Supersymmetric Higgses beyond the MSSM: An update with flavour and Dark Matter constraints

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Abstract

Spurred by the discovery of a boson resonance at the LHC as the result of the search for the Standard Model Higgs, we pursue our investigation of the properties and signatures of Higgses in an effective supersymmetric scenario that goes beyond the usual MSSM. Such scenarios were first introduced to alleviate the naturalness problem of the MSSM Higgs and are found to have a very rich phenomenology that allows departures from the Standard Model in the production rate of the Higgs in many of the search channels. We now include the constraints from flavour observables in particular the rare decays $B \to X_s^\ast \gamma$ and $B_s \to \mu^+ \mu^-$ including the recent measurement from LHCb. We also address the issue of Dark Matter and its impact on Higgs physics. In particular, we incorporate the latest data from XENON100 on the spin independent direct detection rates. These turn out to be powerful constraints, especially if one also imposes that the observed thermal relic density is obtained. We also study models with a low abundance that can more easily evade the direct detection rates. We study the impact of the flavour and Dark Matter observables on the production rates of the Higgs at the LHC, and their correlations in the diphoton, diphoton+jets and 4 leptons. We also comment on the other channels.

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1 Introduction

The July 4th 2012 announcement by both the ATLAS \cite{1,2} and CMS \cite{3} Collaborations of a 5\(\sigma\) resonance as a result for the search of the standard model Higgs boson may well correspond to the discovery of the last missing piece of the standard model, SM. The SM should then be elevated to the status of a theory especially in view of the fact that the mass of this resonance is in accord with the indirect limits from precision measurements. If this particle turns out to be indeed the Standard Model Higgs with perhaps no new particles being discovered, the naturalness argument that has motivated the construction of so many beyond the SM (BSM) models will remain a mystery. These BSM constructions also aimed at providing a dark matter (DM) candidate for which the LHC might have provided some circumstantial evidence. Probing the nature of the newly discovered resonance will certainly take time. Moreover the present data, though compatible with a SM Higgs interpretation when all analyses are combined, seems to deviate from the prediction of the SM in some channels. In particular the 2\(\gamma\) final state channel points to a signal rate that is higher than what is predicted in the SM. Other couplings, like the crucial coupling to \(WW/ZZ\) require more data taking. As soon as the July results were made public, there has been a flurry of analyses aiming at fitting the Higgs couplings in a model independent way \cite{4}. Other analyses concentrated on specific models. Most prominent among the latter analyses was the status of the MSSM \cite{5,6} (MSSM for the Minimal Supersymmetric Standard Model). Unfortunately the mass of the resonance, \(\sim 125\) GeV, is very difficult to reconcile with naturalness in the MSSM, see for example \cite{7}. Moreover, unless one appeals to quixotic \cite{8} choices of the parameters it is impossible for the 2\(\gamma\) rate to be higher in the MSSM than in the SM. Yet, it is hard to give up the idea of supersymmetry, not only because of the DM candidate. One must then seek models beyond the MSSM. The NMSSM (Next to MSSM) for example has been shown to fit better the data \cite{9,10,11,6}. Specific extended versions with ultraviolet (UV) completion have also been proposed. It is therefore important to follow an effective theory approach that encapsulates the effects of a large class of specific UV completed scenarios beyond the MSSM and to parametrise the implications of some unknown model based on the symmetry of the low lying theory, namely the MSSM. The main motivation for such an approach that keeps the same field content as the MSSM, has been that the addition of a few operators in the Higgs sector \cite{12,13,14,15,17,18} alleviates very easily the fine-tuning and naturalness problem. One no longer requires heavy stops to have the lightest Higgs, \(h\), weigh 125 GeV. In fact, before the LHC Higgs data of 2011 these generic BMSSM models accommodated a lightest Higgs as heavy as 250 GeV. The phenomenology of these models is very rich, since the properties of the Higgses can change drastically. Such a set-up could serve for an analysis of the two Higgs doublet model \cite{19,20,21}. Nonetheless the set-up is more restrictive, not only because of the contribution of the higher dimensional operators to Higgs observables but also because the superfield implementation means that the Higgsino sector is affected. There are then implications on dark matter observables and, considering the link between Higgs and heavy fermions, on flavour physics, in particular the rare B-decays \(B_s \rightarrow \mu^+ \mu^-\) and \(B \rightarrow X_s^{\ast} \gamma\). LHCb \cite{22} has for example set new stringent constraints on \(B_s \rightarrow \mu^+ \mu^-\). As far as DM detection is concerned, July 2012 has also seen XENON100 \cite{23} set unprecedented bounds on the rate of direct detection, while the last few years have witnessed a measurement of the relic density of DM that has reached a precision of 3%. One has therefore, no doubt, entered an exciting era in probing the details of symmetry breaking and confront them with models that provide at the same time a dark matter candidate. In view of the LHC results and the improvements that are expected in the coming months and years on the reconstruction of the Higgs properties, an effective theory approach that generalises the usual MSSM and may encompass specific manifestations (extra singlets \cite{24,25}, extra triplets \cite{26,27}).
The updated analysis in this paper is warranted. This paper is an update on our recent detailed analyses that took into consideration all of the constraints on Higgs physics including the LHC 2011 data, the electroweak indirect precision measurements and other constraints such as $t \rightarrow bH^+$. Like in our previous analyses we do not aim at finding the best fits to the 2012 Higgs search/signal data for the effective parameters of the higher order operators, not because they are numerous, but because we consider such an exercise, considering the experimental uncertainty, to be rather premature. Instead, in the signal region with an alleged Higgs of 125 GeV, we will compute the possible signal strengths of the different channels together with the correlations between the different search channels. Although the mass for the alleged signal has narrowed around 125 GeV, we still present our results for the range $122 - 128$ GeV. In this update we include the impact of the rare decays $B_s \rightarrow \mu^+\mu^-$ and $B \rightarrow X^*_\gamma$ on the signal strengths. We will then address the issue of dark matter, in particular the impact of the spin-independent direct detection constraints and then the relic density. Though some model dependence is introduced with DM, we will see that the constraints can shed important light on the nature of DM. In a first stage we will assume that the BMSSM lightest supersymmetric particle (LSP) accounts for all of DM and look how direct detection, in particular XENON100, restricts the parameter space and what consequences on the Higgs signals it brings. In a second stage we investigate which of these scenarios do indeed provide the observed relic abundance. In a third stage we review models where the abundance is low. Although these models can not account for all of DM, the direct detection rates can be more easily evaded. For such configurations we review the Higgs signal strengths.

Very little has so far been done as regards flavour and Dark Matter in the BMSSM and certainly not from the point of view of the Higgs signal. Prior to the Higgs signal results, flavour observables in the BMSSM have been studied in [29]. Dark Matter, in particular the relic density, has been considered in [30, 31, 32, 33]. In all these studies only the case of dim-5 operators has been considered. In our study we include the full set of operators up to dim-6.

