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# WMAP-compliant benchmark surfaces for MSSM Higgs bosons

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**ABSTRACT:** We explore ‘benchmark surfaces’ suitable for studying the phenomenology of Higgs bosons in the minimal supersymmetric extension of the Standard Model (MSSM), which are chosen so that the supersymmetric relic density is generally compatible with the range of cold dark matter density preferred by WMAP and other observations. These benchmark surfaces are specified assuming that gaugino masses  $m_{1/2}$ , soft trilinear supersymmetry-breaking parameters  $A_0$  and the soft supersymmetry-breaking contributions  $m_0$  to the squark and slepton masses are universal, but not those associated with the Higgs multiplets (the NUHM framework). The benchmark surfaces may be presented as  $(M_A, \tan \beta)$  planes with fixed or systematically varying values of the other NUHM parameters, such as  $m_0$ ,  $m_{1/2}$ ,  $A_0$  and the Higgs mixing parameter  $\mu$ . We discuss the prospects for probing experimentally these benchmark surfaces at the Tevatron collider, the LHC, the ILC, in  $B$  physics and in direct dark-matter detection experiments. An appendix documents developments in the `FeynHiggs` code that enable the user to explore for her/himself the WMAP-compliant benchmark surfaces.

**KEYWORDS:** Supersymmetry Phenomenology, Higgs Physics, Supersymmetric Standard Model, GUT.

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## 1. Introduction

Some of the best prospects for probing the minimal supersymmetric extension of the Standard Model (MSSM) [1, 2] might be offered by searches for the bosons appearing in its extended Higgs sector. It may be challenging to distinguish between the lightest MSSM Higgs boson and a Standard Model (SM) Higgs boson with the same mass, and searches for MSSM Higgs bosons are, in many ways, complementary to searches for supersymmetric particles as avenues to establish the existence of physics beyond the SM.

Searches at the Tevatron collider are closing in on the possible existence of an SM-like Higgs boson over a limited range of low masses [3–5], and are also starting to encroach significantly on the options for heavier MSSM Higgs bosons, particularly at large  $\tan\beta$  [6–10]. Studies have shown that experiments at the LHC will be able to establish the existence or otherwise of an SM-like Higgs boson over all its possible mass range, and also explore many options for the heavier MSSM Higgs bosons [11–14]. On the other hand, the LHC might well be unable to distinguish between the lightest MSSM Higgs boson and an SM Higgs boson of the same mass. The ILC would have better chances of making such a distinction [15–22], and might also be able to produce the other MSSM Higgs bosons if they are not too heavy [15–19]. CLIC would also be able to study a light SM-like Higgs boson, as well as extend the search for MSSM Higgs bosons to much higher masses [23]. Searches for new phenomena in  $B$  physics, including rare decays such as  $b \rightarrow s\gamma$ ,  $B_s \rightarrow \mu^+\mu^-$  and  $B_u \rightarrow \tau\nu$ , also have good potential to explore the MSSM Higgs sector and, at least in some specific MSSM scenarios, electroweak precision observables (EWPO) may also provide interesting constraints [24, 25]. In parallel to these accelerator searches for MSSM Higgs bosons and their effects, non-accelerator searches for supersymmetric dark matter [26, 27] will also be able to explore significant regions of the MSSM Higgs parameter space [28–30], since the exchanges of massive MSSM Higgs bosons have significant impacts on dark matter scattering cross sections.

In order to correlate the implications of searches at hadron colliders and linear colliders, in  $B$  physics, in dark matter searches and elsewhere, it is desirable to define MSSM Higgs benchmark scenarios that are suitable for comparing and assessing the relative scopes of different search strategies, see, e.g., refs. [31–38].

Since the MSSM Higgs sector is governed by the two parameters  $M_A$  (or  $M_{H^\pm}$ ) and  $\tan\beta$  at lowest order, aspects of MSSM Higgs-boson phenomenology such as current exclusion bounds and the sensitivities of future searches are usually displayed in terms of these two parameters. The other MSSM parameters enter via higher-order corrections, and are conventionally fixed according to certain benchmark definitions [31–34]. The benchmark scenarios commonly used in the literature encompass a range of different possibilities for the amount of mixing between the scalar top quarks, which have significant implications for MSSM Higgs phenomenology, and also include the possibility of radiatively-induced  $\mathcal{CP}$  violation. The best-known example is the so-called “ $m_h^{\max}$  scenario” [31–33], which allows the search for the light  $\mathcal{CP}$ -even Higgs boson to be translated into conservative bounds on  $\tan\beta$  for fixed values of the top-quark mass and the scale of the supersymmetric particles [39]. The existing benchmark scenarios designed for the MSSM Higgs sector are formulated entirely in terms of low-scale parameters, i.e., they are not related to any particular SUSY-breaking scheme and make no provision for a possible unification of the SUSY-breaking parameters at some high mass scale, as occurs in generic supergravity and string scenarios.

In applications of the existing benchmark scenarios for the MSSM Higgs sector [31–34], one is normally concerned only with the phenomenology of the Higgs sector itself. Besides the direct searches for supersymmetric particles, other constraints arising from EWPO,  $B$ -physics observables (BPO) and the possible supersymmetric origin of the as-

trophysical cold dark matter (CDM) are not usually taken into account. This may be motivated by the fact that the additional constraints from EWPO, BPO and CDM can depend sensitively on soft-supersymmetry breaking parameters that otherwise have minor impacts on Higgs phenomenology. For example, the presence of small flavour-mixing terms in the MSSM Lagrangian would severely affect the predictions for the BPO while leaving Higgs phenomenology essentially unchanged (see also ref. [36] for a discussion of this issue).

In this paper we follow a different approach and adopt specific universality assumptions about the soft SUSY-breaking parameters, restricting our analysis of the MSSM to a well-motivated subspace of manageable dimensionality. It is frequently assumed that the scalar masses  $m_0$  are universal at some high unification scale, as are the gaugino masses  $m_{1/2}$  and the trilinear parameters  $A_0$ , a framework known as the constrained MSSM (CMSSM). In such a scenario, the heavier MSSM Higgs boson masses are fixed in terms of the input parameters and  $\tan\beta$ , so that  $M_A$  is not an independent parameter, and consequently this scenario is too restrictive for our purposes. However, there is no good phenomenological or theoretical reason why the soft supersymmetry-breaking contributions to the Higgs masses should not be non-universal, a scenario termed the NUHM [40–42]. Within the NUHM,  $M_A$  and  $\mu$  can be treated as free parameters for any specified values of  $m_0, m_{1/2}, A_0$  and  $\tan\beta$ , so that this scenario provides a suitable framework for studying the phenomenology of the MSSM Higgs sector. Since the low-scale parameters in this scenario are derived from a small set of input quantities in a meaningful way, it is of interest to take into account other experimental constraints.

The main purpose of this paper is to explore new benchmark surfaces for MSSM Higgs phenomenology that are compatible with the cosmological density of cold dark matter inferred from a combination of WMAP and other observations [43]. While in the CMSSM only narrow strips in  $(m_{1/2}, m_0)$  planes are compatible with WMAP et al. [44, 45] for given values of  $A_0$  and  $\tan\beta$ , the NUHM offers the attractive possibility to specify  $(M_A, \tan\beta)$  planes such that essentially the whole plane is allowed by the constraints from WMAP and other observations [25]. This is done assuming that  $R$  parity is conserved, that the lightest supersymmetric particle (LSP) is the lightest neutralino  $\tilde{\chi}_1^0$ , and that it furnishes most of the cold dark matter required [46]. As we discuss in more detail below, compatibility with WMAP et al. cannot be maintained while keeping all the other NUHM parameters fixed. Accordingly, we discuss two examples of WMAP-compliant benchmark surfaces that are specified for fixed  $m_0, \mu$  and  $A_0 = 0$  but varying  $m_{1/2}$ , and two surfaces that are specified for fixed  $m_{1/2}, m_0$  and  $A_0 = 0$  but varying  $\mu$ . For the first two benchmark surfaces, a simple linear relation between  $m_{1/2}$  and  $M_A$  is imposed as the  $(M_A, \tan\beta)$  plane is scanned, whereas for the other two surfaces  $\mu$  is varied through a relatively narrow range.

Following the specifications of these NUHM benchmark surfaces, we then explore the possibilities for studies of the MSSM Higgs bosons and other supersymmetric signatures across these  $(M_A, \tan\beta)$  planes. We consider the electroweak precision observables, principally  $a_\mu \equiv \frac{1}{2}(g-2)_\mu$  and  $M_h$ , prospects for the search for  $H/A \rightarrow \tau^+\tau^-$  at the Tevatron, prospects at the LHC — including searches for  $h \rightarrow \gamma\gamma$  and  $\tau^+\tau^-$ ,  $H/A \rightarrow \tau^+\tau^-$  and  $H^\pm \rightarrow \tau^\pm\nu$ , and measurements of the ratio of  $h \rightarrow \tau^+\tau^-$  and  $WW^*$  branching ratios, prospects at the ILC — including ways of distinguishing between the light MSSM  $h$  bo-

son and an SM Higgs boson of the same mass by measuring (ratios of) branching ratios, prospects in  $B$  physics — including  $B_s \rightarrow \mu^+ \mu^-$ ,  $b \rightarrow s\gamma$  and  $B_u \rightarrow \tau\nu$ , and the direct detection of supersymmetric cold dark matter. In an appendix we introduce developments in the `FeynHiggs` code that enable the user to explore for her/himself the WMAP-compliant benchmark surfaces. These include the concept of a `FeynHiggs` record, a new data type that captures the entire content of a parameter file in the native format of `FeynHiggs`.

## 2. Specification of the benchmark surfaces

As an introduction to the specification of the benchmark surfaces in the NUHM, we first consider a generic  $(M_A, \tan\beta)$  plane for fixed  $m_{1/2}, m_0, A_0$  and  $\mu$ , adapted from ref. [47]. As we see in figure 1(a), in the  $(M_A, \tan\beta)$  plane for  $m_{1/2} = 600$  GeV,  $m_0 = 800$  GeV,  $\mu = 1000$  GeV and  $A_0 = 0$ , the relic LSP density satisfies the WMAP constraint only in narrow, near-vertical (pale blue) shaded strips crossing the plane. These lie to either side of the vertical (purple) line where  $m_{\tilde{\chi}_1^0} = M_A/2$ . Within the narrow unshaded strip straddling this line, the relic density is suppressed by rapid direct-channel annihilations to a value below the lower limit of the range for the cold dark matter density indicated by WMAP et al. This strip would be acceptable for cosmology if there were some additional component of cold dark matter. Outside the shaded WMAP-compatible strips, at both larger and smaller values of  $M_A$ , the relic LSP density is too high, and these regions are unacceptable.<sup>1</sup>

It is clear from this example that one may arrange for the relic LSP density to remain within the preferred WMAP range over (essentially) the entire  $(M_A, \tan\beta)$  plane if one adjusts  $m_{1/2}$  continuously as a function of  $M_A$  so as to remain within one of the narrow WMAP strips as  $M_A$  increases. Accordingly, we study a benchmark  $(M_A, \tan\beta)$  plane **P1** with the same values of  $m_0 = 800$  GeV,  $\mu = 1000$  GeV and  $A_0 = 0$ , but with varying  $m_{1/2} \sim \frac{9}{8}M_A$ . Since we evaluate observables using a discrete sampling of the NUHM parameter space, we consider values of  $m_{1/2}$  lying within the small range of this central value:

