Do current LHC data really pose a problem for constrained SUSY?

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Recent LHC results, most notably new strong limits from ATLAS and CMS on direct supersymmetry searches, reaching now the TeV scale for superpartner masses, the first measurement by LHCb of BR $\left(\mathrm{B_s} \to \mu^+\mu^-\right)$ consistent with the Standard Model (SM), as well as the recently discovered Higgs boson with mass close to 126 GeVand with SM-like properties, have led some to people to claim that constrained supersymmetry (SUSY) has been (nearly) ruled out, one way or another. In this talk I will map out those ranges of superpartner masses that remain fully consistent with all experimental data, including the relic abundance of dark matter. I will point out that, while the LHC with increased energy will provide a rather directly way to explore those ranges, direct detection searches of dark matter (first LUX, and next one-tonne detectors) will be sensitive to almost all ranges of corresponding SUSY parameters. Improved determination of BR $\left(\mathrm{B_s} \to \mu^+\mu^-\right)$ will potentially provide additional important information by having a capability of independently ruling out the *A*-funnel region in (but not beyond) the constrained MSSM.

1 Framework and main results

In this talk I will address the current status of constrained SUSY in light of some recent results[1,2], where more details and references to the literature can also be found.

There are two main avenues to investigate effective models based on softly-broken global supersymmetry (SUSY). One is to confine oneself to the framework where a given model is defined basically entirely at the electroweak (EW), or $\sim 1\,\mathrm{TeV}$, scale, as is done in the Minimal Supersymmetric Standard Model (MSSM), or in some extensions thereof, like the Next-to-MSSM (NMSSM) with an extra Higgs singlet superfield. In this approach one faces a large number of free parameters, mostly generated by breaking SUSY softly, and strong simplifying assumptions have to be made to reduce the number to a manageable level.

Another, more motivated and over the last two decades more popular, approach has been to consider SUSY in the context of grand unification where soft SUSY breaking parameters are unified. A prime model of this class is the Constrained MSSM (CMSSM) - the most popular and economical effective SUSY model of phenomenological interest, although somewhat more relaxed scenarios, like the Constrained NMSSM (CNMSSM), or Non-Universal Higgs Model, are also often considered.

In the CMSSM, three of its four defining parameters are set at the scale of grand unification. These are the universal scalar mass m_0, the universal gaugino mass $m_{1/2}$, and the universal trilinear coupling A_0. Additionally, $\tan\beta$ (the ratio of the expectation values of the two Higgs

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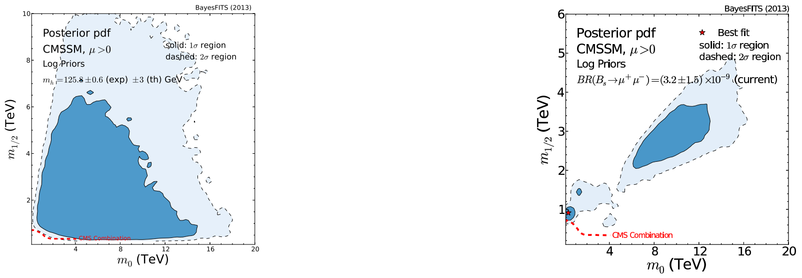

Figure 1: Left: Marginalized 2D posterior pdf in the (m_0, $m_{1/2}$) plane of the CMSSM constrained only by the Higgs mass and the LHC SUSY searches. The 68% credible regions are shown in dark blue, and the 95% credible regions in light blue. The dashed red line shows the CMS combined 95% CL exclusion bound. Right: Marginalized 2-dim. posterior pdf in the (m_0, $m_{1/2}$) plane of the CMSSM for $\mu > 0$, constrained by the experiments listed in Table 2 with current uncertainties for $\mathrm{BR}\left(\mathrm{B_s} \to \mu^+\mu^-\right)$.

doublets), is defined at the electroweak scale, while the sign of the Higgs/higgsino parameter μ remains undetermined.

In the CMSSM mass limits from direct SUSY searches by ATLAS and CMS have now pushed gluino and 1st/2nd generation squark masses far beyond 1 TeV, which corresponds to $m_{1/2} \gtrsim 850$ GeV. Similar conclusions can be expected, and in some cases have been shown to hold, in less constrained models[3]. Furthermore, it has been argued that, it is hard to reproduce the mass of the discovered Higgs boson of about 126 GeV, if one restricts oneself to the SUSY breaking scale M_{SUSY} roughly below 1 TeV. This has been interpreted by some as a death kneel of the constrained SUSY approach. Such conclusions are not, however, based on experimental data but rather on theoretical expectations coming from "naturalness", or "little hierarchy problem". Instead I will adopt a pragmatic, data-driven approach, and map out ranges of SUSY parameters that are consistent with all current data. At present the most important among them are: the Higgs mass and the relic abundance of neutralino as dark matter (DM).