The paper is organised as follows: in section 2 a brief description of the model and the prominent experimental features are presented. Some technical issues having to do with the calculation of the different observables are reviewed in this section. Section 3 implements the constraints from $B_s \rightarrow \mu^+\mu^-$ and $B \rightarrow X^*_\gamma$ and study the consequences on the Higgs observables. With the flavour constraints taken into account, we make the link with DM in section 4. First, we look at the effect of direct detection as set by XENON100 (2012) assuming the model accounts for all of DM. We then impose the bound set by the observed relic density. We finally consider models with an abundance which is lower than what is observed. Section 5 summarises our conclusions.

## 2 Description of the model

Since the interested reader will certainly learn the details of the model in [17] and the references therein, we will only sketch a quick overview. The model is within the effective theory approach where the effects of extra degrees of freedom beyond those that describe the MSSM are taken into account through higher order operators. The scale, $M$, that enters these higher order operators is the heavy scale of the New Physics (beyond the MSSM). We set this scale at

$$M = 1.5 \text{ TeV},$$

(1)

Since our low energy theory is supersymmetry (precisely the MSSM), $L_{\text{low energy}} = L_{\text{MSSM}}$, these effective operators will be products of superfields. Given that we are not assuming anything on the UV completion of the theory, those operators can be any gauge and super Poincaré invariant product of superfields. Since we concentrate on Higgs phenomenology, we only consider operators
involving the Higgs superfields. In any case, in the same way that radiative corrections to the Higgs in the MSSM have a very big impact, we suspect that these operators can change the Higgs phenomenology in an important way. As we [17, 18], and others [12, 13, 14, 15, 16], have done so far, we include the dim-5 (superpotential) and dim-6 (Kähler) operators.

They are the following:

\[
W_{\text{eff}} = \zeta _1 \frac{1}{M} (H_1 H_2)^2, \tag{2}
\]

\[
K_{\text{eff}} = a_1 \frac{1}{M^2} \left( H_1^1 e^{Y_1} H_1 \right)^2 + a_2 \frac{1}{M^2} \left( H_1^1 e^{Y_2} H_2 \right)^2 + a_3 \frac{1}{M^2} \left( H_1^1 e^{Y_3} H_1 \right) \left( H_1^1 e^{Y_2} H_2 \right) \\
+ a_4 \frac{1}{M^2} (H_1, H_2) \left( H_1^1, H_2^1 \right) + \frac{1}{M^2} \left( a_5 H_1^1 e^{Y_5} H_1 + a_6 H_2^1 e^{Y_2} H_2 \right) \left( H_1, H_2 + H_1^1, H_2^1 \right). \tag{3}
\]

\(H_1, H_2\) are Higgs superfields in the gauge basis with hypercharge \(Y_1 = -1, Y_2 = 1\). Supersymmetry breaking is introduced through the spurion formalism \[34\].

\[
\zeta _1 \rightarrow \zeta _{10} + \zeta _{11} m_s \theta ^2, \tag{4}
\]

\[
a_i \rightarrow a_i 0 + a_{i1} m_s \theta ^2 + a_{i2} m_s^2 \theta ^2 + a_{i3} m_s^2 \theta ^2. \tag{5}
\]

The approach, based on a supersymmetric set-up, assumes the physics beyond the MSSM to be approximately supersymmetric and therefore \(m_s\) is taken to be small as compared to \(M\). We take \(m_s = 300\) GeV.

The contribution of the dimensionless new parameters \(a_{ij}, \zeta _{ij}\) to the Lagrangian expressed in terms of the physical fields will be modulated by powers of \(m_s/M\) and \(\mu /M\), where \(\mu\) is the usual supersymmetric Higgs mixing term. At order \(1/M^2\) the modulation enters as \((m_s/M)^2\), \((\mu /M)^2\) and \((\mu m_s/M^2)^2\) together with corrections of order \(\nu^2/M^2\), \(\nu\) being the SM vacuum expectation value. In order not to jeopardise the \(1/M\) expansion we take \(\mu = m_s\). In any case we always impose a set of criteria in order to trust and control the \(1/M\) corrections, see \[18\]. In our analysis, the effective dimensionless coefficients are varied within the range \([-1, 1]\).

We would like to add a word of caution. Since the aim of this paper is to address the flavour (and Dark Matter) issue one can not completely dismiss the possibility of new operators that affect other sectors than the Higgs. We take the view here that these effects are negligible compared to those emerging from the Higgs sector. Our results will then be self-contained.

### 2.1 Parameter space

Usually the low energy theory is fully specified. In our case \(L_{\text{low energy}} = L_{\text{MSSM}}\) and therefore the parameters of the low energy model need to be specified. In \[18\] we considered two set-ups, referred to as scenarios A and B. The reason behind this choice lies in the importance of the stop sector and the impact of the latter on the signature of the Higgs at the LHC. Therefore apart from the third generation squarks, scenarios A and B have the following parameters. All soft scalar masses are set to \(M_{\text{soft}} = 1\) TeV. As advertised earlier, the Higgs \(\mu\) parameter is set to 300 GeV. All trilinear couplings are set to 0, except for the stop sector. The MSSM parameters \(t_\beta, M_{A^0}\) will be varied in the range

\[
t_\beta \in [2, 40], \quad M_{A^0} \in [50, 450] \text{ (GeV)}. \nonumber
\]

\(t_\beta\) is the ratio between the expectation values in the Higgs doublets. \(M_{A^0}\) is the mass of the pseudoscalar Higgs, \(A^0\). The CP-even Higgses will be denoted as \(h\) (the lightest) and \(H\) (the heaviest).

The gaugino masses will only play a role when studying the DM. We set as benchmark \(M_2\) (the
SU(2) gaugino mass) to 300 GeV. $M_1$ (the $U(1)$ bino mass) is fixed by the universal gaugino mass relation $M_1 = \frac{3}{2} \tan^2 \theta_W M_2 \simeq M_2/2$, and $M_2 = 800$ GeV (the $SU(3)$ gaugino mass), with $\cos^2 \theta_W = M_W^2/M_Z^2$. When including DM observables we will keep $M_2 = \mu = 300$ GeV fixed but will scan on $M_1$ in the range $M_1 \in [50, 300]$ GeV in order to generate all possible mixtures of higgsino-bino for the neutralino LSP. Indeed the nature of the LSP (bino, wino, higgsino) is a key ingredient for dark matter observables.

The difference between scenario A and B is in the third generation of squarks.

- In model A we take $M_{u_3 R} = M_{d_3 R} = M_{Q_3} = 400$ GeV, these are respectively the soft masses for the up, down singlet and the doublet. The tri-linear stop mixing is $A_t = 0$. This is a benchmark where the stops are light (as dictated by naturalness considerations) but do not affect much the Higgs loop couplings to $gg$ and $\gamma \gamma$ since they are mass degenerate.