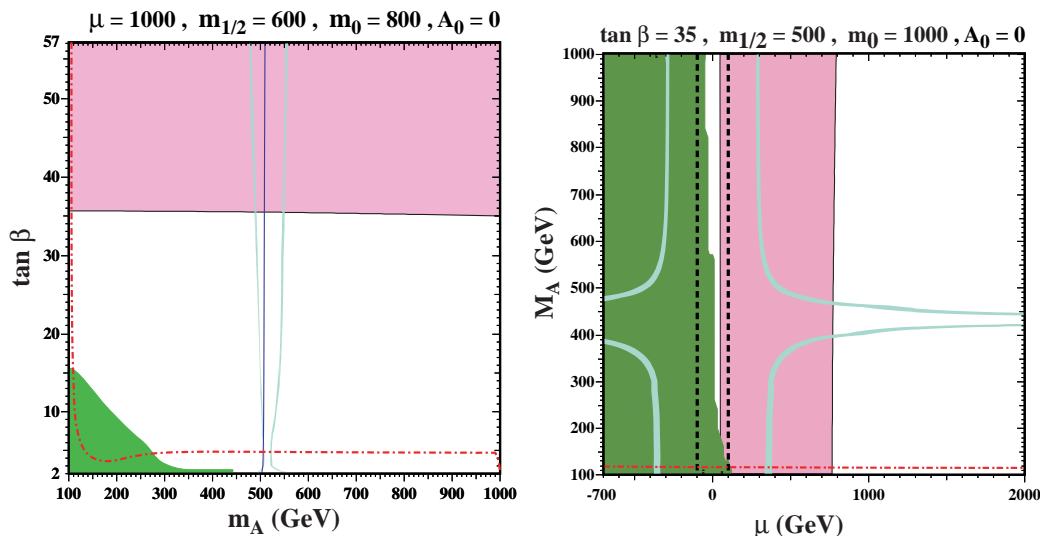
$$\frac{9}{8}M_A - 12.5 \text{ GeV} \leq m_{1/2} \leq \frac{9}{8}M_A + 37.5 \text{ GeV}. \quad (2.1)$$

The observables that we study do not vary significantly as  $m_{1/2}$  is varied across this range. Specifically, we use the  $m_{1/2}$  that gives the value of the cold dark matter density that is closest to the central value within the allowed range,  $0.0882 < \Omega_{\text{CDM}}h^2 < 0.1204$  [43] (see below).

Previous analyses of the CMSSM indicated that values of  $m_{1/2}$  and  $m_0$  below 1 TeV are preferred, in particular by the EWPO [48, 49, 25] (see also ref. [50]). Accordingly, we study also a benchmark  $(M_A, \tan\beta)$  plane **P2** with the fixed values  $m_0 = 300$  GeV,  $\mu = 800$  GeV and  $A_0 = 0$ , with  $m_{1/2} \sim 1.2M_A$  again varying continuously across the plane

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<sup>1</sup>We note in passing that the LEP lower limit on  $M_h$  excludes a strip of this plane at low  $M_A$  and/or  $\tan\beta$  indicated by the dash-dotted (red) line, that  $a_\mu$  (pink shading) prefers relatively large  $\tan\beta > 36$ , that  $b \rightarrow s\gamma$  excludes a (green shaded) region at low  $M_A$  and  $\tan\beta$ , and that the other BPO disfavour a region at low  $M_A$  and high  $\tan\beta$  (not shown).



**Figure 1:** Sample NUHM parameter planes with two parameters varied and the other four fixed, adapted from refs. [47, 51]. The left plot displays a  $(M_A, \tan\beta)$  plane with  $m_{1/2} = 600$  GeV,  $m_0 = 800$  GeV,  $\mu = 1000$  GeV and  $A_0 = 0$ . The range of cold dark matter density preferred by WMAP and other observations is attained in two narrow (pale blue) strips, one on either side of the vertical solid (blue) line where  $m_{\tilde{\chi}_1^0} = M_A/2$ . The dark (green) shaded region at low  $M_A$  and low  $\tan\beta$  is excluded by  $b \rightarrow s\gamma$ , and the medium (pink) shaded region at  $\tan\beta > 36$  is favoured by  $a_\mu$ . The region below the (red) dot-dashed line is excluded by the LEP bounds on  $M_h$ . The right plot displays a  $(\mu, M_A)$  plane with  $m_{1/2} = 500$  GeV,  $m_0 = 1000$  GeV,  $\tan\beta = 35$  and  $A_0 = 0$ . Here the WMAP range of cold dark matter density is attained in two narrow strips at roughly constant positive and negative values of  $\mu$ , which are swept apart by rapid annihilation when  $M_A \sim 2m_{\tilde{\chi}_1^0}$ . The dark (green) shaded region at  $\mu < 0$  is excluded by  $b \rightarrow s\gamma$ , and the  $0 < \mu < 760$  GeV strip (pink shading) is favoured by  $a_\mu$ . The region below the (red) dot-dashed line again is excluded by the LEP bounds on  $M_h$ , and the region between the vertical (black) dashed lines has  $m_{\tilde{\chi}_1^\pm} < 104$  GeV.

so as to maintain the WMAP relationship with  $M_A$ . As before, because of our discrete sampling of the NUHM parameter space, we consider values of  $m_{1/2}$  lying within a small range of this central value:

$$1.2M_A - 40 \text{ GeV} \leq m_{1/2} \leq 1.2M_A + 40 \text{ GeV}. \quad (2.2)$$

Again, the observables that we study do not vary significantly as  $m_{1/2}$  is varied across this range.

More examples could be chosen with different fixed values of  $m_0$ ,  $\mu$  and  $A_0$  but, as long as  $m_{1/2}$  is the parameter being varied to keep the LSP density within the WMAP range, a similar relationship between  $m_{1/2}$  and  $M_A$  will always apply. The only flexibility in the choice of  $m_{1/2}$  is whether one wishes to stay within the left or right near-vertical shaded strip. However, the corresponding values of  $m_{1/2}$  do not differ greatly, and neither do the corresponding phenomenological signatures, though the lightest Higgs boson mass can be somewhat sensitive to this choice. The values of  $m_0$  and (to a lesser extent)  $\mu$  have far more

impact on the phenomenology, and the benchmark choices we have made:  $m_0 = 800$  GeV for **P1** and  $m_0 = 300$  GeV for **P2**, provide significant and interesting differences worthy of examination.

We also study two other  $(M_A, \tan\beta)$  planes, whose motivation can be gained from examination of the  $(\mu, M_A)$  plane shown in figure 1(b), which is adapted from ref. [51]. We see that, for a fixed choice of values of  $m_{1/2} = 500$  GeV,  $m_0 = 1000$  GeV and  $A_0 = 0$ , there is a narrow strip of values of  $\mu \sim 300 \rightarrow 350$  GeV where the relic density lies within the WMAP range for almost all values of  $M_A$ . The exception is a narrow strip centred on  $M_A \sim 430$  GeV, namely the rapid-annihilation funnel where  $m_{\tilde{\chi}_1^0} \sim M_A/2$ , which would be acceptable if there is some other source of cold dark matter. This funnel is narrower (wider) for smaller (larger) values of  $\tan\beta$ , but its location in  $\mu$  does not vary much as a function of  $\tan\beta$ .<sup>2</sup>

Motivated by this example, we explore two benchmark surfaces with different fixed values of  $m_{1/2}$  and  $m_0$ , and  $\mu$  varying within a restricted range chosen to maintain the LSP density within or below the WMAP range. The first example of such a benchmark plane, **P3**, has fixed  $m_{1/2} = 500$  GeV,  $m_0 = 1000$  GeV and  $A_0 = 0$ , with  $\mu$  in the range

$$\mu = 250 - 400 \text{ GeV.} \tag{2.3}$$

In the following, we evaluate observables for a discrete sampling of  $\mu$  values within this range. Since the corresponding variation of the particle mass spectrum is quite small, the impact of the variation of  $\mu$  on the observables discussed below is negligible.

The other example of such a benchmark plane, **P4**, has fixed  $m_{1/2} = 300$  GeV,  $m_0 = 300$  GeV and  $A_0 = 0$ , with  $\mu$  in the range

$$\mu = 200 - 350 \text{ GeV.} \tag{2.4}$$

As in the previous case, the LSP density lies within the WMAP range except for a small range of  $M_A \sim 2m_{\tilde{\chi}_1^0}$  where the density is below the preferred range. However, again this is acceptable if there is some other component of cold dark matter. The parameter choices for this and the other NUHM benchmark surfaces are summarized in table 1.<sup>3</sup>

A likelihood analysis of these four NUHM benchmark surfaces, including the EWPO  $M_W$ ,  $\sin^2\theta_{\text{eff}}$ ,  $\Gamma_Z$ ,  $(g-2)_\mu$  and  $M_h$  and the BPO  $\text{BR}(b \rightarrow s\gamma)$ ,  $\text{BR}(B_s \rightarrow \mu^+\mu^-)$ ,  $\text{BR}(B_u \rightarrow \tau\nu_\tau)$  and  $\Delta M_{B_s}$  was performed recently in ref. [25]. The lowest  $\chi^2$  value in each plane, denoted as  $\chi_{\text{min}}^2$ , is shown in the rightmost column of table 1, corresponding to the points labeled as the best fits in the plots below. We display in each of the following figures the locations of these best-fit points by a (red) cross and the  $\Delta\chi^2 = 2.30$  and 4.61 contours around the best-fit points in the  $(M_A, \tan\beta)$  planes for each of these benchmark surfaces. These contours would correspond to the 68 % and 95 % C.L. contours in

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<sup>2</sup>We note in passing that the LEP lower limit on  $M_h$  excludes a strip of this plane at low  $M_A$  indicated by the (red) dash-dotted line, and the LEP lower limit on the chargino mass excludes values of  $\mu$  between the two vertical (black) dashed lines.

<sup>3</sup>A minor change in the best-fit point and the  $\chi_{\text{min}}^2$  occurred for the **P2** scenario in comparison with ref. [25] due to a slightly different choice of the  $m_{1/2}$  values.



	$m_{1/2}$	$m_0$	$A_0$	$\mu$	$\chi^2_{\min}$
<b>P1</b>	$\sim \frac{9}{8}M_A$	800	0	1000	7.1
<b>P2</b>	$\sim 1.2M_A$	300	0	800	3.1
<b>P3</b>	500	1000	0	250 ... 400	7.4
<b>P4</b>	300	300	0	200 ... 350	5.6

**Table 1:** The four NUHM benchmark surfaces are specified by the above fixed and varying parameters, allowing  $M_A$  and  $\tan\beta$  to vary freely. All mass parameters are in GeV. The rightmost column shows the minimum  $\chi^2$  value found in each plane at the points labelled as the best fits in the plots.

the  $(M_A, \tan\beta)$  planes *if* the overall likelihood distribution,  $\mathcal{L} \propto e^{-\chi^2/2}$ , were Gaussian. This is clearly only approximately true, but these contours nevertheless give interesting indications on the regions in the  $(M_A, \tan\beta)$  planes that are currently preferred. The varied parameter in each scenario (i.e.  $m_{1/2}$  in **P1**, **P2** and  $\mu$  in **P3**, **P4**) is chosen such that the cold dark matter density is closest to the central value within the allowed range,  $0.0882 < \Omega_{\text{CDM}}h^2 < 0.1204$  [43].

On surfaces **P1** and **P2**, where  $m_{1/2}$  scales with  $M_A$  so as to remain in the funnel region, much of the mass spectrum scales with  $M_A$ . Specifically, the lightest neutralino and chargino masses simply scale in direct proportion to  $M_A$  for these surfaces. The light squark masses and stau masses also scale with  $m_{1/2}$  (and hence  $M_A$ ), though the latter are also slightly dependent on  $\tan\beta$  as well. In the range  $M_A \leq 1$  TeV displayed in these planes, the light squark masses range up to  $\sim 2.3$  TeV for surface **P1**, within reach of the LHC. However, because of the relatively large values of  $m_0$ , the light squarks are beyond the current reach of the Tevatron collider even at low  $M_A$  (and hence  $m_{1/2}$ ). For **P2**, the light squark masses range up to  $\sim 1.7$  TeV.