I will argue that generically the Higgs mass of about 126 GeV favors ranges of M_{SUSY} in the multi- TeV regime, which have so far been only very mildly constrained by direct SUSY searches. This is shown in the left panel of Fig. 1 where I show 1- and 2σ (credible) regions of Bayesian total posterior probability. In the likelihood function two constraints were included: information about SM-like Higgs with mass 125.8 GeVwas encoded via a Gaussian function assuming experimental (theory) error of 0.6 (2) GeV, while a lower limit from direct SUSY searches from CMS was included through an approximate but accurate procedure described in [2]. One can see the favored ranges of $m_{1/2}$ and m_0 lie in the multi- TeV regime, and are only very mildly constrained from below by LHC limits on SUSY.

However, as one can see in the right panel of Fig. 1, imposing the relic density of DM select some specific regions: the $\tilde{\tau}$-coannihilation (SC) region at small m_0 and large $m_{1/2}$, the A-funnel (AF) region to the right and above it, which is relatively small at 1σ but much larger at 2σ, and the focus point (FP)/hyperbolic branch (HB) region at large m_0 and $m_{1/2} \lesssim 1$ TeV. The FP/HB region is now disfavored relative to our previous analysis[1], because it produces slightly low Higgs mass and appears at only 2σ.

The region that is most prominently visible in the figure along the diagonal of the box appears as a result of extending the ranges of m_0 and $m_{1/2}$ far beyond those used in [1]; see Table 1. In the new region the lightest neutralino is higgsino-like and its mass is set by the μ-parameter and is close to 1 TeV in order to produce correct relic abundance. In some sense this region most naturally corresponds to the Higgs mass of about 126 GeV. On the other hand, it does imply very large m_0 and $m_{1/2}$ in the multi- TeV regime. While it is the dark matter density that plays the dominant role in selecting the above regions, in our Bayesian analysis and

Table 1: Priors for the parameters of the CMSSM and for the SM nuisance parameters used in our scans. Masses and A_0 are given in GeV.

CMSSM parameter	Description	Prior Range	Prior Distribution
m_0	Universal scalar mass	100, 20,000	Log
$m_{1/2}$	Universal gaugino mass	100, 10,000	Log
A_0	Universal trilinear coupling	-20,000, 20,000	Linear
$\tan\beta$	Ratio of Higgs vevs	3, 62	Linear
$\mathrm{sgn}\,\mu$	Sign of Higgs parameter	$+1$ or -1	Fixed
Nuisance	Description	Central value ± std. dev.	Prior Distribution
M_t	Top quark pole mass	173.5 ± 1.0	Gaussian
$m_b(m_b)^{\overline{MS}}_{\mathrm{SM}}$	Bottom quark mass	4.18 ± 0.03	Gaussian
$\alpha_s(M_Z)^{\overline{MS}}$	Strong coupling	0.1184 ± 0.0007	Gaussian
$1/\alpha_{\mathrm{em}}(M_Z)^{\overline{MS}}$	Inverse of electromagnetic coupling	127.916 ± 0.015	Gaussian

numerical scan we have included all relevant constraints; see Table 2 for a complete list. Suffice it to say that, in addition to dark matter density, at present three recent results from the LHC play a particularly important role in the analysis: (i) SM-like Higgs with mass 125 GeV; (ii) a lower limit on the plane $(m_0, m_{1/2})$ placed by a recent CMS analysis, for which we derived an approximate but very accurate likelihood function (see the right panel of Fig. 1 from Ref. [1]), and a comparable one obtained by ATLAS using 0-lepton search; and finally (iii) a new positive measurement of $\mathrm{BR}\,(\mathrm{B_s} \to \mu^+\mu^-)$ by LHCb.

An obvious question arises whether such large ranges of SUSY mass parameters can be experimentally tested. Clearly, direct searches at the LHC will have only very limited potential in this respect, since gluino and squark masses will be probed up to about 3 and 2.7 TeV, respectively. Fortunately, there are two ways through which much larger ranges can be tested.

Firstly, future direct detection searches are expected to reach the sensitivity needed to explore basically the whole ranges of the spin-independent cross section σ_p^{SI} of dark matter scattering off nuclei. This is presented in Fig. 2. In the left panel we show 2-dim. marginalized posterior pdf in the $(m_\chi,\sigma_p^{\mathrm{SI}})$ plane for the CMSSM obtained by imposing the experiments listed in Table 2. In the left panel the current determination of $\mathrm{BR}\,(\mathrm{B_s} \to \mu^+\mu^-)$, including also a substantial theory error, is used while in the right panel expected future uncertainties are assumed around the current SM value (which is slightly higher than the current central experimental value from LHCb). Note that the AF region is now absent as inconsistent with SM-like values of $\mathrm{BR}\,(\mathrm{B_s} \to \mu^+\mu^-)$.

These properties of the CMSSM will allow one to basically fully explore the CMSSM for $\mu > 0$. In particular, the new generic 1 TeV higgsino region (which also appears in the NUHM[?]) will provide access to multi-TeV regions of M_{SUSY} via direct DM searches. This remains true for $\mu < 0$ as well, although well-known negative interference can reduce σ_p^{SI} way beyond expected experimental sensitivity for lower m_χ. Slight improvement over the current limits in σ_p^{SI} will also firmly rule out the FP/HB region which already now produces slightly too high σ_p^{SI}.