- In model B we consider the case $m_{\tilde{t}_1} = 200$ GeV together with $m_{\tilde{t}_2} = 600$ GeV and a maximal mixing in the stop sector with $\sin 2\theta_t = s^2 \theta_t = 1$. This scenario exemplifies the role of stops in modifying the Higgs couplings to $gg$ and $\gamma \gamma$ as compared to the SM expectations. In [18] we covered a larger spectrum of $t_2$ and considered also $s^2 \theta_t = -1$. Fits to recent LHC data including flavour constraints in a MSSM set up with light stops have just appeared, see [35]. Note however, as we already pointed out in the introduction, such a natural set up has some tension with the rather heavy Higgs mass, which is not the case in the BMSSM.

### 2.2 Snapshot of the BMSSM

Once the effective operators are plugged in the Kähler potential, the superpotential and the susy-breaking potential we can derive the actual alterations to the interactions of the physical fields themselves. The most salient feature that has been discussed thoroughly in the literature (see [12, 36, 34]) has to do with the substantial increase in the lightest Higgs mass, $m_h$, compared to the MSSM case. In these scenarios $m_h$ can be raised up to 250 GeV. Although such high masses are no longer an issue in view of the latest LHC results, this does show that contrary to the MSSM a mass of 125 GeV for the lightest Higgs can be very easily attained, in particular without demanding too much from the stops. What is important and is still of crucial importance in view of the latest trends from the LHC is that the mixing and couplings of the BMSSM Higgses can differ substantially from those of the Standard Model. As we show in [18], these deviations from the SM are however not haphazard despite the relatively large number of parameters that the BMSSM introduces. There exists strong correlations between different searches and signal channels.

### 2.3 Some technicalities on the computation

The impact of these operators on flavour physics and Dark Matter has previously only been addressed for the dim-5 operators arising from the superpotential, see [29] for the flavour observables and [30, 31, 32, 33] for DM observables. However their impact on a Higgs with mass 125 GeV was not studied. The implementation of both dim-5 and dim-6 operators on flavour physics as well as the relic density and direct detection is performed here for the first time. As we outline in a previous publication, the implementation of the effect of all the higher order operators is quite tricky. We perform this with an automated tool from the superfield level to the physical states. We then pass the newly created model file to external codes such as micrOMEGAs [37, 38, 39, 40] for the dark matter observables for example. For our study on the Higgs observables all these changes were a rescaling of the standard model couplings.
2.3.1 Flavour Observables

For the flavour observables all what affects the Yukawa sector is of relevance and hence the importance of these new contributions. For the calculation of observables which involve loop calculations one needs to be careful that these higher order contributions do not generate ultraviolet divergences. One could imagine that all contributions from the higher order operators could be naively counted as of a non renormalisable type. For example, in the calculation of $B_s \to \mu^+\mu^-$ enters the $\tilde{\chi}_j^+\phi\tilde{\chi}_i^-$ vertex which contributes to the penguin diagram, $\chi^\pm$ are the chargino fields and $\phi = h, H, A^0$. At first sight the contribution from the higher order operators exhibits a new Lorentz structure containing derivatives on the chargino field. However, it can be shown that these new structures can be removed by using the equations of motion. At the end, the net effect is fully taken into account by a rescaling of the MSSM coupling. This then permits to easily adapt the calculation performed in the MSSM, in this case [41, 42]. In general all our calculations of the flavour and Dark Matter observables take the codes implemented in micrOMEGAs as a skeleton.

2.3.2 Dark Matter

Since our formulation stems from extra contributions involving Higgs superfields, the neutralino and chargino sector will be directly affected. This has an impact on the calculation of Dark Matter observables in particular within a higgsino configuration. The usual computation of the relic density and direct detection in the BMSSM is particularly affected when higgsino and Higgs are affected. For instance, for the relic density, processes involving Higgs final states such as $hA^0$ that occur when the neutralino is a mixed bino-higgsino get corrected by as much as 30% compared to the same MSSM point. In the Higgsino case, the new operators allow for larger mass splitting between the neutralino and the chargino. This helps evade more easily the LEP constraint on the chargino. Another possibility that opens up is that co-annihilation with a stop are more plausible than in the MSSM due to the fact that very heavy stops are no longer necessary to obtain a Higgs with mass 125 GeV. For other novelties in the computation of the relic density which however do not have a bearing on our study of the Higgs see [33, 31, 32].

2.4 Higgs observables at the LHC

In order to use the results from the ATLAS and CMS collaborations, we have used the following ratios

$$R_{XX} = \frac{\sigma_{pp\rightarrow h\rightarrow XX}}{\sigma_{SM_{pp\rightarrow h\rightarrow XX}}} \quad \text{and} \quad R_{XX}^{\text{exclusion}} = \frac{\sigma_{pp\rightarrow H\rightarrow XX}}{\sigma_{excluded\ 95\%_{pp\rightarrow H\rightarrow XX}}},$$

(6)

where $XX$ denotes a particular final state (say the inclusive $2\gamma$). $\sigma_{excluded\ 95\%}$ stands for the 95% C.L. excluded cross-section reported by the collaborations with the 2011 data [43, 44, 45]: the reason why 2012 data for exclusion has not been used so far is that the most sensitive channels (notably $\phi \rightarrow \tau\tau$, $\phi = A^0, h, H$) have not been updated yet. In practice the $R_{XX}$ will be used in the signal case, to compare with the best fit $\hat{\mu}$ of the so called signal strength $\mu$ given by the experiments. In eq. (6) $h$ in the BMSSM will refer either to the lightest or heaviest CP-even Higgs. $R_{XX}^{\text{exclusion}}$ will be used in the no-signal case as a measure of the sensitivity of the search, here $H$ stands for all Higgses not contributing to a signal in the mass range $122 - 128$ GeV. For $R_{XX}$ the most important channels so far are the inclusive $2\gamma$, $ZZ \rightarrow 4l$ and the exclusive $2\gamma + 2jets$. 

6
We simulate the ratio $R_{\gamma\gamma+2j}$ as

$$R_{\gamma\gamma+2j} = \frac{0.15\sigma_{\text{VBF}} + 0.005\sigma_{gg\to h}}{0.15\sigma_{\text{VBF}}^{SM} + 0.005\sigma_{gg\to h}^{SM}} \times \frac{BR_{\gamma\gamma}}{BR_{\gamma\gamma}^{SM}}$$  \hspace{1cm} (7)$$

We checked that this parametrisation of $\sigma_{\gamma\gamma+2 \text{ jets}}$ when folded in with the SM cross sections for the LHC at 7 TeV \cite{16} and taking into account the luminosity quoted by CMS reproduced quite exactly the number of selected events given by CMS \cite{17}. We assume that this parametrisation that was verified to be excellent for $m_h = 120$ GeV still holds to a very good degree in the range $122 < m_h < 128$ GeV. Note that with the 2012 data there exist three different $2\gamma + 2 \text{ jets}$ channels (one for ATLAS and two for CMS) which correspond to three different efficiencies. Given the high statistical uncertainty we will however only consider one set of efficiencies as a representative of the channel.