Turning to surfaces **P3** and **P4**, because they have fixed values of  $m_{1/2}$  and  $m_0$ , there are very small variations in the sparticle mass spectra across these planes. For example, the lightest neutralino and chargino masses are determined primarily by  $m_{1/2}$ , and so they both take almost constant values on the benchmark surfaces. Similarly, the light squark masses are determined by a combination of  $m_{1/2}$  and  $m_0$  and show little dependence on either  $M_A$  or  $\tan\beta$ . On the other hand, the lightest stau mass has a slight dependence on  $\tan\beta$ , due to the variable splitting of the third-generation sparticle masses. These mass splittings increase at large  $\tan\beta$ , leading to smaller stau masses.

We display in each plane the region excluded (black shaded) at the 95 % C.L. by the LEP Higgs searches in the channel  $e^+e^- \rightarrow Z^* \rightarrow Zh, H$  [53, 52]. For a SM-like Higgs boson we use a bound of  $M_h > 113$  GeV. The difference from the nominal LEP mass limit allows for the estimated theoretical uncertainty in the calculation of  $M_h$  for specific values of the input MSSM parameters [54]. In the region of small  $M_A$  and large  $\tan\beta$ , where the coupling of the light  $\mathcal{CP}$ -even Higgs boson to gauge bosons is suppressed, the bound on  $M_h$  is reduced to  $M_h > 91$  GeV [52].

### 3. Electroweak precision observables

In this section we summarize key predictions for electroweak precision observables (EWPO) over the four benchmark surfaces. In ref. [25] it was shown that  $M_W$ ,  $\sin^2 \theta_{\text{eff}}$  and  $\Gamma_Z$  agree within  $\sim 1\sigma$  with the current experimental value over all the benchmark surfaces. Since their variations are relatively small, we do not display these observables in this paper, though they are included in the overall  $\chi^2$  function. Here we focus on two other EWPO, namely the mass of the lightest Higgs boson,  $M_h$ , and the anomalous magnetic moment of the muon,  $a_\mu \equiv \frac{1}{2}(g - 2)_\mu$ .

The evaluation of  $M_h$  is performed using `FeynHiggs` [55, 56, 54, 57]. In figure 2 we show the contours for  $M_h = 113, 114, 115, 116, 117, 118$  and  $120$  GeV. As discussed in the previous section, the boundary of the region excluded by the LEP searches for the lightest MSSM Higgs boson does not coincide with the nominal limit  $M_h = 114.4$  GeV on the mass of a Standard Model Higgs boson. Nevertheless, it can be seen in figure 2 that the  $\Delta\chi^2 = 2.30$  and  $4.61$  contours are highly correlated with the  $M_h$  contours at low values of  $M_A$  and  $\tan\beta$ . This is a consequence of the fact that the full likelihood information from the LEP Higgs exclusion limit (as well as the theoretical uncertainty) is incorporated into the overall  $\chi^2$  function (see ref. [25]). Note that for the plane **P4** (and to a lesser extent **P3**) the maximum value for the Higgs mass is limited by the relatively low value of  $m_{1/2}$ .

Concerning  $a_\mu$ , we recall that, according to a recent evaluation of the Standard Model contribution based on low-energy  $e^+e^-$  data, there is a discrepancy with the experimental measurement by the E821 Collaboration [62, 63]. It would be premature to regard this deviation as solid evidence for new physics. However, within the SUSY framework we explore here, this discrepancy does impose a significant constraint on the parameter space, and makes an important contribution to the global  $\chi^2$  function whose contours are shown in figure 2. Our evaluation of  $a_\mu$  is based on refs. [58–61], which yields [64, 65]:

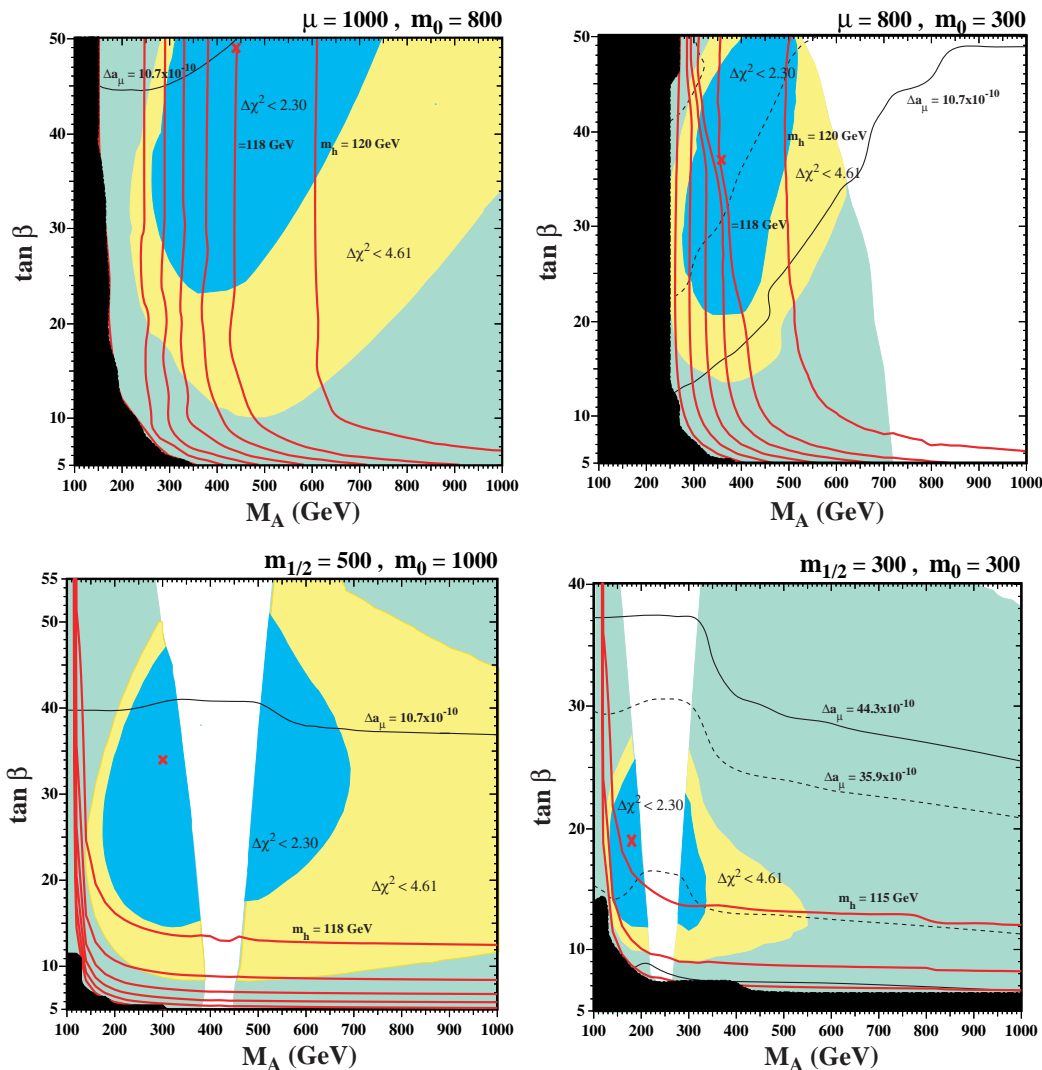
$$a_\mu^{\text{exp}} - a_\mu^{\text{theo}} = (27.5 \pm 8.4) \times 10^{-10}, \quad (3.1)$$

equivalent to a  $3.3\text{-}\sigma$  effect.<sup>4</sup>In figure 2 we show the contours  $\Delta a_\mu = 10.7, 19.1, 35.9, 44.3 \times 10^{-10}$  for the net supersymmetric contribution to  $a_\mu$ .

In the case of surface **P1**, we see that the best-fit point corresponds to  $M_h \sim 118$  GeV and  $\Delta a_\mu \sim 10.7 \times 10^{-10}$ . In most of the displayed region of the surface that is favoured at the global  $\Delta\chi^2 < 4.61$  level,  $\Delta a_\mu$  is considerably *lower* than the range favoured in eq. (3.1). In the case of surface **P2**, the best-fit point has  $M_h \sim 118$  GeV, and  $\Delta a_\mu$  is within the  $1\text{-}\sigma$  range given by eq. (3.1). In the case of surface **P3**, the best-fit point has  $M_h > 118$  GeV and again a low value of  $\Delta a_\mu$ . Finally, the best-fit point in surface **P4** has  $M_h \sim 115$  GeV and an excellent value of  $\Delta a_\mu$ , according to eq. (3.1). The fact that the best-fit points do not always have favoured values of  $\Delta a_\mu$  reflects the importance of other precision observables, notably the BPO discussed later.

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<sup>4</sup>Three other recent evaluations yield slightly different numbers [66–69], but similar discrepancies with the SM prediction.



**Figure 2:** The  $(M_A, \tan \beta)$  planes for the NUHM benchmark surfaces (a) **P1**, (b) **P2**, (c) **P3** and (d) **P4**, displaying the contours of  $\Delta\chi^2$  found in a recent global fit to EWPO and BPO [25]. All surfaces have  $A_0 = 0$ . We also display individually the contours of  $M_h$  found using FeynHiggs [55, 56, 54, 57] and the contours of  $a_\mu$  found using refs. [58–61]. The 1(2)- $\sigma$  range for  $a_\mu$  is demarcated by dashed (solid) lines. The dark shaded (black) region corresponds to the parameter region that is excluded by the LEP Higgs searches in the channel  $e^+e^- \rightarrow Z^* \rightarrow Zh, H$  [53, 52].

#### 4. Tevatron phenomenology

We first consider how experiments at the Tevatron collider in the next years could probe the benchmark surfaces **P1**, **P2**, **P3** and **P4**. We consider one possible Tevatron signature for the MSSM Higgs sector, namely  $H/A \rightarrow \tau^+\tau^-$ , for which expectations are evaluated using the results from ref. [70]. They are based on the expectation of a 30% improvement in the sensitivity with respect to ref. [6]. We see in figure 3 that, at the Tevatron with 2 (4,

8)  $\text{fb}^{-1}$  of integrated and analyzed luminosity per experiment,<sup>5</sup> the channel  $H/A \rightarrow \tau^+\tau^-$  would provide a 95% C.L. exclusion sensitivity to  $\tan\beta \sim 35(30, 25)$  when  $M_A \sim 200$  GeV, and the sensitivity decreases slowly (rapidly) at smaller (larger)  $M_A$ . In the case of the benchmark surface **P1**,  $8 \text{ fb}^{-1}$  would start accessing the region with  $\Delta\chi^2 < 4.61$ . For **P2**, however, the area accessible to the Tevatron is not visible in the figure since it is completely covered by the excluded region from the LEP Higgs searches. The region  $\Delta\chi^2 < 4.61$  could be accessed already with  $2 \text{ fb}^{-1}$  in case **P3**, and  $8 \text{ fb}^{-1}$  would give access to the region with  $\Delta\chi^2 < 2.30$ . However, even the  $\Delta\chi^2 < 4.61$  region of the **P4** surface would be inaccessible with  $8 \text{ fb}^{-1}$ .

We note that the CDF Collaboration has recently reported a  $\sim 2\text{-}\sigma$  excess of candidate  $H/A \rightarrow \tau^+\tau^-$  events [9], which would correspond to  $M_A \sim 160$  GeV and  $\tan\beta > 45$ . As discussed in ref. [30], taking into account all the available experimental constraints, this possible excess could be accommodated within the NUHM only for rather different values of the parameters from those considered in the benchmark scenarios, namely  $m_{1/2} \sim 650$  GeV,  $m_0 \sim 1000$  GeV,  $A_0 \sim -1900$  GeV,  $\mu \sim 385$  GeV. A likelihood analysis yields values of  $\chi^2 \sim 9\text{--}10$ , somewhat higher than the values for the benchmark surfaces. Within the four benchmark scenarios here, the precision observables are not in good agreement with low  $M_A$  and large  $\tan\beta$ , reflecting the fact that the points with  $M_A \sim 160$  GeV and  $\tan\beta > 45$  lie well outside the regions with  $\Delta\chi^2 < 4.61$  on all of these benchmark surfaces.