Beyond the CMSSM the role of direct detection of DM will remain very strong, including the CNMSSM [3] and even the MSSM with nine free parameters [4]. On the other hand, the discriminating role of $\mathrm{BR}\,(\mathrm{B_s} \to \mu^+\mu^-)$ is less clear. While in general reducing the uncertainties in its determination (assuming it remains consistent with the SM) will rule out many otherwise allowed choices of parameters, it appears that only in the CMSSM this constraint can lead to removing the AF region from the $(m_0,m_{1/2})$, or alternatively $(m_\chi,\sigma_p^{\mathrm{SI}})$, plane. In more extended models the AF region overlaps with the other cosmologically favored regions and the impact of imposing projected $\mathrm{BR}\,(\mathrm{B_s} \to \mu^+\mu^-)$ will be less clear-cut.

Table 2: The experimental measurements used to constrain the CMSSM's parameters. Masses are given in GeV.

Measurement	Mean or Range	Error: (Exp., Th.)	Distribution
Combination of:			
CMS razor 4.4/fb , $\sqrt{s} = 7\,\text{TeV}$	See text	See text	Poisson
CMS α_T 11.7/fb , $\sqrt{s} = 8\,\text{TeV}$	See text	See text	Poisson
m_h by CMS	$125.8\,\text{GeV}$	$0.6\,\text{GeV}, 3\,\text{GeV}$	Gaussian
$\Omega_\chi h^2$	0.1120	0.0056, 10%	Gaussian
$\delta\,(g-2)_\mu^{\text{SUSY}} \times 10^{10}$	28.7	8.0, 1.0	Gaussian
$\text{BR}\left(\overline{\text{B}} \to \text{X}_\text{s}\gamma\right) \times 10^4$	3.43	0.22, 0.21	Gaussian
$\text{BR}\,(\text{B}_\text{u} \to \tau\nu) \times 10^4$	1.66	0.33, 0.38	Gaussian
ΔM_{B_s}	$17.719\,\text{ps}^{-1}$	$0.043\,\text{ps}^{-1},\ 2.400\,\text{ps}^{-1}$	Gaussian
$\sin^2\theta_\text{eff}$	0.23116	0.00012, 0.00015	Gaussian
M_W	80.385	0.015, 0.015	Gaussian
$\text{BR}\left(\text{B}_\text{s} \to \mu^+\mu^-\right)_\text{current} \times 10^9$	3.2	$+1.5-1.2$, 10% (0.32)	Gaussian
$\text{BR}\left(\text{B}_\text{s} \to \mu^+\mu^-\right)_\text{proj} \times 10^9$	3.5 (3.2*)	0.18 (0.16*), 5% [0.18 (0.16*)]	Gaussian

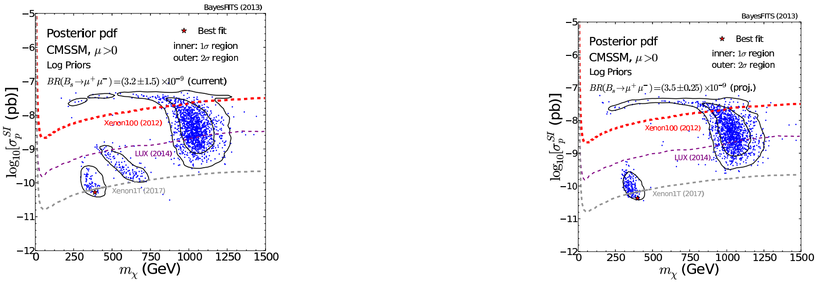

Figure 2: Left: A 2-dim. marginalized posterior pdf in the $(m_\chi,\ \sigma_p^{\text{SI}})$ plane for the CMSSM constrained by the experiments listed in Table 2, including current uncertainties in $\text{BR}\left(\text{B}_\text{s} \to \mu^+\mu^-\right)$. The current XENON100 (dash-dot red) and projected LUX (dash purple) and 1-tonne (dash grey) limits are shown but not imposed. Right: The same but assuming a projected determination of $\text{BR}\left(\text{B}_\text{s} \to \mu^+\mu^-\right)$.

2 Procedure

In our analysis we simultaneously scan over wide ranges of the four CMSSM parameters and, in addition, over four SM nuisance parameters, as specified in Table 1. Random scans are done with our numerical code BayesFITS. The physical constraints that we impose are listed in Table 2. They are all defined and discussed in our papers [1,3,2,?].

Space limitations do not allow me to enter into a longer discussion of the procedure used and the whole range of our results. Below I will therefore only briefly summarize the main points and refer the reader to our papers for a detailed presentation of our analysis and a list of references.

The physical constraints, along with their respective experimental and theoretical errors, if available, are all incorporated in the analysis via a likelihood function. Positive measurements (e.g., the relic density $\Omega_\chi h^2$of neutralino dark matter) are all approximated by a Gaussian distribution, while experimental limits are smeared out by an error function.

References

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