We must note that we impose constraints from the electroweak precision data. Therefore the slightest SU(2) custodial symmetry breaking effect is wiped out. The models have therefore $R_{WW}/R_{ZZ} = 1$.

### 3 Impact of flavour on Higgs signals

We first consider the impact of $B_s \to \mu^+\mu^-$, $B \to X_s^*\gamma$ and $(g-2)_\mu$ and look at how these observables can constrain the rates for Higgs production in the different channels

- **$B_s \to \mu^+\mu^-$**
  
  We apply the latest bounds on $B_s \to \mu^+\mu^-$
  
  $$B_s \to \mu^+\mu^- < 4.7 \times 10^{-9} \quad \text{LHCb} \ [22]$$

- **$B \to X_s^*\gamma$**
  
  For $B \to X_s^*\gamma$ we take
  
  $$B \to X_s^*\gamma = 3.55 \pm 16 \pm 9 \times 10^{-4} \quad \text{Heavy Flavour Averaging Group} \ [18]$$

  where we have required the prediction to stay within two sigma deviations from the mean value. We have taken the SM prediction to be $BR(B \to X_s^*\gamma) = 3.27 \times 10^{-4}$ (see \cite{19}). Note that any extra contribution beyond the SM is rather small.

- **$(g-2)_\mu$.**
  
  $$\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (2.8 \pm 0.8) \times 10^{-9} \quad [50, 51]$$

  With the values of the MSSM parameters that we have taken (heavy sleptons) there is no effect from $(g-2)_\mu$, either in terms of constraining the parameter space or alleviating the apparent $2\sigma$ discrepancy with the SM. For $B_s \to \mu^+\mu^-$, the effect is sensitive to quite high values of $t_\beta$, $t_\beta \geq 20$ and small values of $M_{A_0}$, $M_{A_0} \leq 150$ GeV. This set of parameter space is constrained by $B_s \to \mu^+\mu^-$ in fact no longer allowed by the Higgs exclusion limits set by the LHC itself in the analysis $\phi \to \tau\tau$, $\phi = h, H, A^0$ \cite{45}, see later. Since the latter are folded in our Higgs analysis, $B_s \to \mu^+\mu^-$ does not add much. Note also that the effect of the dim-5 operators in particular are more important for small values of $t_\beta$, therefore the BMSSM does not impact much more than the MSSM. $B \to X_s^*\gamma$ is much more sensitive to the stop sector. We have observed that in our case most of the supersymmetric corrections are brought by the Wilson operators.
\[ O_T = (8L \sigma^{\mu \nu} b_R) F_{\mu \nu} \] 

it is driven by the charged Higgs loop on one side and the stops-charginos loop on the other. The former depends on the value of \( M_{A^0} \) and to a lesser extent on \( t_\beta \). The latter shows a \( t_\beta \)-enhanced term whose size is driven by \( s_{2\theta_t} \) and \( \Delta m_{\tilde{t}_1^2} = m_{\tilde{t}_1^2} - m_{\tilde{t}_1} \). It is sensitive to the sign of \( \mu \). In this study we take \( \mu > 0 \). Since the experimental value of \( B \to X_s^* \gamma \) is close to the SM prediction, it means that the supersymmetric contribution must be quite small. This will drive us either to a small \( t_\beta \) region, a small mass splitting \( \Delta m \) between stops or a small mixing \( s_{2\theta_t} \approx 0 \). The last two instances characterise model A.

In model B, where we have a light stop \( m_{\tilde{t}_1} = 200 \text{ GeV} \) and a heavier one with \( m_{\tilde{t}_2} = 600 \) (GeV), we expect \( B \to X_s^* \gamma \) to be more constraining.

### 3.1 Impact on Higgs observables

The signal and correlations that we will show have \( 0 < R_{\gamma \gamma} < 4 \). This is a very generous band which allows to read the predictions in a most transparent manner. The reader can easily select a particular range. We prefer not to select a narrow range since the measurements on the different rates will evolve and get more precise.

#### 3.1.1 Model A facing flavour

![Figure 1](image-url) 

**Figure 1:** Allowed regions in scenario A after applying the flavour constraints for a signal with \( m_h = 125 \) GeV. We plot here the signal strengths and the correlations for a) Left panel: \( \gamma \gamma \) (x-axis), \( ZZ \) (red points) and \( \gamma \gamma + 2 \) jets (blue points), b) right panel: \( \tau \tau \) and \( b \bar{b} \).

In the case of model A with degenerate stops with mass of 400 GeV, the correlations between the signal strengths in the \( \gamma \gamma \), \( ZZ \) and \( \gamma \gamma + 2j \) are unaffected by the flavour constrained. Nor is the range of the signal strengths further reduced by the flavour constraints. We note that in this particular case of degenerate stops the signals are all strongly correlated with \( R_{\gamma \gamma} \sim R_{ZZ} \) and \( R_{\gamma \gamma + 2j} \) is unconstrained by the flavour constraints. The correlations are shown in Fig. [1]. For \( R_{\gamma \gamma} \sim 2 \) we can obtain the following ranges for the other channels: \( R_{ZZ} = 2 - 2.05 \) and \( R_{\gamma \gamma + 2j} = 1.6 - 1.8 \), \( R_{b\bar{b}} = 0.5 - 0.7 \), \( R_{\tau \tau} = 0.6 - 1 \). It is important to point out that for this particular value, \( R_{\gamma \gamma} \sim 2 \), the \( \tau \tau \) and \( b \bar{b} \) need not be dramatically reduced. Much higher signal rates in the \( \gamma \gamma \) channels are only possible with very much reduced of the latter two channels.

What is not visible in the projections of Fig. [1] is the fact that the flavour observables do eliminate quite a few configurations. Indeed we obtain the constraint \( M_{A^0} > 200 \) GeV and \( t_\beta < 20 \), see Fig. [2] These bounds come from the \( B \to X_s^* \gamma \) observable. Indeed at low \( M_{A^0} \)
the contribution of the charged Higgs loop is enhanced. This can in principle be cancelled by $t_\beta$-enhanced terms from the stop sector whose contribution has an opposite sign to the one of the charged Higgs loop, however since there is practically no effect of the stop sector in the model A the $t_\beta$ dependence of $B \to X_s^* \gamma$ is very mild. Thus, in order to reproduce the correct value for $B \to X_s^* \gamma$ with $M_{A^0} < 200$, one would require $t_\beta > 20$, a value which is already excluded by the $\phi \to \tau\tau$ search at the LHC. Since $A^0$ is pushed to $M_{A^0} > 200$ GeV. This means that the hypothesis of the heavy CP-even Higgs boson generating the signal is disfavoured. Such possibility was entertained prior to applying the flavour constraints [18]. Fig. 2 reveals that for $t_\beta \sim 2$ we get $R_{\gamma\gamma} \sim 1$, while for $t_\beta \sim 5$ we obtain $0.5 < R_{\gamma\gamma} < 2$. For higher values of $t_\beta$ a much large range for $R_{\gamma\gamma}$ opens up. We therefore see that, despite the many higher order operators, precision measurements on the Higgs combined with flavour measurements can give a good measure of $t_\beta$. We also see that in model A, values of $R_{\gamma\gamma} \sim 2$ are possible for any value of $M_{A^0} > 250$ GeV, as long as $t_\beta > 5$. $R_{\gamma\gamma} < 0.5$ would mean that the pseudo scalar mass is lighter than 400 GeV.
Fig. 3 is very instructive. It reveals that $B_s \rightarrow \mu^+\mu^-$ does not restrict the parameter space once the LHC limit on the search $A^0 \rightarrow \tau\tau$ has been imposed. On the other hand, $B \rightarrow X_s^*\gamma$ carves out a significant region of parameter space.