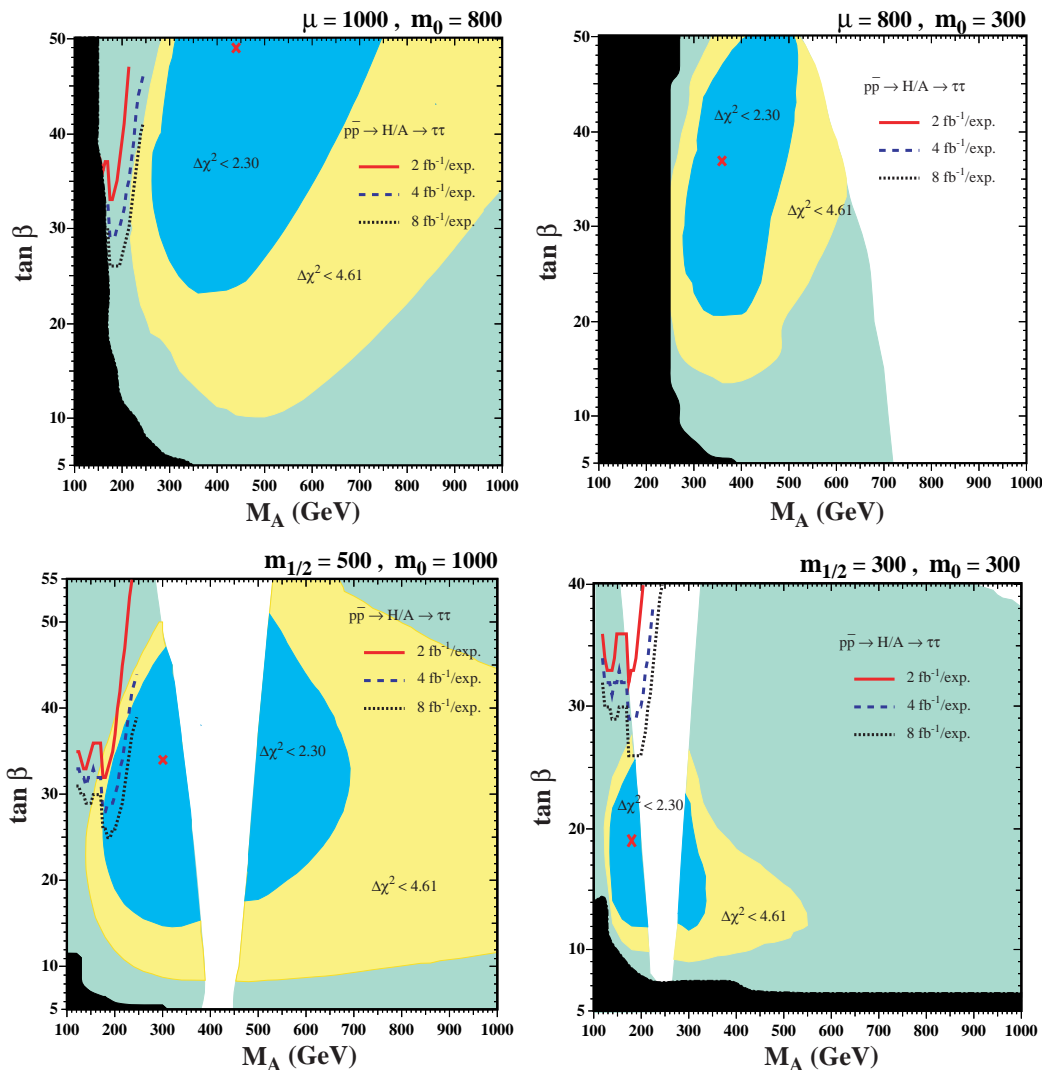
## 5. LHC phenomenology

In this section we present and compare the sensitivities of various LHC searches for MSSM Higgs bosons as functions of  $M_A$  and  $\tan\beta$  in the benchmark surfaces **P1**, **P2**, **P3** and **P4**. The Higgs bosons can either be produced 'directly' or via cascades, starting with gluino or squark production [71]. We focus here on the first possibility, but it should be kept in mind that the production via cascades could offer additional channels for the Higgs detection. A full evaluation of these channels across the benchmark surfaces must await a more complete evaluation of the experimental sensitivities to such decay modes.

We start the analysis with the light MSSM Higgs boson that behaves like the SM Higgs boson for  $M_A \gg M_Z$ . As a consequence, the region  $M_A \gg M_Z$  can be covered in all benchmark scenarios if a SM Higgs with  $M_H^{\text{SM}} = M_h$  is accessible at the LHC [11, 12, 14]. In figure 4 we display on the WMAP-compatible  $(M_A, \tan\beta)$  planes the  $5\text{-}\sigma$  discovery contours for  $pp \rightarrow h \rightarrow \gamma\gamma$  at the LHC with  $30 \text{ fb}^{-1}$  in the CMS detector [14], where the areas to the right of the lines (i.e. for larger  $M_A$ ) are covered by the  $pp \rightarrow h \rightarrow \gamma\gamma$  search. This channel is particularly important for a precise mass measurement of the lightest MSSM Higgs boson. We show separately the sensitivities for a cut-based analysis (blue solid line) and for an "optimized" analysis (black dotted line), see ref. [14] for details. The cut-based analysis should be regarded as a conservative result, while the "optimized" analysis should perhaps be regarded as an optimistic expectation [72]. In the cases of surfaces **P1** and **P2**, the LHC cut analysis for the  $pp \rightarrow h \rightarrow \gamma\gamma$  search covers all of the  $\Delta\chi^2 < 2.30$  region

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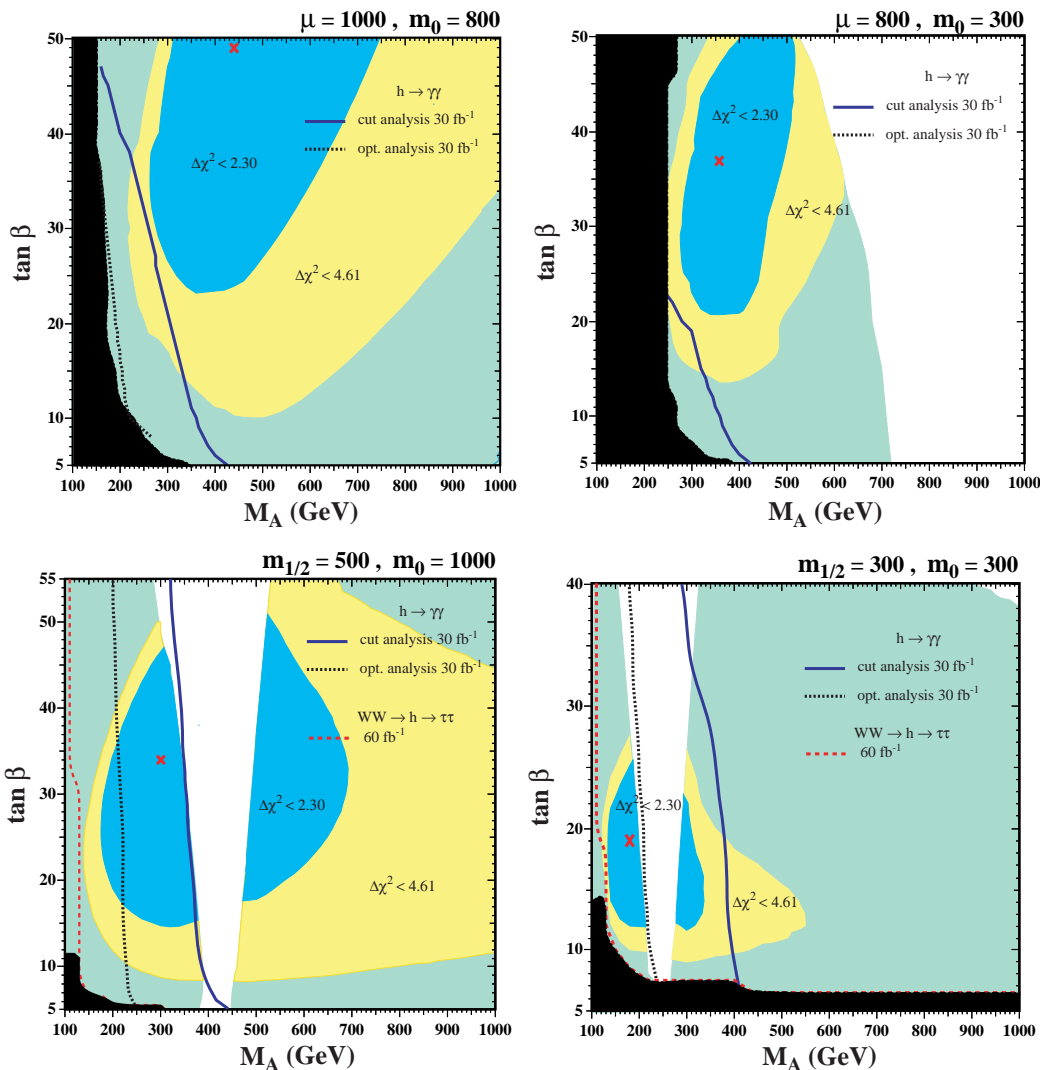
<sup>5</sup>We note that both CDF and D0 have already recorded more than  $2.5 \text{ fb}^{-1}$  of integrated luminosity.



**Figure 3:** The same  $(M_A, \tan \beta)$  planes for the NUHM benchmark surfaces (a) **P1**, (b) **P2**, (c) **P3** and (d) **P4** as in figure 2, displaying also the expected 95% C.L. exclusion sensitivities of searches for  $H/A \rightarrow \tau^+\tau^-$  at the Tevatron collider with 2, 4, 8  $\text{fb}^{-1}$  in each of the CDF and D0 experiments (see text).

