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Low-energy SUSY facing LHC constraints

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Summary. — Supersymmetry (SUSY) represents one of the most theoretically interesting extensions of the Standard Model (SM) and probably one of the most widely studied. In its low-energy incarnation it provides a simple solution to the hierarchy problem and it offers the perspective of being accessible to the LHC. However, up to now, no signs of the superpartners have been detected. In this talk we review the current status of low-energy SUSY in light of the current LHC constraints, using the results from the global fits of the `MasterCode` Collaboration as our main tool.

1. – Introduction

Supersymmetry is one of the most sensibly motivated extensions of the Standard Model (SM) —and one of the most widely studied. Indeed it provides a solution to several open theoretical issues of the SM, such as the hierarchy problem and the nature of dark matter. In its minimal incarnation, the Minimal Supersymmetric Standard Model (MSSM), it predicts, for each SM particle, the existence of a superpartner which differs by one-half unit of spin. Moreover it features an enlarged Higgs sector, composed of two Higgs doublets instead of one.

However, the negative results from SUSY searches during LHC Run 1 [1, 2] have started to constraint significantly various MSSM scenarios, especially those that are based on unification assumptions at some Grand Unified Theory (GUT) scale. Indeed, in these models (*e.g.*, the CMSSM [3-5], NUHM1 [6] and NUHM2 [7], $SU(5)$ [8]) unification imposes a correlation between the masses of colored sparticles, which are strongly constrained by the LHC, and the masses of electroweakly-interacting sparticles, whose bounds from direct experimental searches are much less severe (see fig. 1). These relations make it difficult to explain the discrepancy between the observed $(g-2)_\mu$ value and the SM prediction via the additional contribution from SUSY particles, since the electroweakly interacting sparticles are bounded to be relatively heavy by the limits on

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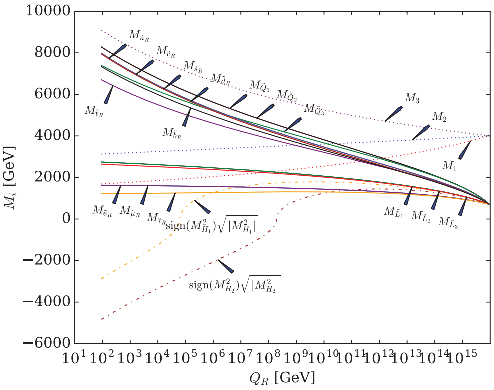

Fig. 1. – Renormalisation group flow for soft SUSY-breaking masses for an example point in the CMSSM, showing an example of the correlation between the colored and uncolored sector in the GUT scenarios of the MSSM such as the CMSSM.

squarks and gluinos. Therefore phenomenological models, whose SUSY parameters are instead given at a low energy scale and are not correlated by any theoretical assumptions, are becoming more and more appealing.

The complete, unconstrained, phenomenological MSSM (pMSSMn [9]) introduces a large number of new parameters and it is therefore difficult to study effectively. One possibility is then to focus our attention on a pMSSM version with a reduced number of parameters, in such a way to satisfy a few reasonable phenomenological assumptions: no new sources of CP violation should be introduced; no new sources of Flavour Changing Neutral Current (FCNC); universality of the first two generations is assumed.

2. – Global likelihood studies

The proper way to approach the study of the allowed parameter space of supersymmetric models, in light of the current LHC constraints, is to perform a global likelihood study. Several different Collaborations are (or were) active in this field [10-13]. In the following we present the results obtained by the `MasterCode` Collaboration. Results will be presented for $SU(5)$ GUT [8], mAMSB [14] and the pMSSM10 [15] models.

The `MasterCode` is a frequentist fitting framework written in C++, Python and Cython. It interfaces several different public and private codes that provide the theoretical predictions for the observables that enter the global χ^2 function. All codes are linked together using the SUSY Les Houches Accord (SLHA) [16] standard.

The sampling of the multi-dimensional parameter space is performed using the `MultiNest` algorithm [17-19].

For the study of the pMSSM10 (the most difficult scenario due to the high number of dimensions), a total of $\sim 1.2 \times 10^9$ points of the parameter space were sampled. In the other scenarios, less sampling is required, due to the smaller number of free parameters.