3.1.2 Model B facing flavour

Figure 4: Allowed region in $M_{A^0}$ versus $R_{\gamma\gamma}$ and $t_\beta$ versus $R_{\gamma\gamma}$ in scenario B after applying the flavour constraints.

Model B has been introduced in order to obtain the hierarchy $R_{\gamma\gamma+2j} > R_{\gamma\gamma} > R_{ZZ}$ by decreasing the contribution of the gluon fusion with respect to the $WW$ fusion. This is obtained through strong mixing in the stop sector and with one of the stops relatively light. The underlying strong Yukawa coupling of the stops can therefore have an important impact on $B$ observables in particular $B \rightarrow X_s^*\gamma$. To illustrate this scenario we take the case of maximal mixing with $S_{2\theta_t} = 1$, more moderate effects are obtained with smaller values of $S_{2\theta_t}$.

The effect of the $B \rightarrow X_s^*\gamma$ constraint is quite different from what we observed in model A. Indeed, while the contribution of the charged Higgs is still the same, with an important contribution for small $M_{A^0}$, there is now a significant contribution from the stop-chargino loop (since $S_{2\theta_t} = 1$ and $\Delta m_{\tilde{t}}$ is non-zero) which is moreover $t_\beta$ enhanced. Since the latter has an opposite sign to the Standard Model contribution, it will tend to decrease $BR(B \rightarrow X_s^*\gamma)$ as $t_\beta$ grows. The conclusion is twofold: first, the contribution of the charged Higgs can be cancelled by the effect of the stop-chargino loop. Therefore, in model B, on the one hand flavour constraints do not provide a lower bound for $M_{A^0}$, which is backed up by the results shown in Fig. 4. On the other hand, observe that $M_{A^0}$ does not extend beyond $M_{A^0} > 400$ GeV, otherwise the compensation between the charged Higgs contribution and the stop contribution in $B \rightarrow X_s^*\gamma$ will not be effective. Second, for the cancellation in $B \rightarrow X_s^*\gamma$ to be effective and in order to control the stop-chargino loop, $t_\beta$ is restricted to be small ($t_\beta < 5$) for any value of $M_{A^0}$. This is what is conveyed by Fig. 4. The range of $t_\beta$ is very much reduced compared to what we found in Model A. Moreover for the largest allowed values of $M_{A^0}$ $R_{\gamma\gamma} < 1$. The fact that in this decoupling regime one does not recover the SM value is due to the reduction in $\sigma(gg \rightarrow h)$ brought up by the stops.

This restriction to small $t_\beta$ makes it difficult to obtain a maximal suppression of the $g_{hbb}$ coupling that would lead to an increase in $R_{\gamma\gamma}$, this is why in Fig. 5 where we plot the allowed points in scenario B, we have much fewer points with $R_{\gamma\gamma} > 2$ than before applying the flavour constraints. We note however that solutions with $R_{\gamma\gamma} > 2$ can not be obtained with $M_{A^0} > 250$ GeV. With
large values of $M_{A^0}$ decoupling will set in. Still, there are configurations with $R_{\gamma\gamma} \sim 2$ which exhibit the hierarchy $R_{\gamma\gamma+2j} > R_{\gamma\gamma} > R_{ZZ/WW}$. With $M_{A^0} < 250$ GeV we can attain $R_{\gamma\gamma} = 2$ together with $R_{ZZ} = 1.6 - 1.8$, $R_{\gamma\gamma+2j} = 1.9 - 2.4$, $R_{bb} = 0.3 - 0.6$, $R_{\tau\tau} = 0.2 - 0.5$, see Fig. 6. Observe that $R_{\gamma\gamma} \sim 2$ corresponds to much lower rates for the $bb$ and $\tau\tau$ channels than in Model A, see Fig. 3. With $M_{A^0} > 250$ GeV, the increase in the bosonic final states ($\gamma\gamma, ZZ, \gamma\gamma + 2j$) is reduced. While the correlations are maintained with $R_{\gamma\gamma+2j}/R_{\gamma\gamma} \sim 1.3$, $R_{ZZ}/R_{\gamma\gamma} = 0.8$, we now have $R_{\gamma\gamma} < 1.5$ (for $M_{A^0} > 250$ GeV).

![Figure 5: Allowed regions in scenario B](image1.png)

**Figure 5:** Allowed regions in scenario B with $s_{2\theta_t} = 1$ before (left panels) and after (right panels) applying the flavour constraints. We distinguish the case of heavy ($M_{A^0} > 250$ GeV) and light ($M_{A^0} < 250$ GeV) pseudoscalar masses. We plot here the features of a signal with $m_{h^\pm} = 125$ GeV, that is to say the signal strength in the following channel: $\gamma\gamma$ (x-axis), $ZZ$ (red points) and $\gamma\gamma + 2$ jets (blue points).

## 4 Dark Matter

Within the BMSSM, new features brought about by the extra operators have an impact also on non-Higgs observables in particular the interaction of the higgsino components. As such the properties of the lightest neutralino that could constitute a Dark Matter candidate are affected, more so if the higgsino fraction is important or else if the amount of mixing in the neutralino sector is important. Talking about the higgsino component, we should emphasize that in the BMSSM framework the value of $\mu$ is not large. In this study we have fixed $\mu = 300$ GeV.
Figure 6: As in Fig. but for the signal strengths for $\tau\tau$ and $\bar{b}b$ channels after flavour constraints are imposed.