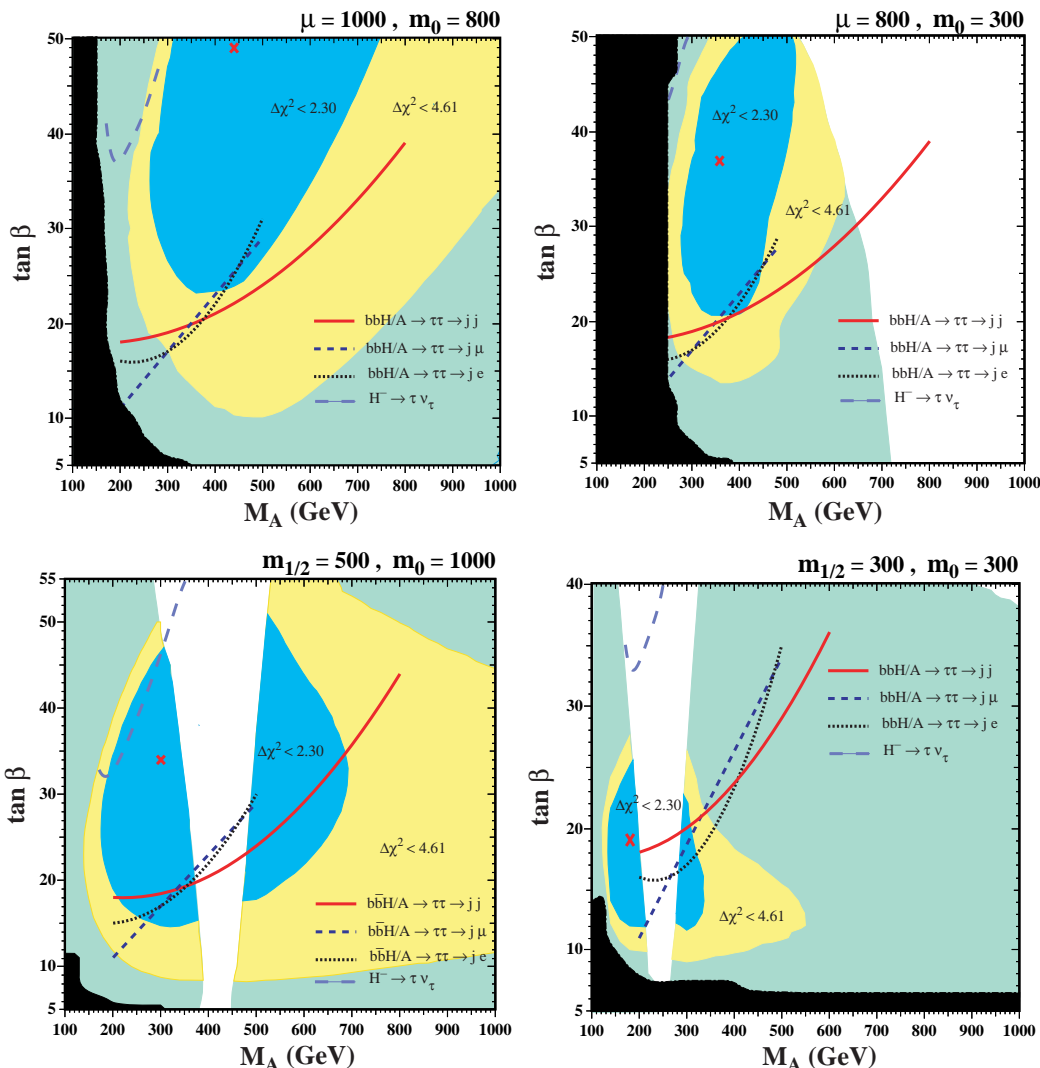
and the optimized analysis nearly the whole parameter plane. For **P3** only parts of the preferred region can be covered, while for **P4** even with the optimized analysis the best-fit point as well as large parts of the  $\Delta\chi^2 < 2.30$  area remain uncovered. In this region, more luminosity would need to be accumulated in order to see a 5- $\sigma$  signal in the  $pp \rightarrow h \rightarrow \gamma\gamma$  channel.

We turn next to the reaction  $W^+W^- \rightarrow h \rightarrow \tau^+\tau^-$ . On the WMAP-compatible  $(M_A, \tan \beta)$  planes in figure 4 we display the 5- $\sigma$  discovery contours for  $W^+W^- \rightarrow h \rightarrow \tau^+\tau^-$  at the LHC with 60  $\text{fb}^{-1}$  in the CMS detector [14], where the areas to the right of the lines (i.e. for larger  $M_A$ ) are covered by this search. In the cases of surfaces **P1** and **P2**, the



**Figure 4:** The same  $(M_A, \tan \beta)$  planes for the NUHM benchmark surfaces (a) **P1**, (b) **P2**, (c) **P3** and (d) **P4** as in figure 2, displaying the expected sensitivities of searches for  $pp \rightarrow h \rightarrow \gamma\gamma$  at the LHC with  $30 \text{ fb}^{-1}$  in the CMS detector using a cut analysis or an “optimized” analysis (see text) as well as the searches for  $W^+W^- \rightarrow h \rightarrow \tau^+\tau^-$  with  $60 \text{ fb}^{-1}$  in the CMS detector. The parameter regions to the right of the contours are covered at the  $5\text{-}\sigma$  level. For **P1** and **P2** the  $W^+W^- \rightarrow h \rightarrow \tau^+\tau^-$  channel covers the whole region of the  $(M_A, \tan \beta)$  plane that is unexcluded by LEP.

$5\text{-}\sigma$  discovery contours lie within the region already excluded by LEP, so this search covers all the unexcluded parts of the surfaces. In the cases of surfaces **P3** and **P4**, however, the  $W^+W^- \rightarrow h \rightarrow \tau^+\tau^-$  discovery contours leave uncovered narrow strips at low  $M_A$  for  $\tan \beta > 11, 14$ , respectively. In this part of the parameter space the search for  $H \rightarrow \tau^+\tau^-$  should be investigated. In all cases, the  $5\text{-}\sigma$  discovery contours cover the entire  $\Delta\chi^2 < 4.61$  regions. However, we note that this channel does not permit a very accurate measurement



**Figure 5:** The same  $(M_A, \tan \beta)$  planes for the NUHM benchmark surfaces (a) **P1**, (b) **P2**, (c) **P3** and (d) **P4** as in figure 2, displaying the 5- $\sigma$  discovery contours for  $H/A \rightarrow \tau^+\tau^-$  at the LHC with 60 or 30  $\text{fb}^{-1}$  (depending on the  $\tau$  decay channels) and for  $H^\pm \rightarrow \tau^\pm\nu$  detection in the CMS detector when  $M_{H^\pm} > m_t$  (see text).

of  $M_h$ , unlike the  $pp \rightarrow h \rightarrow \gamma\gamma$  channel.

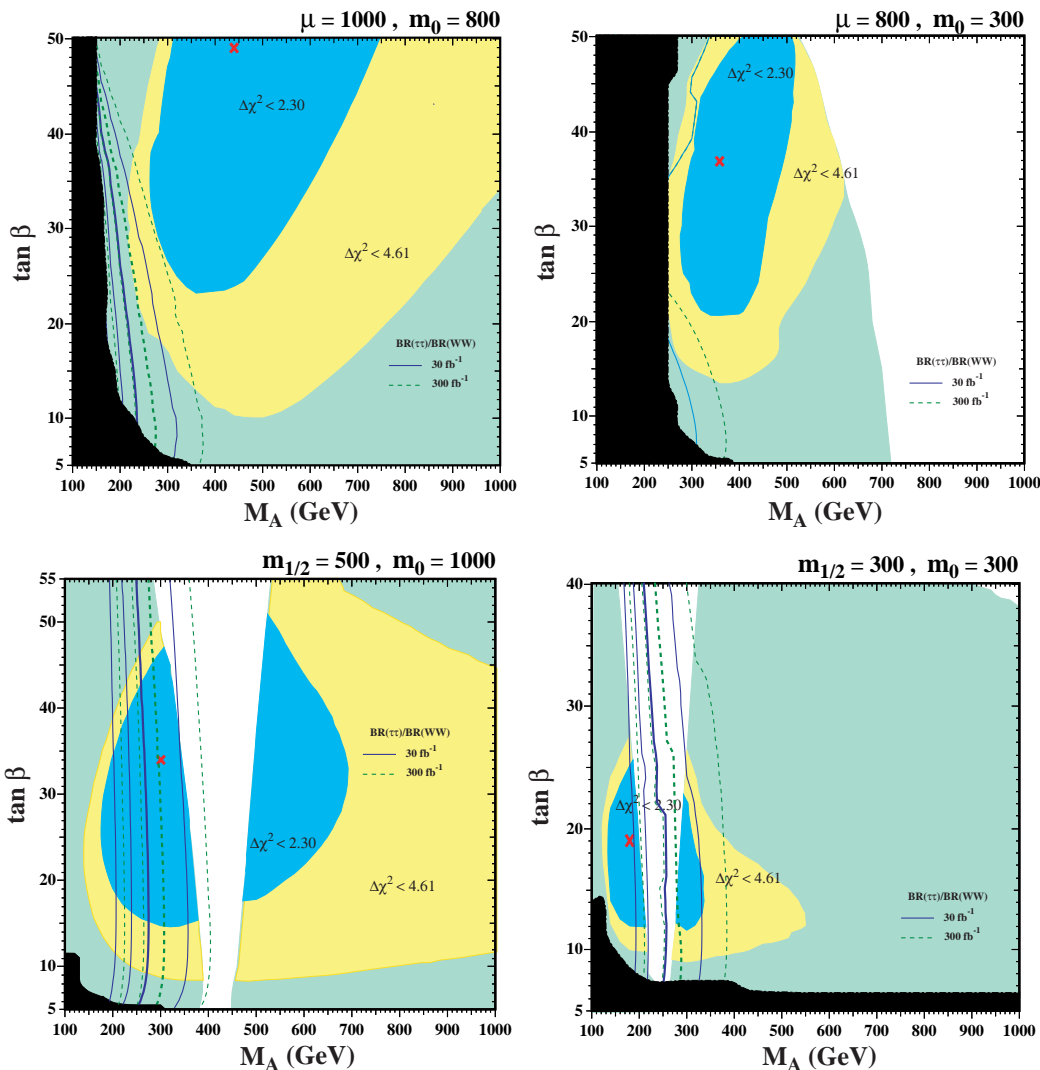
We now turn to the heavy MSSM Higgs bosons. In figure 5 we display in the  $(M_A, \tan \beta)$  planes the 5- $\sigma$  discovery contours for  $b\bar{b} \rightarrow H/A \rightarrow \tau^+\tau^-$  at the LHC, where the  $\tau$ 's decay to jets and electrons or muons (in the BR evaluation for the heavy Higgs bosons possible decays to SUSY particles [73–75] have also been taken into account). The analysis is based on 60  $\text{fb}^{-1}$  for the final state  $\tau^+\tau^- \rightarrow \text{jets}$  [76] and on 30  $\text{fb}^{-1}$  for the  $\tau^+\tau^- \rightarrow e + \text{jet}$  [77] and  $\tau^+\tau^- \rightarrow \mu + \text{jet}$  [78] channels, collected with the CMS detector. As shown in ref. [79], the impact of the supersymmetric parameters other than  $M_A$  and  $\tan \beta$  on the discovery contours is relatively small in this channel, and the decays of  $H/A$

to SUSY particles [73–75] are in general suppressed by large sparticle masses. Only in **P4** the decay to the lightest neutralinos and charginos is possible over nearly the whole plane (see also section 2). Including such decays in the evaluation of the discovery reach could increase the coverage for heavy Higgs bosons somewhat. As a consequence of the relatively small impact of the other SUSY parameters, the discovery contours in the four benchmark surfaces are similar to each other and to those in the “conventional” benchmark scenarios [79]. The 5- $\sigma$  discovery contours for the various  $\tau$  decay modes are shown separately: they may each be scaled individually for different values of the jet (j),  $\mu$  and electron (e) detection efficiencies, see ref. [79]. The sensitivities of the three different search strategies could in principle be combined, but information required for making such a combination is not yet available from the CMS Collaboration. Nor is the information available that would be needed to extend the discovery contours to small  $M_A < 200$  GeV or to large  $M_A > 500$  to 800 GeV. Nevertheless, we see that the whole  $\Delta\chi^2 < 2.30$  regions of the surfaces **P1** and **P2** would be covered by the LHC  $H/A \rightarrow \tau^+\tau^-$  searches, and most of the corresponding regions of the surfaces **P3** and **P4**. Comparing the LHC sensitivities shown in figure 5 with the Tevatron sensitivities shown in figure 3, we see that the LHC provides access to considerably heavier  $H/A$ , up to about 800 GeV, and that the covered region extends to lower values of  $\tan\beta$ , reaching  $\tan\beta \sim 10$  at low  $M_A$ . Comparing with figure 4, we see that the  $H/A \rightarrow \tau^+\tau^-$  searches presumably also cover the regions at  $M_A < 150$  GeV and  $\tan\beta > 11, 14$  that were left uncovered in the **P3** and **P4** surfaces, respectively, by the  $W^+W^- \rightarrow h \rightarrow \tau^+\tau^-$  searches. It would be interesting to verify this by means of an extension of the available CMS analysis.

