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On the MSSM with hierarchical squark masses and a heavier Higgs boson(*)

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Summary. — In the context of supersymmetric extensions of the Standard Model, we consider a spectrum in which the lightest Higgs boson has mass between 200 and 300 GeV and the first two generations of squarks have masses above 20 TeV, considering the Higgs boson mass and the Supersymmetric Flavour Problem as related naturalness problems. After the analysis of some models in which the previous spectrum can be naturally realized, we consider the phenomenological consequences for the LHC and for Dark Matter.

PACS 11.30.Pb – Supersymmetry.
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1. – Introduction and statement of the problem

Supersymmetry is surely one of the best motivated extensions of the Standard Model (SM). However, it is well known that the Minimal Supersymmetric Standard Model (MSSM) suffers for at least two phenomenological problems: on the one hand, the MSSM predicts $m_h \leq m_Z |\cos 2\beta|$ as upper bound for the lightest Higgs boson mass at tree level, in potential conflict with the LEP II lower bound $m_h \geq 114\,\text{GeV}$ [2]. On the other hand, the MSSM general flavour structure predicts signals potentially in conflict with the present good agreement between the SM prediction and the data. As is well known, the first problem is a naturalness problem: the sensitivity of the Fermi scale on the average stop mass makes unnatural to raise the mass of the lightest Higgs boson much above the tree level upper bound [3, 4]. At the same time, the flavour problem can be solved (or at least ameliorated) allowing the masses of the first two generations of squarks to be heavy enough to suppress unwanted signals [5]. Up to which value they can be pushed can be a naturalness problem as well, so that we argue in favour of a view in which the two issues, the "Higgs problem" and the "Flavour problem" may be related naturalness problems.

(*) Review of [1].

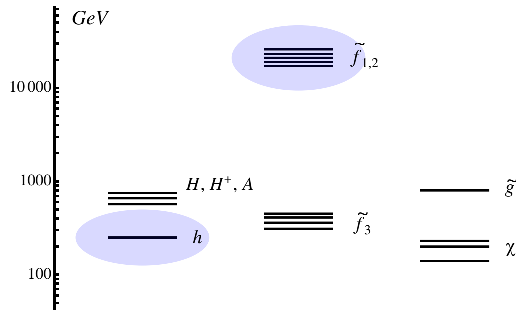

Fig. 1. – A representative of the spectrum we are considering, with $m_h = 200$–$300\,\text{GeV}$ and $m_{\tilde{q}_{1,2}} \geq 20\,\text{TeV}$.

To be more precise, the more stringent bounds on the masses of the squarks of the first two generations come from the $\Delta S = 2$ transitions, both real and especially imaginary [6]; demanding only for heavy squark masses, one ends up with masses of the order of hundreds of TeV, while demanding also for degeneracy and alignment between the first two generations of order of the Cabibbo angle, the lower bounds are relaxed: *i.e.* assuming $\delta^{LL} \gg \delta^{RR,LR}$ (where, according to the standard notation, $\delta \simeq \frac{|m_1^2 - m_2^2|}{(m_1^2+m_2^2)/2}$ and LL, RR and LR refers to left and right sector, respectively) and $\delta^{LL} \simeq \lambda \simeq 0.22$ we have (for details, see [1])

$$\begin{array}{rcl} \Delta C = 2 & \Rightarrow & m_{\tilde{q}_{1,2}} \geq 3\,\text{TeV}, \\ \text{Im}(\Delta S) = 2, \sin\varphi_{CP} \simeq 0.3 & \Rightarrow & m_{\tilde{q}_{1,2}} \geq 12\,\text{TeV}. \end{array} \tag{1}$$

Let us now formulate in equations our starting point: the two naturalness bounds (where $1/\Delta$ is the amount of fine-tuning and $m_{\tilde{t}}$ is the average stop mass) [3]

$$\frac{m_{\tilde{t}}^2}{m_h^2}\frac{\partial m_h^2}{\partial m_{\tilde{t}}^2} < \Delta, \qquad \frac{m_{\tilde{q}_{1,2}}^2}{m_h^2}\frac{\partial m_h^2}{\partial m_{\tilde{q}_{1,2}}^2} < \Delta \tag{2}$$

must be considered together. It is clear from eq. (2) that increasing the Higgs boson mass goes in the direction of relaxing any naturalness bound, so that it is conceivable to have squarks of the first two generations with masses high enough to solve the flavour problem without introducing too much fine-tuning. In summary, we seek for models in which the spectrum of fig. 1 can be realized in a natural manner.