The results we have presented so far depend quite crucially on the value of $\mu$, in particular the expansion in the effective operators is based on the ratio $\mu/M$. The values of $M_{1,2}$ that determine the nature of the neutralino LSP have almost no impact on the Higgs observables we have studied. With $M_2 \sim 2M_1$ and with $M_1 > 70$ GeV, invisible decays to dark matter neutralinos is not possible and the contribution of charginos to $h \rightarrow \gamma\gamma$ is negligible. Direct detection has a more direct connection with Higgs physics, due to the contribution of Higgs exchange. The relic density requires the knowledge of more parameters. For instance, lighter sleptons would have an important impact. This is the reason why we first consider the constraint of direct detection on the Higgs observables. In doing so we will, in a first stage, assume that the density of Dark Matter is totally accounted for by neutralinos. Even if the relic density turns out to be outside what is measured by WMAP, $\Omega h^2 \sim 0.1$, one can always appeal to non thermal scenarios which can bring the relic density to the desired experimental value $\Omega h^2$. We evoke this possibility only as a way out not to include the impact of the relic density at this stage. In a second stage we compute the relic density within a standard thermal cosmological model and ask which scenarios can indeed be compatible with the correct relic density and pass the direct detection constraint. Models that do not pass the cold dark matter relic density constraint but give a value that is smaller than what is measured are acceptable at the expense that the neutralino does not account for the totality of DM in the Universe. Such possibilities are reviewed in a third stage. In this case, given a spin-independent cross section, the direct detection rate is smaller due to the smaller neutralino halo fraction. We assume that this fraction is the same as the one on cosmological scales which is set by the relic density. The observed relic density $\Omega h^2$ is the result of the fit of $\Lambda$CDM whereas the direct detection rate is proportional to the number density of the neutralinos passing through the detector $\Omega h^2$. In this case we reweight the result on the spin-independent cross section and look at the effect on the Higgs signal strength. Let us at this point recall some important differences between model A and model B as regards the DM candidate. In model B, the lightest stop weighs 200 GeV, therefore the LSP must be lighter. As a consequence, in these scenarios $M_1, M_2$ can not be taken very high, with $\mu = 300$ GeV we can not have $\mu \ll M_1, M_2$. 

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4.1 Direct Detection

We have used the latest (July 2012) XENON 100 [23] results on the spin independent cross-section of the dark matter candidate on the nucleus. We have used the routines of micrOmegas-2.4 [38].

In the framework we have chosen with squarks of the first and second generation being heavy and with the possibility that the Higgses of the model, including the pseudoscalar, can have mass below 300 GeV, the rates for direct detection can provide a further constraint on the parameters in the Higgs sector. The interplay between direct detection and flavour in the context of the MSSM was emphasized in [54]. The impact of direct detection depends also on the composition of the neutralino, of course. This composition is determined by the values of the $\mu$ parameter and the $U(1)$ ($M_1$) and $SU(2)$ ($M_2$) gaugino masses. The latter played practically no role in the properties of the Higgs and the rates at the LHC. What determines the cross section is the coupling of the higgses to the LSP neutralino and the coupling of the Higgses to the quarks. These effects will naturally be more important if the exchanged Higgs is not too heavy. For the coupling to quarks, high $t_\beta$ give the largest effect. We therefore expect that adding the direct detection limit will constrain the Higgs couplings to the LSP. The latter requires mixing between the Higgsino and the gaugino ($M_{1,2}$, in our case essentially $M_1$) components.

We first stick to the values of $M_1$ and $M_2$ that define models A and B. In this case with $M_1 \sim M_2/2 = 150$ GeV giving $m_{\tilde{\chi}_1^0} \sim 146$ GeV for $t_\beta = 20$, our benchmark points barely make it. We find that very few points pass the new direct detection test for both models. In fact as will be seen shortly, our benchmark choice for $M_{1,2}$ is borderline. This is not difficult to explain. Indeed, although the bino component is large (90%), there is nonetheless about 10% higgsino component. With the latest limits from XENON100, such combined mixing and therefore such configurations are almost ruled out both for model A and model B. The message is that XENON100 is now providing a very strong constraint (also on many MSSM implementations).

We expect that in these scenarios reducing the amount of higgsino-gaugino mixing will help. $M_1$ needs to be much further removed from $\mu$. We will therefore scan on $M_1$ so as to allow smaller values than our benchmark $M_1 = 150$ GeV. In this study we do not entertain the possibility of $M_{1,2} \gg \mu$. In model B with $m_{\tilde{t}_1} = 200$ GeV a DM candidate is not possible, while for model A, $M_1$ would not extend above 400 GeV and therefore we will be in a quite mixed bino-higgsino configuration anyhow. With $M_1 < \mu$, our scan covers $M_1 : 70 - 300$ GeV (we keep $\mu = M_2 = 300$ GeV). The lower value of $M_1$ is taken so as to avoid possible invisible decays of the Higgs that we have not taken into account for our analysis (see however our paper [17]).

We first assume that neutralinos account for all of dark matter. The flavour constraints are taken into account.

Looking at Fig. 7 we see that we can find, in both model A and model B, points that pass the XENON100 (2012) but only for neutralino lighter than about 150 GeV. Our benchmark point with $M_1 = 150$ GeV was indeed borderline. Many configurations of the parameters including $M_{A^0}, t_\beta$, are therefore excluded. This shows that assuming that the models account for the bulk of DM, the new limit from XENON100 (2012) are now extremely powerful. No doubt that future XENON1T [55] which will improve the sensitivity by at least an order of magnitude will either soon discover such models or will exclude all of them. This is a conclusion that should apply to all natural susy models with small enough $\mu$ (see for example [56]).

The correlations between the different Higgs signal channels are, of course, unchanged. What
Figure 7: We show the allowed parameter space in $m_{\chi_0^1}$-$\sigma_{SI}$ after imposing XENON100 (2012) (left panels) and the impact on $R_{\gamma\gamma}$ (right panels). The upper (lower) plots are for model A (B).

is important to check is whether the signal strengths are affected. We find that the only change concerns Model A where direct detection now imposes $R_{\gamma\gamma} > 0.5$, see Fig. 7. After inspection we have found that direct detection now cuts on the small values of $M_{A_0}$ in particular those with largest $t_{\beta}$. In this case the couplings to $b$$\bar{b}$ of the Higgs are not so large and hence the reduction in $R_{\gamma\gamma}$ is more modest. In model A, $R_{\gamma\gamma} > 1$ is possible (we even obtain $R_{\gamma\gamma} \sim 2$) for all values of the neutralino mass in the considered range 60 – 150 GeV. This is not the case of Model B, where in the range $120 < m_{\tilde{\chi}_0^1} < 150$ GeV, an enhancement of $R_{\gamma\gamma}$ is not easy to find.

4.2 Relic Density

Combining the results of the 7-year \textit{WMAP} data\cite{57} on the 6-parameter $\Lambda$CDM model, the baryon acoustic oscillations from SDSS\cite{58} and the most recent determination of the Hubble constant\cite{59,60} one\cite{60} arrives at $\Omega h^2 = 0.1126 \pm 0.0036$, where $\Omega$ is the density of cold dark matter normalised to the critical density, and $h$ is the Hubble constant in units of 100 km s$^{-1}$Mpc$^{-1}$. This experimental results is very precise with only 3% uncertainty. However, it has been shown,
in particular in supersymmetry, that such a precision was difficult to match on the theoretical side. Indeed the loop corrections can easily be higher than 10% on different processes. Despite the efforts to account for those contributions (see references [61, 62, 63, 64]), it remains a challenge and is so far not implemented in the code we have used, micrOmegas-2.4. We will thus impose the value of the relic density within 15% uncertainty:

$$\Omega h^2 = 0.1126 \pm 0.016.$$  \hfill (8)

Let us briefly sketch the main channels that enter the computation of the relic density in our scenarios:

- $\tilde{\chi}^0_1 \tilde{\chi}^0_1 \rightarrow f \bar{f}$: this is the most frequent case when the lightest neutralino is mainly bino-like. Though the cross section of this process is usually too small to respect the relic density constraint, it can be enhanced by an $A^0$ resonance, requiring $M_{A^0} \sim 2m_{\tilde{\chi}^0_1}$.