It is computationally impossible to check the consistency of all these points with all the available collider searches. To overcome this obstacle the SUSY searches are split into three categories. The first one includes those searches that constraint the production of colored sparticles. We use then the approach outlined in ref. [20] to build a look-up table that depends only on the gluino, squark ($m_{\tilde{q}_{1,2}}$ and $m_{\tilde{q}_3}$) and LSP masses. The second one contains searches that are relevant for the production of electroweakly interacting particles, while the third one is dedicated to compressed stop spectra. For these last two categories, we use specialized algorithms validated using the `Atom` [21] and `Scorpion` [22] codes. In all cases, all the information from the latest ATLAS and CMS searches has been included. Besides collider searches, we also include the constraints coming from:

- electroweak precision observables (`FeynWZ` [23]);
- flavor observables (`SuFla` [24], `SuperISO` [25]);
- cosmological and direct detection dark matter constraints. In detail, we consider the spin independent proton cross section (`SSARD` [26]) and the cold dark matter relic density (`micrOMEGAs` [27]);
- higgs sector observables, specifically the light Higgs mass and the production rates (`FeynHiggs` [28, 29], `HiggsSignals` [30], `HiggsBounds` [31]).

In the list above, we have specified in parenthesis the code that the we use in each case for the corresponding theoretical prediction. To generate the MSSM spectrum we have used `SoftSUSY` [32], while `SDECAY` [33] was used to calculate the sparticle branching ratios. We refer the reader to refs. [8, 14, 15] for an extensive explanation of the implementation of all the different experimental constraints included in our analyses.

3. – Results

In this section we highlight only a few phenomenological features from our studies, using results from our CMSSM, NUHM1, NUHM2, $SU(5)$, mAMSB and pMSSM analyses. We are obliged to make a selection because a complete description of the phenomenology of each of these scenario requires much more space to be completely described and for that we refer the reader to our articles [8, 14, 15, 34, 35].

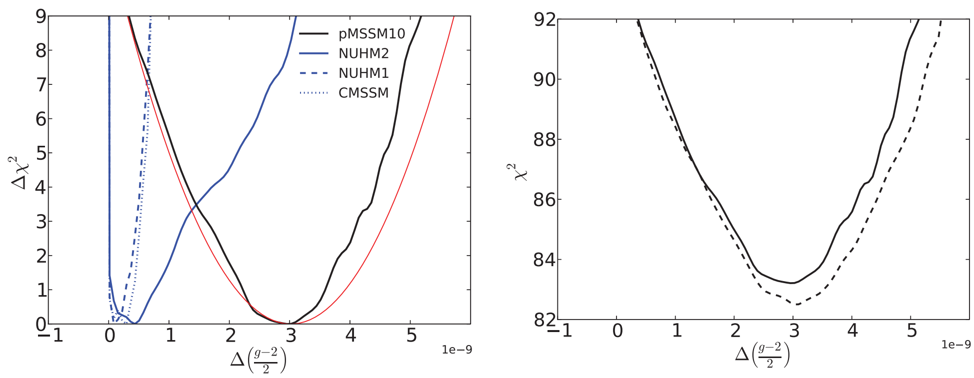

Fig. 2. – On the left: $\Delta\chi^2$ contribution of the $(g-2)_\mu$ constraint to the global fit for the CMSSM (dotted blue), NUHM1 (dashed blue), NUHM2 (solid blue) and the pMSSM10 (solid black). We also plot, as a reference, our assumed experimental likelihood using a solid red curve. On the right: global χ^2 curve, in the pMSSM10, with (solid black) and without (dashed black) the constraints coming from electroweakly interacting sparticle searches at the LHC.