Extensions of the MSSM that allow for a significant increase of the Higgs boson mass have been studied in the literature; a representative set is the following:

– *Extra* $U(1)$ *factor* [7]. The MSSM gauge group is extended to include an additional $U(1)_X$ factor with coupling g_x and charge $\pm 1/2$ of the two standard Higgs doublet. The extra gauge factor is broken by two extra scalars, ϕ and ϕ_c, at a scale significantly higher than v. The tree level upper bound on the mass of the lightest scalar becomes

$$m_h^2 \leq \left(m_Z^2 + \frac{g_x^2 v^2}{2\left(1 + \frac{M_X^2}{2M_\phi^2}\right)} \right) \cos^2 2\beta \tag{3}$$

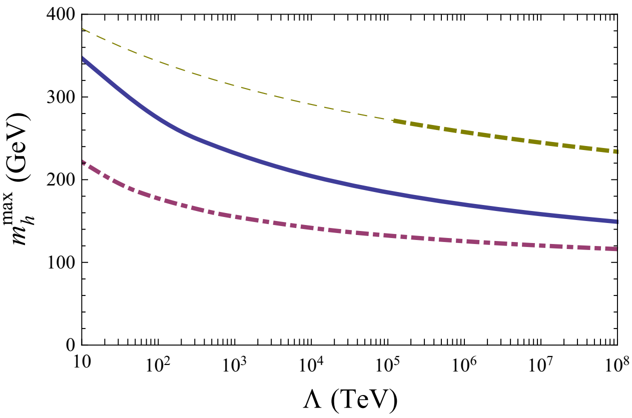

Fig. 2. – Upper bounds on m_h as a function of the scale Λ where some couplings become semi-perturbative in the three different cases: extra $U(1)$ (dot-dashed), λSUSY (solid) and $SU(2)$ (dashed).

where M_X and M_ϕ are the masses of the gauge boson and the soft breaking mass of ϕ and ϕ_c taken approximately degenerate.

– *Extra* $SU(2)$ *factor* [7, 8]. The extended gage group is now $SU(3)_{\rm c} \times SU(2)_{\rm I} \times SU(2)_{\rm II} \times U(1)_{\rm Y}$ where the two $SU(2)$ gauge groups are broken down to the diagonal subgroup by a chiral bidoublet Σ at a scale much higher than the electroweak scale. The upper bound on the mass of the Higgs boson is now

$$m_h^2 \le m_Z^2 \frac{g'^2 + \eta g^2}{g'^2 + g^2}\,, \qquad \eta = \frac{1 + \frac{g_I^2 M_\Sigma^2}{g^2 M_X^2}}{1 + \frac{M_\Sigma^2}{M_X^2}}\,, \tag{4}$$

where g_I is the gauge coupling associated to $SU(2)_I$, M_Σ the soft breaking mass of the Σ scalar and M_X the mass of the quasi-degenerate heavy gauge triplet vectors.

– $\lambda SUSY$ [9, 10]. This is the NMSSM [11] with a largish coupling λ between the singlet and the two Higgs doublets. The upper bound in this case is

$$m_h^2 \le m_Z^2 \left(\cos^2 2\beta + \frac{2\lambda^2}{g^2 + g'^2} \sin^2 2\beta \right). \tag{5}$$

Figure 2 shows the maximal value of m_h in the three different cases ($\tan\beta \gg 1$ in the extra-gauge cases and low $\tan\beta$ for λSUSY) as a function of the scale at which the relevant coupling becomes semi-perturbative.