- $\tilde{\chi}^0_1 \tilde{\chi}^0_1 \rightarrow WW/ZZ$: This occurs when the higgsino component is highest and the channels are open. With $\mu = 300$ GeV this takes place when $M_1 \geq \mu$.

- $\tilde{\chi}^0_1 \tilde{\chi}^0_1 \rightarrow WH/ZH/hA^0$: this channel only opens up for high masses, that is $m_{\tilde{\chi}^0_1} > 200$ GeV.

- $\tilde{\chi}^0_1 \tilde{t}_1$ co-annihilation is also possible, in particular for Model B.

We now investigate whether in all scenarios we studied and that pass the direct detection constraint one could still obtain the correct relic density within a standard thermal cosmological model. We will start with model B where it is easier to illustrate why we perform scans in steps of 10 GeV over $M_1$.

### 4.2.1 Model B with the correct abundance

The good news is that it is possible to reproduce the correct thermal relic density and be in accord with the latest measurement from XENON100 (2012) over the whole range $60 < m_{\tilde{\chi}^0_1} < 150$ GeV that passed the XENON100 (2012) limit, Fig. 8.

It is important to observe that a scan over $M_1$ returns values for the relic density that span a range over orders of magnitude in $\Omega h^2$: $10^{-4} - 10$, with a small subset that leads to the correct relic density and includes configurations in accord with direct detection, see Fig. 8. Among the points that have passed the previous direct detection limit some are associated either with an overabundance or an underabundance. The figure does not include configurations where the spin-independent cross section is too large but which indeed corresponds to an underabundance. We will deal with these scenarios next. Note at this point that for $m_{\tilde{\chi}^0_1} > 160$ GeV, all scenarios represent underabundance. The figure illustrates the fact that as the mass of the neutralino increases, and therefore the higgsino component increases, annihilation of higgsino dominated LSP becomes more and more efficient and the relic density drops. The scan we have performed was done in steps of varying $M_1$ in order to reveal an important feature. As the value of $M_1$ increases and we enter the higgsino domain, the strips in $M_1/m_{\tilde{\chi}^0_1}$ become wider for the highest values (though still small) of the relic density. The pole-like structure (without a "head") for low values of $M_1$ corresponds in fact to the contribution of a Higgs resonance, $M_{A^0} \sim 2m_{\tilde{\chi}^0_1}$. Around these tuned resonant regions the value of the relic density fluctuates vastly. An example of this is shown in Fig. 9. Obtaining the correct relic density could then be considered fine-tuned with $M_{A^0} \sim 2m_{\tilde{\chi}^0_1}$. As we reach the higgsino domain, these resonant processes become irrelevant since other channels are more efficient. This explains the “pole with the head” structure, see Fig. 8. These regions correspond to underabundance.
Figure 8: Model B. Values of the relic density (red/light grey) are superimposed with those that have passed the XENON100 (2012) limit (blue/dark grey). The WMAP bound is shown. The scan has been done by increasing the value of $M_1$ in steps, rather than randomly (see text of why this was done).

Figure 9: Model B. We show the result of a scan on $M_{A^0}$ on the relic density as a function for $M_1 = 93$ GeV (left panel) and $M_1 = 180$ GeV right panel.

The relic density constraint does not change the conclusions concerning the signal rates. We find that in the range $60 < m_{\tilde{\chi}_1^0} < 120$ GeV we can have $R_{\gamma\gamma} > 1$ ($R_{\gamma\gamma} \sim 2$ is possible here) while for the rest of the allowed mass range $120 < m_{\tilde{\chi}_1^0} < 150$ GeV we have $R_{\gamma\gamma} < 1$. Because the models which are retained are those with $M_{A^0} \sim 2m_{\tilde{\chi}_1^0}$ due to imposing the relic density constraint, these ranges can be converted to ranges over $M_{A^0}$. Fig. 4 confirms the behavior of the 2-photon Higgs signal strength.
4.2.2 Model B with an underabundance, a reappraisal of the direct detection

If neutralinos do not make up all of the dark matter, one can reconsider those scenario for which the spin-indepenent cross section seemed to high. Naturally configurations with $m_{\tilde{\chi}_1^0} > 160$ GeV are now possible since the annihilation cross section for higgsinos are large and do not require the contribution of a Higgs resonance contrary to scenarios with $m_{\tilde{\chi}_1^0} < 160$ GeV. Fig. 10 shows how $R_{\gamma\gamma}$ is affected. Up to $m_{\tilde{\chi}_1^0} \sim 160$ GeV we again observe a gradual decline of the di-photon rate. In particular in the range of neutralino masses between 120-160 GeV, this rate drops below that of the SM narrowing around a value of 0.5. These values can be interpreted in terms of the dependence of the $R_{\gamma\gamma}$ as a function of $M_{A^0}$, see Fig. [taking into account the fact that for these configurations $M_{A^0} \sim 2m_{\tilde{\chi}_1^0}$. On the other hand as soon as we enter the higgsino regime (and also co-annihilation with stops), any value of $M_{A^0}$ will do to give a small enough relic density of neutralinos. In this case the di-photon rate is spread over a wide range, in particular large enhancements are now possible.

Figure 10: Model B : points with underabundance of the relic density for which the modified XENON100 limit is respected.

4.2.3 Model A with the correct thermal abundance

Many of the arguments that were detailed in the previous two sections for Model B can be invoked when looking at the impact of the relic density on Model A. One common feature shared by the two models is that the dominance of the higgsino component in the calculation of the relic density kicks in at about the same value of $m_{\tilde{\chi}_1^0}$, i.e. $m_{\tilde{\chi}_1^0} \sim 160$ GeV. We have extended the range of $m_{\tilde{\chi}_1^0}$ to about 250 GeV, because the lightest stop is much heavier in Model A. At around $m_{\tilde{\chi}_1^0} \sim 200$ GeV, we do not have the added contribution of the stop co-annihilation. As Fig. [11 shows, the maximum value of the relic density drops steadily as the neutralino mass increases. The pole like structures, indicative of an annihilation through a resonance, are still present. Recall however that contrary to Model B, the flavour constraints have imposed $M_{A^0} > 200$ GeV, while allowing the larger range $2 \sim 17$ for $t_\beta$. Yet we see a resonance like contribution that is much thinner around $m_{\tilde{\chi}_1^0} \sim 60$ GeV. This in fact is due to precisely the lightest Higgs. This
said, although some of these configurations pass the XENON100 (2012) constraint they do not simultaneously provide the standard relic density, in fact these correspond to overabundances. Insisting on producing the present abundance while abiding by the XENON limit, the masses of allowed neutralinos are in a narrower range than in Model B: 100 – 160 GeV.