We also show in figure 5 the 5- $\sigma$  contours for discovery of the  $H^\pm$  via its  $\tau^\pm\nu$  decay mode at the LHC, in the case  $M_{H^\pm} > m_t$ . We see that the coverage is limited in each of the scenarios **P1**, **P2**, **P3** and **P4** to  $M_A < 300$  GeV and  $\tan\beta > 30$ , reaching a small part of the  $\Delta\chi^2 < 2.30$  region of surface **P3**, only a small part of the  $\Delta\chi^2 < 4.61$  region of surface **P1**, and not even reaching this region in scenarios **P2** and **P4**. One may also search for  $H^\pm \rightarrow \tau^\pm\nu$  for lighter  $M_{H^\pm} < m_t$ , but in the cases of surfaces **P1** and **P2** this would be useful only in the regions already excluded by LEP, and the accessible regions in surfaces **P3** and **P4** would also be quite limited.

Another class of possible measurements at the LHC comprises the precise determinations of  $h$  decay branching ratios [80], and using their ratios to search for deviations from the SM predictions for a Higgs boson of the same mass. Such deviations may arise in the MSSM due to differences in the tree-level couplings and due to additional (loop) corrections. The most sensitive observable is likely to be the ratio of  $\text{BR}(h \rightarrow \tau^+\tau^-)/\text{BR}(h \rightarrow WW^*)$ . We display in figure 6 the 1-, 2-, 3- and 5- $\sigma$  contours (2- $\sigma$  in bold) for SUSY induced deviations of this ratio of branching ratios from the SM prediction (with  $M_H^{\text{SM}} = M_h$ ). The contours correspond to an integrated luminosity at the LHC of 30 or 300  $\text{fb}^{-1}$  [81] (assuming SM decay rates). An experimental resolution for  $\text{BR}(h \rightarrow \tau^+\tau^-)/\text{BR}(h \rightarrow WW^*)$  between 30% (28%) and 45% (33%) can be achieved for 30 (300)  $\text{fb}^{-1}$ . For  $M_h = 120$  GeV the corresponding precision is 38% (29%). The most promising surfaces are **P3** and **P4**, and we see that over essentially all the left lobe of the  $\Delta\chi^2 < 4.61$  region for **P4** a 5- $\sigma$





**Figure 6:** The same  $(M_A, \tan \beta)$  planes for the NUHM benchmark surfaces (a) **P1**, (b) **P2**, (c) **P3** and (d) **P4** as in figure 2, displaying the 1-, 2-, 3- and 5- $\sigma$  contours (2- $\sigma$  in bold) for SUSY-induced deviations on the ratio  $\text{BR}(h \rightarrow \tau^+\tau^-)/\text{BR}(h \rightarrow WW^*)$  at the LHC with 30 or 300  $\text{fb}^{-1}$  (see text). In the case of surface **P2**, only 1- $\sigma$  curves are seen in the lower part of the figure. The upper curves correspond to 0- $\sigma$ .

discrepancy with the SM should be detectable.<sup>6</sup> On the other hand, only partial coverage of the left lobe of surface **P3** would be possible, and the sensitivities in the right lobes of **P4** and **P3** and in the **P1** and **P2** surfaces are considerably less promising. Nevertheless, measuring  $\text{BR}(h \rightarrow \tau^+\tau^-)/\text{BR}(h \rightarrow WW^*)$  does offer the prospect of distinguishing between the NUHM and the SM in the low  $M_A$  regions of surfaces **P3** and **P4**.

<sup>6</sup>It should be kept in mind that the actual experimental precision on the ratio  $\text{BR}(h \rightarrow \tau^+\tau^-)/\text{BR}(h \rightarrow WW^*)$  will be different in this parameter region from the numbers quoted above which assume SM rates.

collider	channel	exp. precision [%]
ILC(500)	$\text{BR}(h \rightarrow b\bar{b})$	1.5
ILC(500)	$\text{BR}(h \rightarrow \tau^+\tau^-)$	4.5
ILC(500)	$\text{BR}(h \rightarrow WW^*)$	3.0
ILC(1000)	$\text{BR}(h \rightarrow b\bar{b})/\text{BR}(h \rightarrow WW^*)$	1.5

**Table 2:** Experimental precisions at the ILC for various branching ratios of the lightest MSSM Higgs boson (assuming SM decay rates) [82, 18, 83]. The experimental precision in the last column corresponds to  $1\sigma$  in the plots below. ILC(500,1000) refers to a center-of-mass energy of 500, 1000 GeV, respectively.

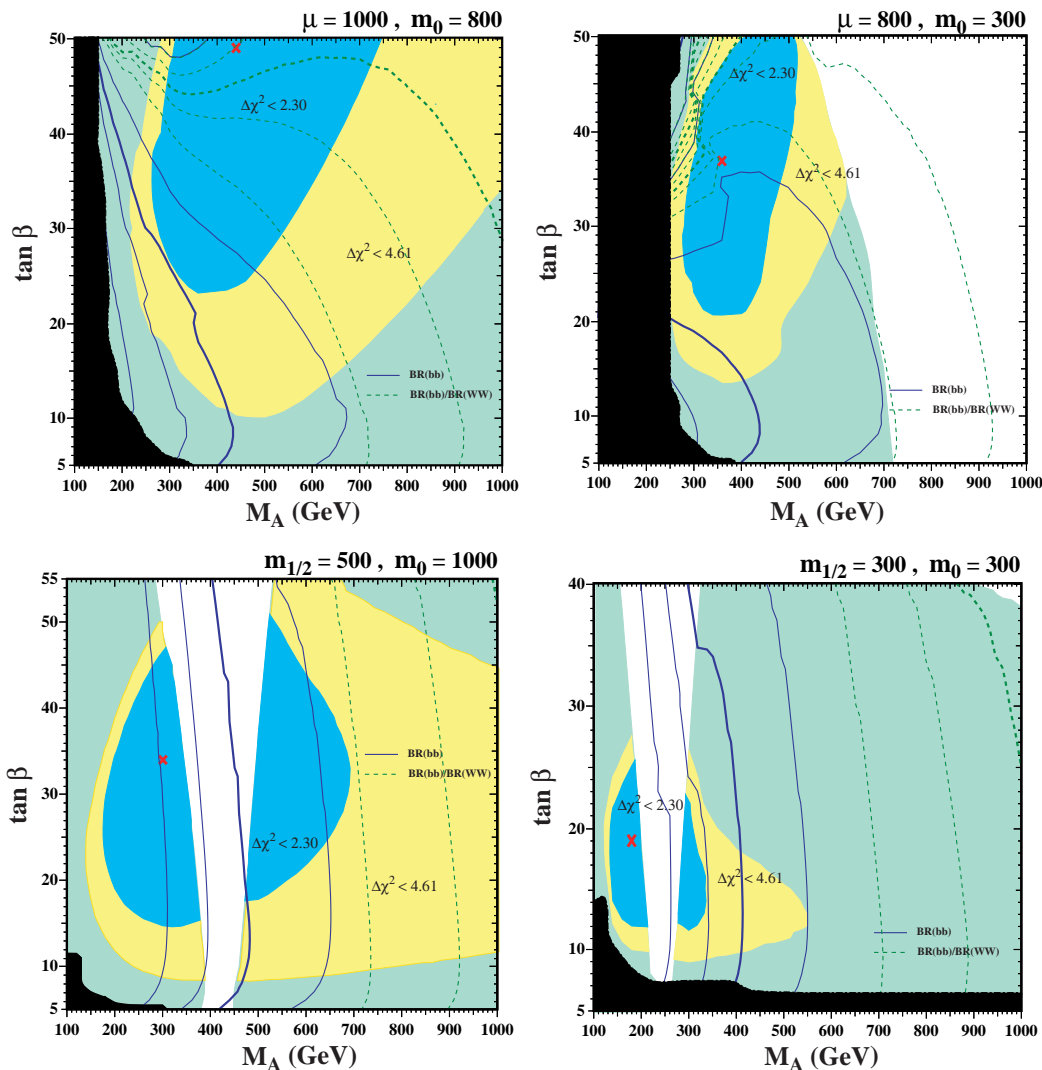
## 6. ILC phenomenology

In this section we analyze the deviations in the branching ratios of the lightest MSSM Higgs boson to SM fermions and gauge bosons in comparison with a SM Higgs boson of the same mass that could be measured at the ILC (see also ref. [21]). The experimental precisions for the branching ratios we analyze are summarized in table 2.

We show in figure 7 the prospective sensitivity of an ILC measurement of the  $\text{BR}(h \rightarrow b\bar{b})$  in the four  $(M_A, \tan\beta)$  planes. The experimental precision is anticipated to be 1.5%, see table 2. We display as solid (blue) lines the contours of the  $+5, +3, +2, +1, 0\sigma$  deviations (with  $+2\sigma$  in bold) of the MSSM result from the corresponding SM result (for low  $M_A$  and large  $\tan\beta$  in **P2** we also find contours for  $-2, -1\sigma$ , with  $-2\sigma$  in bold). The separations between the contours indicate how sensitively the SUSY results depend on variations of  $M_A$  and  $\tan\beta$ . Also shown in figure 7 via dashed (green) lines is the sensitivity to SUSY effects of the ILC measurement of the ratio of branching ratios  $\text{BR}(h \rightarrow b\bar{b})/\text{BR}(h \rightarrow WW^*)$  (for low  $M_A$  and large  $\tan\beta$  in **P2** we also find contours for  $-5, -3, -2, -1\sigma$ ). The precision measurement of the ratio  $\text{BR}(h \rightarrow b\bar{b})/\text{BR}(h \rightarrow WW^*)$  clearly provides a much higher sensitivity to SUSY effects than the measurement of  $\text{BR}(h \rightarrow b\bar{b})$  alone (see also ref. [20]).

