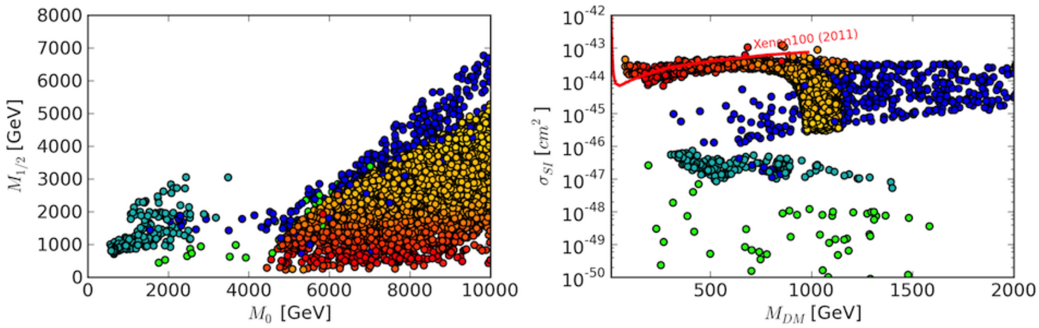

Figure 1: Points in the CMSSM parameter space yielding $M_H = 125 \pm 1$ GeV. Colours represent different dominant DM freeze-out processes. Light blue: slepton co-annihilation; green: stop co-annihilation; red to orange: well-tempered neutralino; yellow: higgsino; dark blue: heavy Higgs resonances. No $(g-2)_\mu$ constraint is imposed.

distinctive parameter space regions according to the dominant DM annihilation processes [272].

- The light blue points with small m_0 and $M_{1/2}$ represent the slepton co-annihilation region. They feature very large values of $\tan\beta$. Those points represent the best fit value of the CMSSM [277] and have low enough sparticle masses to allow potential SUSY discovery at the LHC. However, their spin-independent direct detection cross section is predicted to be below 10^{-46} cm^2 and remains unobservable by XENON100. The present XENON100 experimental bound is plotted in the right panel by a solid red line. This is the only parameter region that survives at 3σ level after the $(g-2)_\mu$ constraint is imposed.
- The green dots represent the stop co-annihilation region. Consequently those points have the lowest possible stop mass and, due to the mass degeneracy with DM, stops can be long lived and seen as stable very slow particles (R-hadrons) at the LHC. The feature of those points is an enormous trilinear coupling and very large mixing. In addition, the gluino mass can be in reach of the LHC. The spin-independent direct detection cross section is, unfortunately, unobservable.
- The dots represented by continuous colour code from red to orange represent the so called well-tempered neutralino, i.e., neutralinos with large bino-higgsino mixing. The colour varies according to the higgsino component from red (predominantly bino) to yellow (pure higgsino). Therefore those points can simultaneously have small DM mass and large DM-nucleon scattering cross sections that can be well tested by XENON100. However, apart from the DM, all other sparticle masses are predicted to be too heavy to be directly produced at the LHC.
- The yellow dots around $M_{\rm DM} \sim 1$ TeV represent the pure higgsino DM that is almost degenerate in mass with the chargino. The sparticle mass spectrum is predicted to be even heavier than in the previous case because the DM scale is fixed to be high. These points represent the most general and most abundant bulk of the $M_H = 125$ GeV Higgs scenario – apart from the light DM and heavy Higgs boson there are no other observable consequences because stops can completely decouple. In our case the 10 TeV bound on stops is imposed only because we did not generate larger values of m_0.
- The dark blue points represent heavy Higgs resonances. Those points are featured by

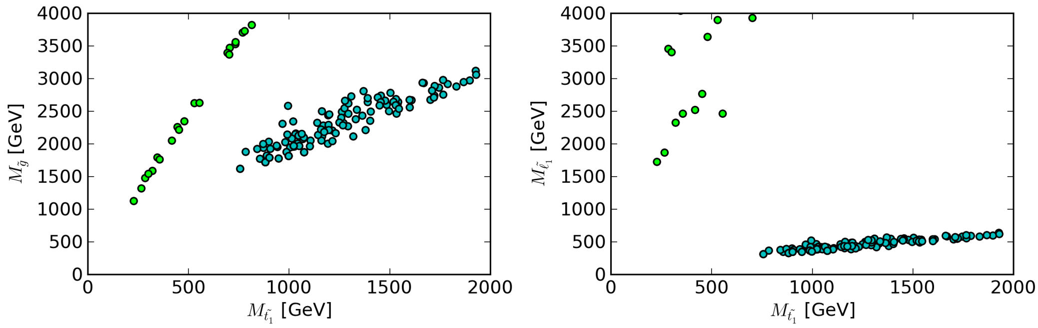

Figure 2: Scatter plots presenting correlations between physical lightest stop and gluino and lightest slepton masses.