4.2.4 Model A with an underabundance, a reappraisal of the direct detection

Figure 11: Model A. Values of the relic density (red/light grey) are superimposed with those that have passed the XENON100 (2012) limit (blue/dark grey). The WMAP bound is shown.

Figure 12: Model A: points with underabundance for which the modified XENON100 limit is respected.
We now allow that the neutralinos of Model A do not account for all of DM and assess which neutralino masses are possible after imposing the flavour constraint and the direct detection limit, see Fig. 12. The range \(\sim\) neutralino masses are possible after imposing the flavour constraint and the direct detection limit, for the latter, the di-photon rate is SM like. For the range \(m_{\tilde{\chi}} = 100 - 250\) GeV we span \(0 < R_{\gamma\gamma} < 3.5\). Contrary to model B, where the relic density proceeds through the pseudoscalar resonance for \(m_{\tilde{\chi}}: 100 - 160\) GeV corresponding to \(M_{A} > 200\) GeV, we reproduce \(0 < R_{\gamma\gamma} < 3.5\) as could have been guessed from Fig. 2. For \(m_{\tilde{\chi}} > 160\) GeV, the situation is similar to what we have seen with Model B.

5 Conclusions

The results that the LHC Collaborations have announced in July 2012 are most probably pointing to the discovery of a Higgs boson. If this is the SM Higgs boson, the naturalness argument upon which one justified, for decades, the construction of new models for better explanation of symmetry breaking would be most baffling. It is therefore important to seek whether the Higgs signals could be incorporated within a natural set-up, see for example the recent arguments in [59]. Supersymmetry would be an ideal framework that could provide also a solution to the DM problem. However the relatively heavy mass of the resonance discovered at the LHC suggests that the much studied MSSM will not be as natural as wished, moreover if the excess in the di-photon signal is established, the MSSM will have to be abandoned. Even before the LHC started taking data, there were signs of tension between the MSSM and naturalness. Keeping the supersymmetric framework but allowing for a more general set-up had been advocated through the BMSSM to alleviate the problem. The series of analyses we have been performing is to investigate whether the BMSSM is a viable alternative in the light of the new data. Despite the large number of new parameters these effective models are rather constrained and predictive. The study we have performed here aimed at reviewing what predictions and correlations for the different signals of the Higgs are possible. While we eagerly await more precision on many of the Higgs rates, it is important that one confronts these predictions with measurements concerning flavour and those that address the DM observables. In this paper we considered two sets of scenarios. A BMSSM model with degenerate stops at 400 GeV (Model A) and a strongly mixed scenario in the stop sector with a lightest stop at 200 GeV and a heavier one at 600 GeV, Model B. We find that the heavy flavour observables, in particular \(B \to X_{s}^{+}\gamma\) (and to a lesser extent the new constraint from \(B_{s} \to \mu^{+}\mu^{-}\)) delimit in an important way the parameter space of the general BMSSM. For Model A, the pseudoscalar mass is restricted to \(M_{A} > 200\) GeV while allowing for a relatively large range for \(t_{3}, t_{5} < 20\). Such restrictions exclude the possibility that the signal at the LHC could originate from the heavier CP-even Higgs. Despite these constraints, we still have scenarios for a 125 GeV Higgs with rates higher in the di-photon signal than in the SM. Model A can still give for example \(R_{\gamma\gamma} \sim R_{ZZ} \sim 2\) while \(R_{\gamma\gamma+2j} \sim 1.6\) while \(R_{b\bar{b}} \sim 0.7\) and \(R_{\tau\tau} \sim 0.7\). In Model B, the flavour constraints could be considered even stronger. Indeed, for the maximal scenarios we have taken \(M_{A} < 400\) GeV and \(t_{3} < 5\). While the hierarchy \(R_{\gamma\gamma+2j} > R_{\gamma\gamma} > R_{ZZ} \sim 2\) is maintained it is possible to have \(R_{\gamma\gamma} \sim 2\). The BMSSM models are also natural in the sense that the usual Higgs mixing parameter \(\mu\) is not large. In our study this was set at \(\mu = 300\) GeV, justifying the approach of new operators associated with a new physics at a scale 1.5 TeV. This parameter is also important in defining the nature of the DM candidate through the composition of the neutralino LSP. This composition depends on the weak gaugino parameters \(M_{1}, M_{2}\) which have, contrary to \(\mu\) within the BMSSM, little impact on Higgs observables. By looking at various \(M_{1}\) versus \(\mu\) hierarchies, we imposed the newly published XENON100 limits. These are very strong limits. We first assumed that the BMSSM LSP
neutralino accounts for all of DM. In both Model A and Model B, we find that only neutralinos
with as little as possible higgsino component pass the new limit. Therefore the LSP can not
have mass above 160 GeV. The projected XENON1T will exclude all configurations with this
assumption on the abundance. We then ask whether the configurations that do indeed pass the
XENON100 test have the correct relic density as set by WMAP. We find that this is possible to
achieve only if annihilation occurs through the pseudoscalar resonance with $M_A \sim 2m_{\tilde{\chi}^0_1}$. This
could be considered as fine tuned. In turn, in model B, for $120 < m_{\tilde{\chi}^0_1} < 150$ GeV even a small
enhancement of the di-photon rate is difficult to achieve. For model A, $R_{\gamma\gamma} > 1$ is possible over
the whole allowed range $60 < m_{\tilde{\chi}^0_1} < 150$ GeV, in fact the additional direct detection constraint
imposes $R_{\gamma\gamma} > 0.5$. We have then asked how some configurations can be rescued if we instead
also accept scenarios with underabundance and underdensity in the halo that lead to smaller
direct detection rates even for large spin-independent cross section. Masses of neutralinos up to
the lightest stop mass are now possible. Apart from neutralinos with mass in the range $120 – 160$
GeV in Model B where the Higgs signal strength is small, in all other configurations we now
span a large range of $R_{\gamma\gamma}$. The drawback in many of these scenarios is that the BMSSM does
not provide all of the observed DM, at least within a standard cosmological scenario.
Although we have not explored all the possibilities within the BMSSM implementations (e.g.
we could have considered larger values of $\mu$ together with a larger scale $M$, study more imple-
mentations of the stop and stop mixings or the effect of a wino component), this study shows
the importance of a global study including Higgs, flavour and DM especially that new powerful
data is pouring in. We eagerly await the results from the projected XENON1T. Above all we
keep a very close eye on the upcoming analyses of the Higgs at the LHC. These include better
measurements of as many channels in the signal region and also further investigations of other
mass regions that can probe the other Higgses of these two doublet models. We stress once more
that, despite the addition of many new operators beyond the usual MSSM, there are strong
correlations between the Higgs observables in the BMSSM. Direct searches for the stops will also
bring important information in these scenarios.

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