2. – Constraints from naturalness and from colour conservation

We can now discuss what happens to the naturalness bounds of eqs. (2) once we raise the Higgs boson mass. First of all, the bound on the stop mass is relaxed, but now its

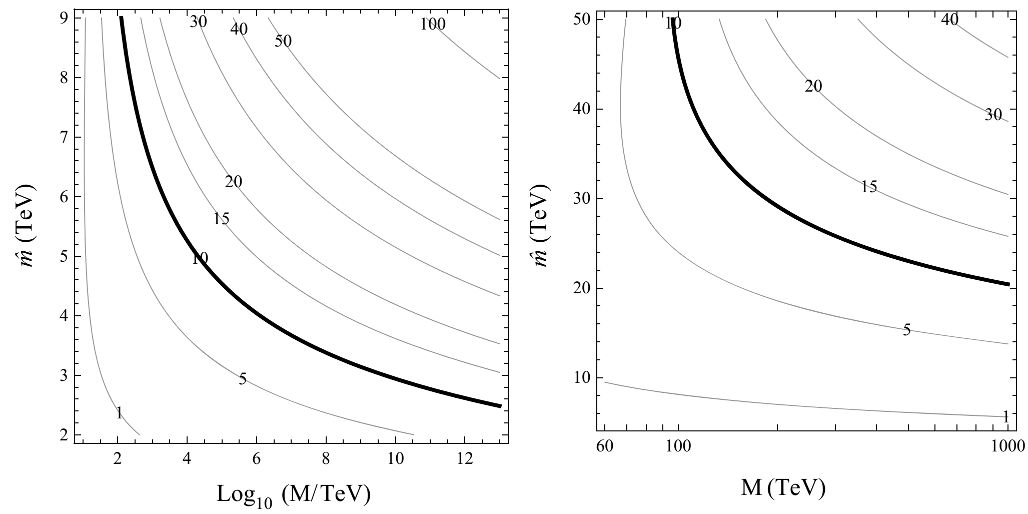

Fig. 3. – Naturalness upper bounds on the common mass of the squarks of the first two generations as a function of the scale M at which the renormalization group flow begins. Left panel: MSSM ($m_h = 120\,\text{GeV}$, $\tan\beta \gg 1$), right panel: λSUSY ($m_h = 200\,\text{GeV}$, $\tan\beta \simeq 1$).

value is no longer relevant for the "Higgs boson problem", since the mass of the lightest Higgs boson is above the LEP bound already at tree level. Concerning the bound on the mass of the squarks of the first two generations, fig. 3 shows the comparison between the MSSM ($m_h = 115\,\text{GeV}$, $\tan\beta \gg 1$) and λSUSY ($m_h = 250\,\text{GeV}$, $\tan\beta \simeq 1$), assuming a common mass $m_1 = m_2 = \hat{m}$ at the scale M at which the RGE flow begins (for details, see [1]). We do not show the analogous plot for the two gauge extensions since the bounds are much stronger than the MSSM case.

A complementary issue we have to care about is colour conservation, since the large values of the masses of the squarks of the first two generations can drive to negative values the squared mass of the third one [12]. To properly analyse the problem, we proceed as follows: first of all we take a value of $m_{\tilde{Q}_3}$ at M that gives at most a 10% fine-tuning on the Fermi scale; we then demand the running due to the squarks of the first two generation not to drive $m_{\tilde{Q}_3}$ to negative values. The upper bounds on $\hat{m}$ are shown in fig. 4 for different values of the gluino mass, in the MSSM (left panel) and λSUSY (right panel), for $m_h = m_Z$ and $m_h = 250\,\text{GeV}$, respectively. As can be seen, they are similar or weaker than the corresponding bounds obtained from naturalness considerations.

3. – Phenomenology

We now focus on the main phenomenological features of λSUSY: sparticle production and decays at the LHC, Higgs boson phenomenology and Dark Matter Direct Detection.