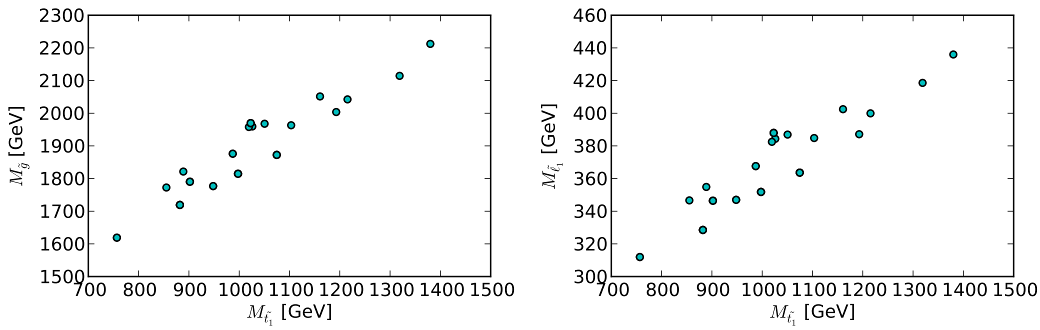

Figure 3: The same as in Fig. 2 after imposing a 3σ constraint on the $(g-2)_\mu$ prediction.

very large values of $\tan\beta$ and give the heaviest mass spectrum. In essence those points are just smeared out higgsino points due to additional Higgs-mediated processes.

In order to study the testability of those parameter space regions at the LHC we plot in Fig. 2 the physical gluino mass against the lightest stop mass and the lightest slepton mass against the lightest stop mass. Clearly, the slepton and stop co-annihilation regions are the only two regions that are of interest for the LHC phenomenology. According to Ref. [289] sparticles with those masses may be discovered already at the 7 TeV LHC. Interestingly, due to the stop mass degeneracy with DM the stops can be long-lived. In this case one must search for R-hadrons at the LHC experiments.

So far we have ignored the $(g-2)_\mu$ constraint. If we impose a hard 3σ cut on the generated parameter space, only the slepton co-annihilation region survives. The result is plotted in Fig. 3 where we repeat the content of Fig. 2 but with the additional $(g-2)_\mu$ constraint. As expected, the observed deviation in $(g-2)_\mu$ from the SM prediction is hard to explain in SUSY models with heavy spectrum. Therefore the two measurements, $(g-2)_\mu$ and $M_H = 125$ GeV, are essentially in conflict in the CMSSM. The conflict is mildest in the slepton co-annihilation case because of large $\tan\beta$ and the lightest sparticle spectrum. Therefore, for the $M_H = 125$ GeV Higgs boson, we predict definite sparticle masses and correlations between them, shown in Fig. 3, for the LHC. If the CMSSM is realized in Nature and if it contributes significantly to $(g-2)_\mu$, the sparticle spectrum is essentially fixed and potentially observable at the LHC.

3 DISCUSSION AND CONCLUSIONS

We studied the CMSSM by scanning over its parameter space allowing the sparticle mass parameters to be very large. We required the Higgs boson mass to be in the range 125 ± 1 GeV. The first considered case was without attempting to explain $(g-2)_\mu$ in the context of the CMSSM. We confirmed that for very large A-terms there exists a stop co-annihilation region where all DM, stop and gluino are preferably light. Due to the mass degeneracy between stop and DM the stops can be long lived resulting in non-trivial LHC phenomenology. The second parameter region that is potentially testable at the LHC is the slepton co-annihilation region. For all other cases the $M_H \approx 125$ GeV Higgs boson implies very heavy sparticle masses. The exception is, of course, the DM that can be light due to bino-higgsino mixing even if other sparticles are as heavy as 10 TeV. In this case the CMSSM cannot be tested at the LHC but there still is a chance to see the DM scattering off nuclei in the XENON100. Those results imply that from the point of view of the LHC phenomenology, the CMSSM sparticle spectrum is known and the LHC experiments should perform detailed studies of the stop and slepton co-annihilation spectra. Those, however, are the difficult ones at the LHC because of soft leptons produced in sparticle decays to the DM sparticles.

If, in addition, one attempts to explain also $(g-2)_\mu$ in this framework, there is immediate tension between the high SUSY scale and the large value of the needed $(g-2)_\mu$ contribution. We found that imposing the $(g-2)_\mu$ constraint, only the slepton co-annihilation region survived at 3σ level. In this case the CMSSM has a definite predictions of the sparticle masses and spectrum to be tested at the LHC experiments.

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