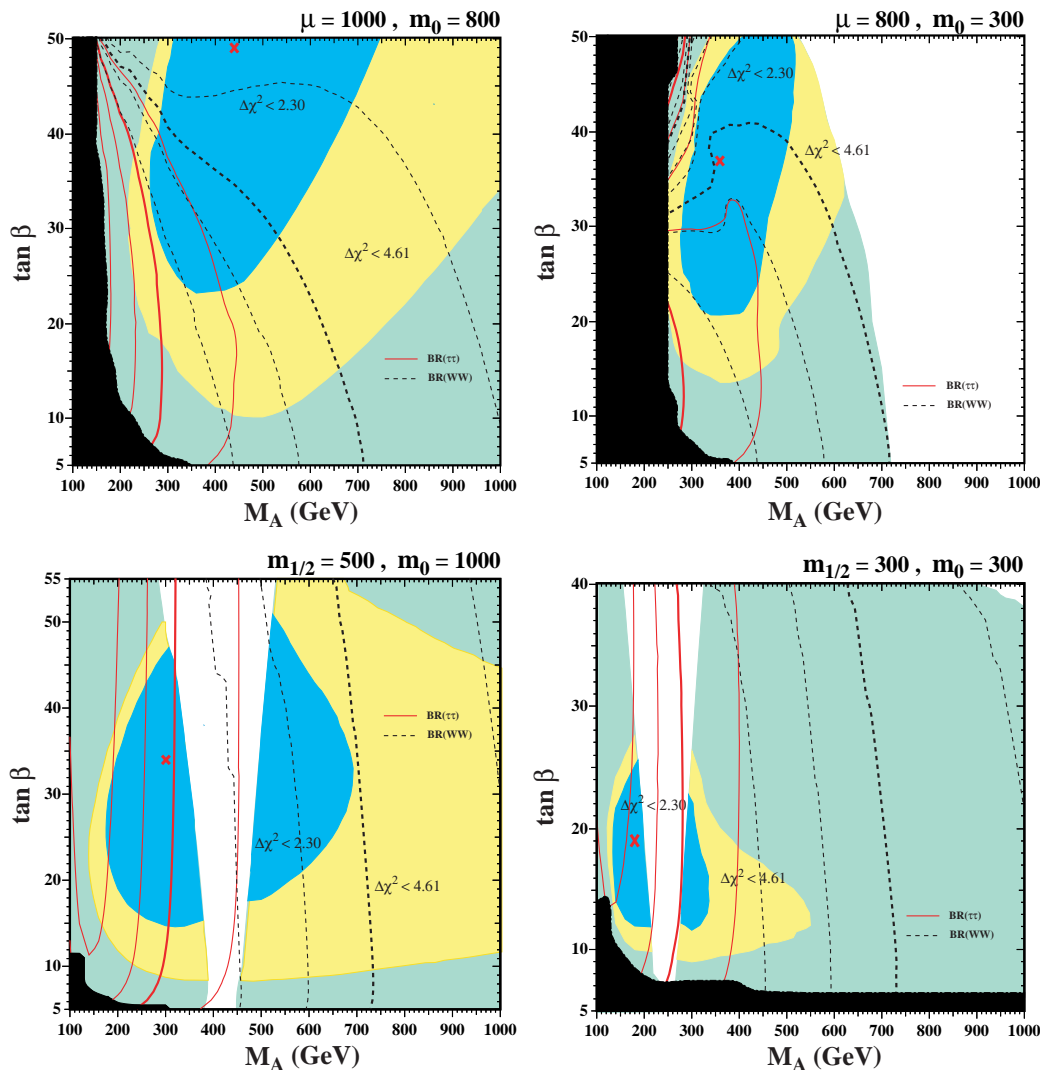
For the ILC measurement of the  $\text{BR}(h \rightarrow b\bar{b})$ , in the cases of **P1** and **P2** we see that the prospective sensitivities are less than  $3\sigma$  throughout almost all the regions with  $\Delta\chi^2 < 4.61$ . The situations are different, however, for the planes **P3** and **P4**. In each case, the cosmologically-favoured region is divided into separate lobes at low and high  $M_A$ . In the **P3** case, the measurement of  $\text{BR}(h \rightarrow b\bar{b})$  would be sufficient to establish a SUSY effect with more than five  $\sigma$  throughout most of the low- $M_A$  lobe, and all of it in the **P4** case. A precision measurement of  $\text{BR}(h \rightarrow b\bar{b})/\text{BR}(h \rightarrow WW^*)$  yields a significant improvement for all benchmark surfaces. We see that, in case **P1**, the sensitivity already exceeds  $5\sigma$  in much of the region with  $\Delta\chi^2 < 2.30$ , and the fraction of this region covered at the  $5\sigma$  level is even larger in the case **P2**. Even more encouragingly, in the case **P3** the sensitivity exceeds  $5\sigma$  throughout the  $\Delta\chi^2 < 2.30$  region, and in the case **P4** it exceeds  $5\sigma$  by a substantial amount throughout the  $\Delta\chi^2 < 4.61$  region.

Next, we show in figure 8 the prospective sensitivity of an ILC measurement of the  $\text{BR}(h \rightarrow \tau^+\tau^-)$  in the four  $(M_A, \tan\beta)$  planes, using solid (red) contours. In the cases of **P1** and **P2**, we again see that the prospective sensitivities are less than  $3\sigma$  throughout almost



**Figure 7:** The same  $(M_A, \tan \beta)$  planes for the NUHM benchmark surfaces (a) **P1**, (b) **P2**, (c) **P3** and (d) **P4** as in figure 2, displaying 5, 3, 2, 1, 0- $\sigma$  sensitivity contours (2- $\sigma$  in bold) for SUSY effects on  $\text{BR}(h \rightarrow b\bar{b})$  (solid blue lines) and  $\text{BR}(h \rightarrow b\bar{b})/\text{BR}(h \rightarrow WW^*)$  (dashed green lines) at the ILC (see text). Note that for surface **P2** for low  $M_A$  and large  $\tan \beta$  also  $-2, -1$ - $\sigma$  are shown for  $\text{BR}(h \rightarrow b\bar{b})$ , and  $-5, -3, -2, -1$ - $\sigma$  are shown for  $\text{BR}(h \rightarrow b\bar{b})/\text{BR}(h \rightarrow WW^*)$ .

all the regions with  $\Delta\chi^2 < 4.61$ . In the cases of planes **P3** and **P4**, the sensitivities are greater, but less than the corresponding sensitivities to the  $\text{BR}(h \rightarrow b\bar{b})$  shown previously in figure 7. Of all the single ILC measurements, the one with the greatest sensitivity to SUSY effects is that of the  $\text{BR}(h \rightarrow WW^*)$ , which is also shown in figure 8 using dashed (black) lines. In the cases **P1** and **P2**, we see that the sensitivity may rise above 5  $\sigma$  already within the  $\Delta\chi^2 < 4.61$  region. In the case of **P3**, the sensitivity is well above 5  $\sigma$  throughout the low- $M_A$  region. In the case of **P4**, a 5- $\sigma$  significance is exceeded already in much of the high- $M_A$  lobe, where the sensitivity never falls as low as 3  $\sigma$  in the  $\chi^2$  favored



**Figure 8:** The same  $(M_A, \tan \beta)$  planes for the NUHM benchmark surfaces (a) **P1**, (b) **P2**, (c) **P3** and (d) **P4** as in figure 2, displaying 5, 3, 2, 1- $\sigma$  sensitivity contours for SUSY effects on the  $\text{BR}(h \rightarrow \tau^+\tau^-)$  at the ILC (solid red lines). Also shown are the  $-5, -3, -2, -1$ - $\sigma$  sensitivity contours for the SUSY effects on  $\text{BR}(h \rightarrow WW^*)$  at the ILC (dashed black lines). Note that for surface **P2**  $\pm 2, \pm 1$  and  $0$ - $\sigma$  are shown for  $\text{BR}(h \rightarrow \tau^+\tau^-)$ , and  $\pm 5, \pm 3, \pm 2, \pm 1$  and  $0$ - $\sigma$  are shown for  $\text{BR}(h \rightarrow WW^*)$ .

region.

We have not made a complete study of the combined sensitivity of the ILC measurements to the benchmark surfaces, but it is clear from this brief survey that the ILC measurements would in general provide interesting tests of the MSSM at the loop level. In the absence of detailed studies, we expect that CLIC measurements would have similar sensitivities, since  $h$  production would be more copious at the higher CLIC energies, and the CLIC luminosity at lower energies could be similar to that of the ILC [23]. In addition

to the precision measurements described here, the ILC and CLIC would be able to produce directly associated  $H + A$  pairs above the kinematic threshold.

## 7. $B$ physics

We display in figure 9 the results for three BPO  $\text{BR}(b \rightarrow s\gamma)$ ,  $\text{BR}(B_s \rightarrow \mu^+\mu^-)$ ,  $\text{BR}(B_u \rightarrow \tau\nu_\tau)$ , in the four benchmark  $(M_A, \tan\beta)$  planes.

The prediction of  $B_s \rightarrow \mu^+\mu^-$  is based on ref. [84, 47]. The solid (beige) line indicates  $\text{BR}(B_s \rightarrow \mu^+\mu^-) = 10^{-7}$ , corresponding roughly to the current upper bound from CDF [85] and D0 [86]. The latest bound reported by CDF has recently been lowered to  $5.8 \times 10^{-8}$  [87]. The dashed (beige) line indicates a BR of  $2 \times 10^{-8}$ . In figure 9 we see that the current upper limit on  $B_s \rightarrow \mu^+\mu^-$  already excludes regions of the planes at small  $M_A$  and large  $\tan\beta$ , starting to cut into the region with  $\Delta\chi^2 < 4.61$ . The prospective sensitivities would extend as far as the best-fit points.

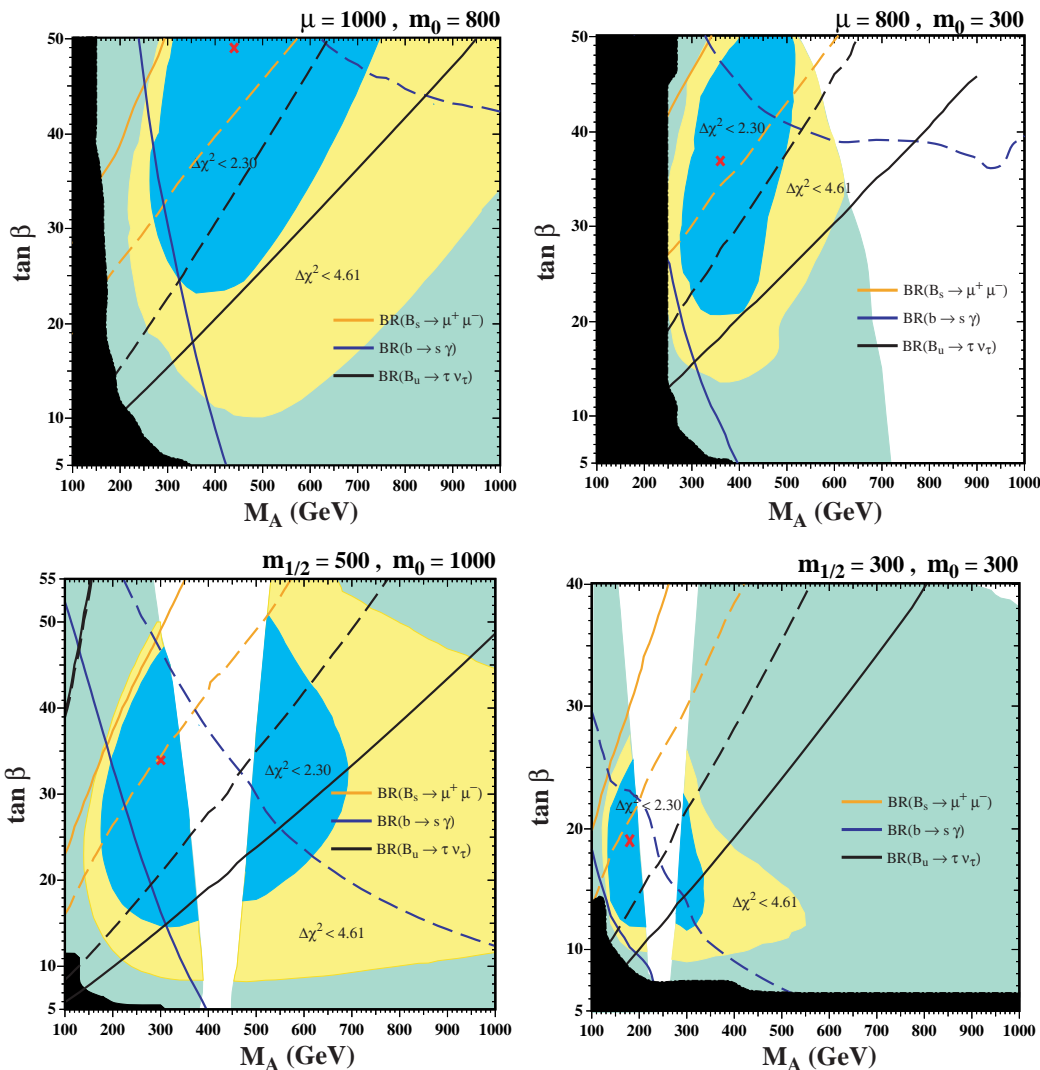
For  $b \rightarrow s\gamma$  our numerical results have been derived with the  $\text{BR}(b \rightarrow s\gamma)$  evaluation provided in refs. [88], incorporating also the latest SM corrections provided in ref. [89]. The results in figure 9 are shown as the two blue lines indicating  $\text{BR}(b \rightarrow s\gamma)$  of  $4 \times 10^{-4}$  (solid) and  $3 \times 10^{-4}$  (dashed). These have to be compared to the experimentally preferred value of  $\text{BR}(b \rightarrow s\gamma) = (3.55 \pm 0.24_{-0.10}^{+0.09} \pm 0.03) \times 10^{-4}$  [90]. The best-fit point together with large parts of the  $\chi^2$  preferred regions lie between the two lines, i.e., large parts of the four benchmark planes are in good agreement with the current experimental value.