– It is well known that, at least in the first stage of the LHC run, the relatively more interesting signals will probably come from gluino pair production (at least for gluino masses not too large). An effective way to parametrize the signal is to consider the semi-inclusive branching ratios into $t\bar{t}\chi$ (B_{tt}), $t\bar{b}\chi$ (B_{tb}) and into $b\bar{b}\chi$ (B_{bb}) where χ stands for the LSP plus W and/or Z bosons. To an excellent

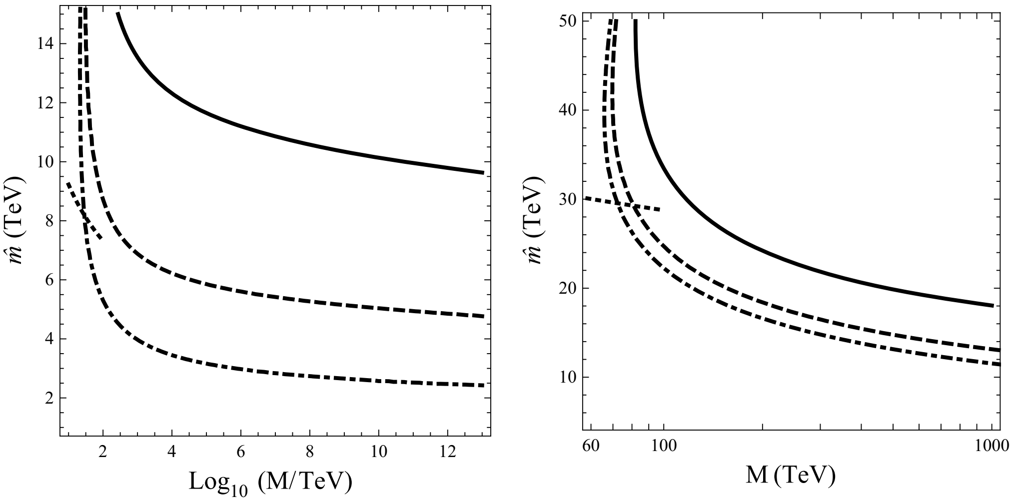

Fig. 4. – Upper bounds on the common mass $\hat{m}$ coming from colour conservation for different values of the gluino mass: 2 TeV (solid), 1 TeV (dashed) and 0.5 TeV (dot-dashed). Left panel: MSSM ($m_h = m_Z$), right panel: λSUSY ($m_h = 250$ GeV).

approximation,

$$B_{tt} + 2B_{tb} + B_{bb} \simeq 1 \tag{6}$$

in most of the relevant parameter space [1], so that the final state of gluino pair production is $pp \to \tilde{g}\tilde{g} \to qq\bar{q}\bar{q} + \chi\chi$ with q either a top or a bottom quark. A particularly interesting signal comes from same-sign dilepton production, with a branching ratio given by $BR(\ell^\pm\ell^\pm) = 2B_\ell^2(B_{tb} + B_{tt})^2$ where $B_\ell = 21\%$ is the branching ratio of the W boson into leptons. In a relevant portion of the parameter space, $BR(\ell^\pm\ell^\pm) = (2–4)\%$, unless the two sbottoms become the lightest squarks and/or $m_{\tilde{g}} \leq m_{LSP} + m_t$.

– As a consequence of the large Higgs boson mass, the most striking feature of λSUSY is the discovery of the Golden Mode $h \to ZZ$ with two real Z bosons. However, it must be stressed that such a signal depends on the chosen superpotential: indeed, in a non scale-invariant case [13], the decoupling of the singlet allows to simply have a heavier Higgs boson with standard couplings to fermions and gauge bosons, so that the Golden decay mode is typical. On the other hand, choosing a scale-invariant superpotential [14, 15], in a relevant region of the parameter space the decay of the lightest Higgs boson into a pair of pseudoscalars is the dominant decay channel, so that the discovery potential relies essentially on the ability of analyse signatures coming from this decay. Also intermediate situations are conceivable [16] in which, depending on the region of parameter space, both behaviours can be present.