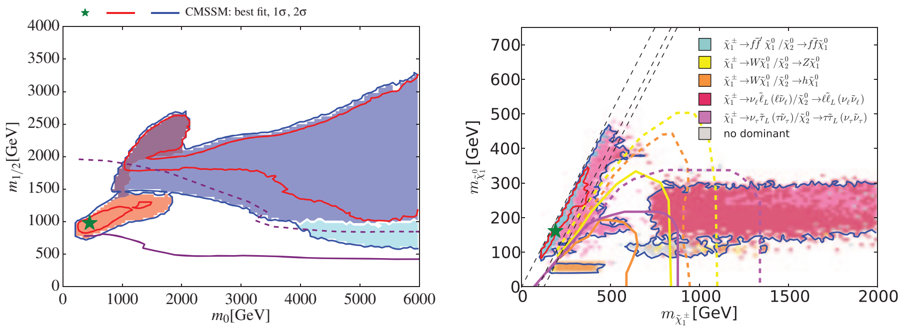

Fig. 3. – On the left: two-dimensional likelihood profiles at 68% CL (red) and 95% CL (blue), for the CMSSM, in the m_0-$m_{1/2}$ plane. The green star represents the location of the best fit point. The color shadings indicate which DM annihilation mechanism is important to satisfy the constraint coming from the observed relic density. The solid purple line shows the current limits from the LHC, while the dashed purple one shows the discovery reach after 3000 fb^{-1}. On the right: two-dimensional likelihood profiles at 68% CL (red) and 95% CL (blue), for the pMSSM, in the $m_{\tilde{\chi}^\pm_1}$-$m_{\tilde{\chi}^0_1}$ plane. The color shadings represent the dominant decay for the $\chi^\pm_1$; the colored lines represent the reach of the LHC with 300 fb^{-1} (solid) and 3000 fb^{-1} (dashed) for the searches which are sensitive to the decays highlighted with the same color in the plane.

One important qualitative difference between the pMSSM and the other scenarios is the ability of the former to reproduce the observed value of $(g-2)_\mu$ even after the inclusion of the limits on the SUSY particles coming from the LHC. Indeed, in the left of fig. 2 we show the one-dimensional likelihood for the CMSSM, NUHM1, NUHM2 (blue curves) and the pMSSM10 (black curve) relative to the best fit point of each scenario.

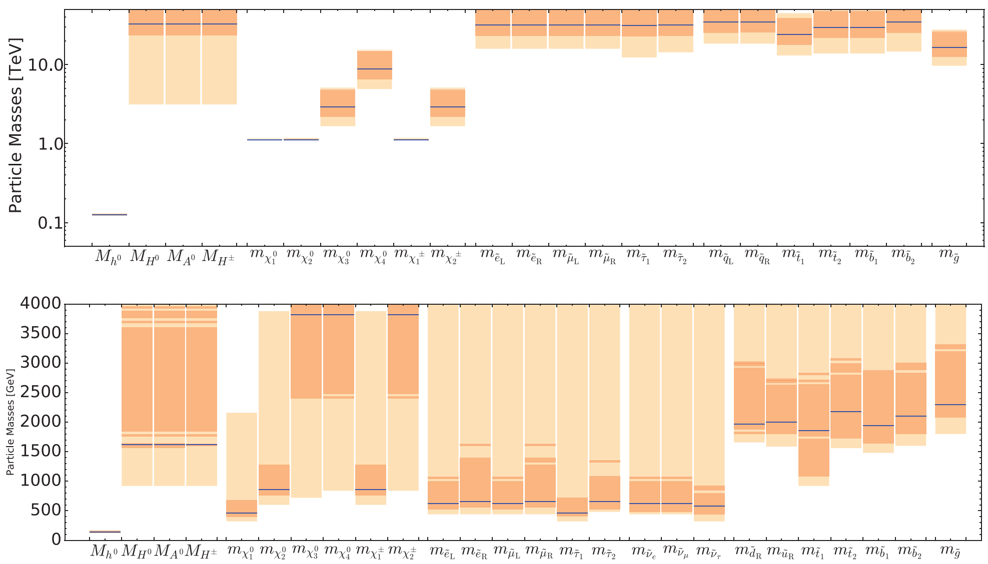

Fig. 4. – One-dimensional likelihood profiles for the sparticle masses at 68% CL (dark peach) and 90% CL (light peach) in the Higgsino region of the mAMSB model (with $\mu > 0$) and in the $SU(5)$ GUTs scenarios. The solid blue line indicates the values for the best fit point.

In red we overlay the experimental likelihood, observing that the pMSSM10 likelihood is very close to the experimental one. From the right plot, where we show the impact of the electroweakino searches at LHC Run I (solid *versus* dashed curve) we observe that those affect very little the pMSSM results.

Concerning the current allowed mass range for the sparticles after current LHC runs, it depends strongly on the scenario considered. In fig. 3 we show the two-dimensional likelihood contours for the CMSSM in the m_0-$m_{1/2}$ plane (left) and for the pMSSM10 in the $m_{\tilde{\chi}_1^\pm}$-$m_{\tilde{\chi}_1^0}$ plane (right). In the left plot we also show the current reach of the LHC (solid purple) and the after $3000\,\mathrm{fb}^{-1}$ of integrated luminosity (dashed purple). We observe that LHC will, at the end, be able to probe the stau coannihilation region (pink) completely but that at the same time large part of the parameter space will not be covered. In the right plot, future LHC searches are shown with a color coding corresponding to the color indicating the dominant decays they are sensitive to (shown in the plots as shaded areas). The line style (solid *vs.* dashed) represents the exclusion reach with $300\,\mathrm{fb}^{-1}$ and with $3000\,\mathrm{fb}^{-1}$, respectively . The interesting feature of this plot is that it shows that the 68% CL region and the best fit point will not be probed by the LHC, since they are characterized by a compressed $\tilde{\chi}_1^\pm - \tilde{\chi}_1^0$ spectrum, even if mass of the chargino is as low as a few hundred GeVs.

Turning now our attention to other scenarios, in fig. 4 we show a summary plot of the allowed mass range for the mAMSB model (with $\mu > 0$), in the region where the LSP turns out to be predominantly an Higgsino (top) and in the $SU(5)$ GUT model (bottom). The allowed mass range at 68% CL is shown with a dark peach color, while the 95% interval is shown with a light peach band. The best fit point values are plotted with a solid blue bar. The interesting information we can gather from these two plots is how different the SUSY spectrum can be depending on the theoretical assumptions on the soft SUSY-breaking mechanism. Indeed, in the mAMSB case, we observe that the allowed mass range makes it difficult for the sparticles to be observed at the LHC, while in the $SU(5)$ case the mass ranges extended to much lower values.

Finally, in fig. 5, we show the two-dimensional likelihood contours in the $m_{\tilde{\chi}_1^0}$-σ_p^{SI} plane for the mAMSB (left) and the pMSSM10 (right) scenarios. The color coding and line style is the same as in the previous figures. The shadings represent the LSP nature

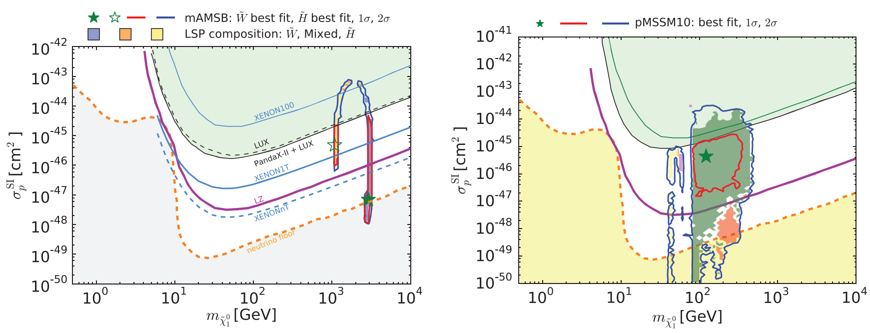

Fig. 5. – Two-dimensional likelihood profiles in the $m_{\tilde{\chi}_1^0} - \sigma_p^{SI}$ plane, on the left for the mAMSB model in the Higgsino region ($\mu > 0$) and on the right for the pMSSM10 scenario. Color shading indicates: on the left the nature of the LSP; on the right, the dominant DM annihilation mechanism.

in the leftmost plot and the dominant DM annihilation mechanism in the rightmost one. From the left plot it is interesting to observe that, while as it was shown in fig. 4 (top), this scenario is difficult to probe at collider due to the relatively heavy masses, it will be sensibly probed by the future generation of DM direct detection experiments. It stands therefore as one interesting example of complementarity between the collider and non-collider experiments. The same reasoning is valid also for the rightmost plot, where we can observe that the best fit-point of the MSSM and the whole 68% CL region will be completely probed by the future LZ experiment (purple solid line).

4. – Conclusions

In this talk we have described the current status of SUSY in its minimal realization, the MSSM, in a variety of different scenarios. We have underlined how the spectrum —and therefore also the ability of the LHC to probe SUSY— strongly depends on the scenario considered. However, even in the case of scenarios characterized by relatively heavy spectra, it is possible to probe the MSSM by using other experiments, as direct DM detection ones.

Concerning low-energy observables, we have also observed that the currently measured value for $(g-2)_\mu$ is difficult to explain in GUT scenarios as the CMSSM, while it can be perfectly accounted for in phenomenological scenarios where there is no correlation between the colored and the uncolored sector in the soft SUSY-breaking part of the Lagrangian (pMSSM).

New data from the LHC will allow us to put stronger limits on SUSY particles in a significant way, though the information coming from the LHC alone will not be probably sufficient to fully settle the status of low-energy supersymmetry, because of the difficulty of probing it in a specific region of the parameter space (*e.g.*, the compressed regions). However, complementarity between colliders and other experiments, at all energy scales, will allow us to have a better defined picture.

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