– In λSUSY the LSP can acquire a singlino component, in contrast to what happens in the MSSM. Let us consider the case in which this component is negligible due to a decoupled singlino, so that the LSP is as usual an higgsinos/gauginos admixture

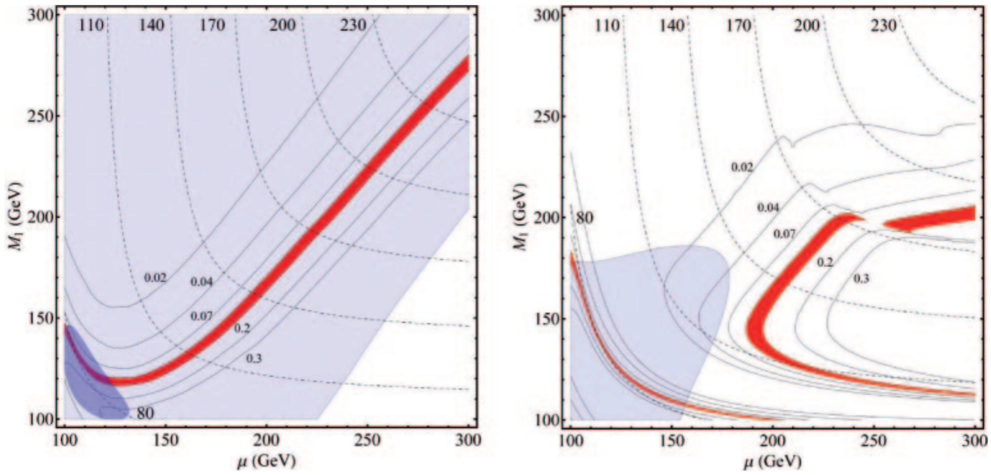

Fig. 5. – (Colour on-line) Isolines of DM abundance (solid) and of LSP masses (dashed) for a decoupled Wino. Dark blue regions: CDMS exclusion, light blue: Xenon100 2010 exclusion projection. Left: MSSM, $m_h = 120\,\text{GeV}$, $\tan\beta = 7$. Right: λSUSY, $m_h = 200\,\text{GeV}$, $\tan\beta = 2$.

that must satisfy the "Well-Temperament" [17] in order to reproduce correctly the Dark Matter (DM) relic abundance. To be more precise, let us focus on the well-tempered bino/higgsino with a decoupled wino. The situation is shown in fig. 5 for the MSSM ($m_h = 120\,\text{GeV}$, $\tan\beta = 7$) and λSUSY ($m_h = 200\,\text{GeV}$, $\tan\beta = 2$). The solid lines represent the DM abundance while the dashed lines are the LSP mass. The red region corresponds to a DM abundance compatible with the experiments, the dark blue region is the CDMS exclusion while the light blue region is the 2010 exclusion projection for Xenon100. As can be seen, in the MSSM case there is a precise correlation between μ and M_1, manifestation of the Well-Temperament. This is not the case for λSUSY, in which the Well-Temperament is completely disrupted around the region corresponding to a resonant Higgs boson exchange in the s-channel. Moreover, the exclusion coming from the direct searches are much weaker in the λSUSY case, since the spin-independent cross section of a DM particle on a nucleon falls off as $1/m_h^4$.

4. – Conclusions

We considered the possibility of regarding the "Higgs boson problem" and the "Supersymmetric Flavour Problem" as related naturalness problems, giving attention to models in which the Higgs boson mass is increased already at tree level. Among the considered possibilities, we found that in λSUSY [13] an Higgs boson mass of 250–300 GeV allows to raise the masses of the squarks of the first two generations up to 20 TeV without introducing too much fine-tuning, softening in this way the supersymmetric flavour problem. Among the main phenomenological consequences, it is interesting to stress the possibility of detecting the golden decay mode $h \to ZZ$ in association to typical supersymmetric signals due to multi-top final states. Regarding the DM, and focusing on a bino/higgsino LSP, the effect of an increased Higgs boson mass is twofold: on the one hand, the "Well-Temperament" pointed out in [17] is completely disrupted; on the other hand, only a small portion of parameter space is constrained by direct detection experiments, since the cross section falls off as $1/m_h^4$.

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