Our results for  $\text{BR}(B_u \rightarrow \tau\nu_\tau)$  are based on ref. [91]. In the four benchmark scenarios of figure 9 the results are shown in form of the NUHM result divided by the SM prediction as black lines. The solid (dashed) lines correspond to a ratio of 0.9 (0.7), where the current central value is  $0.93 \pm 0.41$  [92, 93]. It can be seen that the best fit value as well as large parts of the  $\chi^2$  preferred parts of the benchmark planes predict a value somewhat lower than the current experimental result. However, with the current precision no firm conclusion can be drawn.

## 8. Direct detection of supersymmetric dark matter

In figure 10 we show how the direct detection of the LSP via spin-independent scattering on nuclei probes the four  $(M_A, \tan\beta)$  planes. We focus here on the bound from the XENON10 experiment that was recently published by the XENON collaboration [27], which improves on the previous CDMS results [26]. We note that the XENON10 experiment has seen some potential signal events which are, however, interpreted as background.

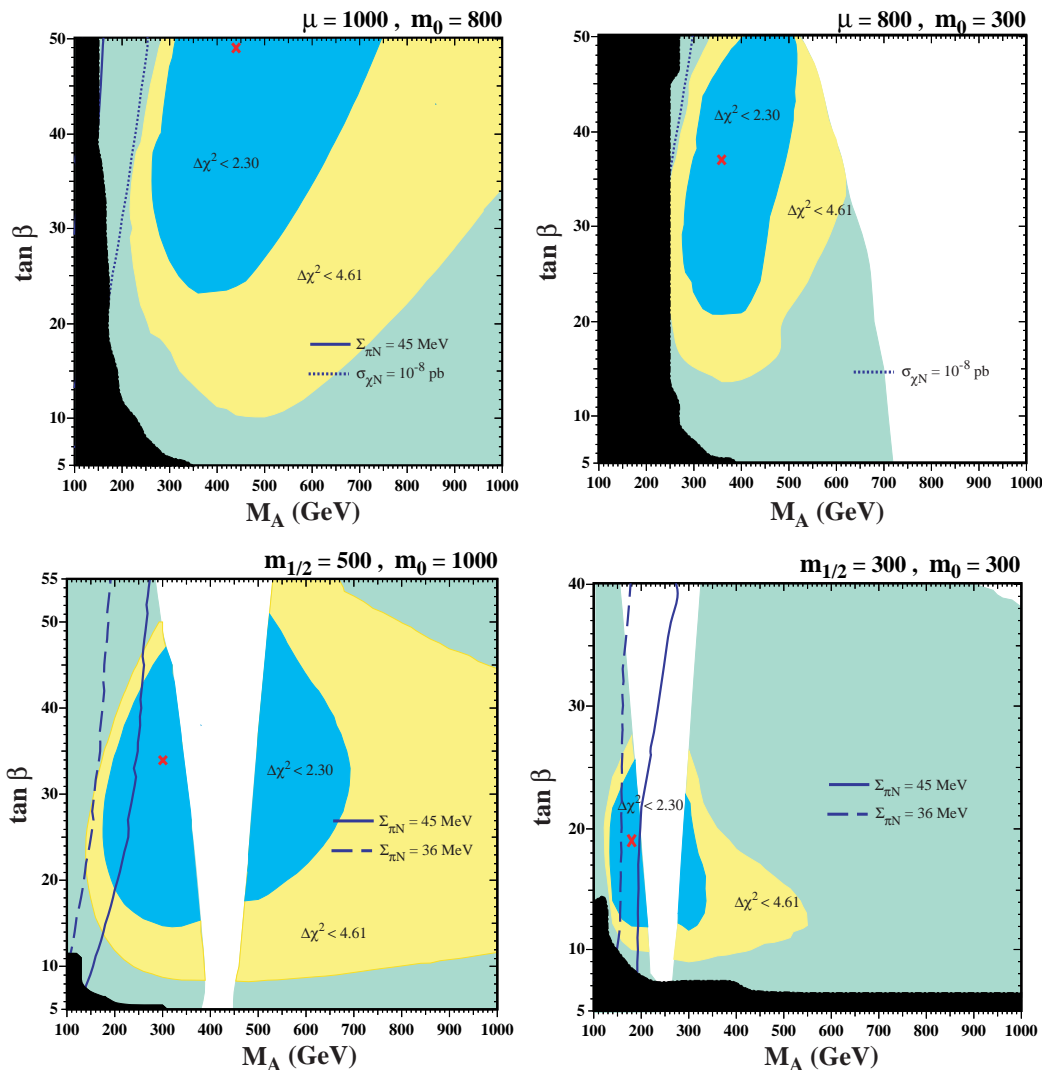
The constraint imposed by the limits from direct detection experiments is sensitive to two theoretical uncertainties that are independent of the specific dark matter model. One is the local density of cold dark matter, which is normally estimated to be  $\rho_{\text{CDM}} = 0.3 \text{ GeV}/\text{cm}^3$ , although smaller values may be consistent with some models of the Galaxy. The other important uncertainty is that in the nucleonic matrix element of the local operator responsible for the spin-independent scattering amplitude. This is related,



**Figure 9:** The same  $(M_A, \tan\beta)$  planes for the NUHM benchmark surfaces (a) **P1**, (b) **P2**, (c) **P3** and (d) **P4** as in figure 2, displaying the expected sensitivities of the  $B$  physics observables  $B_s \rightarrow \mu^+\mu^-$ ,  $b \rightarrow s\gamma$  and  $B_u \rightarrow \tau\nu$ . The various lines indicate:  $\text{BR}(B_s \rightarrow \mu^+\mu^-) = 10^{-7}$  ( $2 \times 10^{-8}$ ) as solid (dashed),  $\text{BR}(b \rightarrow s\gamma) = 4(3) \times 10^{-4}$  as solid (dashed),  $\text{BR}(B_u \rightarrow \tau\nu_\tau)_{\text{MSSM/SM}} = 0.9(0.7)$  as solid (dashed).

in particular, to the so-called  $\sigma$  term,  $\Sigma_{\pi N}$ , that may be derived from measurements of low-energy  $\pi$ -nucleon scattering.

The solid lines in figure 10 correspond to the XENON10 bound obtained assuming  $\rho_{\text{CDM}} = 0.3 \text{ GeV/cm}^3$  and using  $\Sigma_{\pi N} = 45 \text{ MeV}$  as input, corresponding to a relative strange-quark density  $y \equiv 2\langle N|\bar{s}s|N\rangle/\langle N|(\bar{u}u + \bar{d}d)|N\rangle = 0.2$  [94]. These assumptions are realistic, though there is a large uncertainty in the strangeness contribution which may lead to larger rates if  $\Sigma_{\pi N}$  is larger or significantly lower rates if the strangeness contribution to the proton mass is small. The dashed lines show the bounds that one would obtain from



**Figure 10:** The same  $(M_A, \tan \beta)$  planes for the NUHM benchmark surfaces (a) **P1**, (b) **P2**, (c) **P3** and (d) **P4** as in figure 2, displaying the expected sensitivities of present and prospective future direct searches for the scattering of dark matter particles (see text).

the XENON10 experiment assuming the same value of  $\rho_{\text{CDM}}$ , but with  $\Sigma_{\pi N} = 36$  MeV corresponding to  $y = 0$ , and therefore representing more conservative assumptions. Finally, as an example of the possible sensitivity of future experiments, the dotted lines show the contours one would obtain for a spin-independent cross section of  $10^{-8}$  pb, assuming the same value of  $\rho_{\text{CDM}}$  and  $\Sigma_{\pi N} = 45$  MeV as input.

We see from figure 10 that the surfaces **P1** and **P2** are not probed by the current limits from the XENON10 experiment. Only the possible future sensitivity at  $10^{-8}$  pb starts to cut into the  $\Delta\chi^2 < 4.61$  region. For these planes, accelerator searches are clearly more powerful. The situation is different for the planes **P3** and **P4**, due to the relatively low

values of  $m_{1/2}$  across these planes. We recall that, for planes **P1** and **P2**,  $m_{1/2}$  scales with  $M_A$  and the sparticle spectrum is typically heavier at large  $M_A$  than at the corresponding points in planes **P3** and **P4**. As a result, the spin-independent  $\tilde{\chi}_1^0 - p$  elastic cross section is suppressed for planes **P1** and **P2**. On the other hand, we see that the current XENON10 bound probes large parts of the  $\Delta\chi^2 < 2.30$  areas of **P3** and **P4** planes, if one uses the moderate values of  $\Sigma_{\pi N} = 45$  MeV and the strange-quark content. Indeed, in the case of the **P4** surface, the current XENON10 bound would even cover the best-fit point for this value of  $\Sigma_{\pi N}$  and the default value for the local density of cold dark matter. The more conservative analysis, on the other hand, is sensitive only to smaller  $M_A$  values, and probes only a much smaller part of the regions preferred by the  $\chi^2$  analysis. Finally, we note that a future sensitivity to a cross section of  $10^{-8}$  pb would cover the entire **P3** and **P4** surfaces.

## 9. Conclusions

The value of benchmark studies is that they allow one to understand better the range of possibilities opened up by supersymmetry. It is therefore desirable that benchmarks be chosen in such a way as to respect, as far as possible, the definitive experimental constraints, and also that they be susceptible to systematic study. We have demonstrated in this paper how NUHM benchmark surfaces chosen so that the relic cold dark matter density falls within or below the range favoured by WMAP and other experiments may be used to probe supersymmetric phenomenology. Our approach based on the NUHM scenario significantly differs from previous proposals of benchmark scenarios for the MSSM Higgs sector that were entirely formulated in terms of low-scale parameters and that were not suitable for a phenomenologically acceptable prediction of the cold dark matter density. The analysis of our proposed benchmark surfaces is facilitated by developments in the `FeynHiggs` code that are described in the appendix. These will enable the interested reader to explore the prospects for her/his favourite experimental probe of supersymmetry in these benchmark surfaces.

We have displayed the constraints currently imposed in the new benchmark surfaces by electroweak precision observables, and explored the prospects for Higgs searches at the Tevatron collider, the LHC and the ILC, and we have also explored indirect effects in  $B$  physics and in dark matter detection. Whereas the Tevatron collider will be able only to nibble at corners of these NUHM benchmark surfaces, experiments at the LHC will be able to cover them entirely, and the ILC will have good prospects for precision measurements. There are good prospects for  $B$  experiments in parts of the benchmark surfaces, and direct dark matter may be detectable in some cases.

It should of course be noted that benchmark studies may soon be rendered obsolete — namely by the discovery of supersymmetry.

*As we were completing this paper, we heard the sad news of the passing away of Julius Wess, one of the discoverers and founding fathers of supersymmetry. Julius did so much to develop our understanding of supersymmetry, to awaken our appreciation of its beauty, and to convince us of its importance for physics. Humbly and respectfully, we dedicate this paper to his memory.*



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## A. Evaluation of benchmark surfaces with FeynHiggs

The new benchmark surfaces have been implemented into the code `FeynHiggs` [55, 56, 54, 57]. In this way, any user may apply them to perform phenomenological analyses.

From the mathematical point of view, the NUHM/CDM constraints introduce non-trivial relations between input parameters, which thus cannot be scanned naively by independent loops. To solve this in a generic way, `FeynHiggs` 2.6 allows the user to interpolate the inputs from a Parameter table into which arbitrary relations can be encoded. The tables containing the four benchmark surfaces can be downloaded from <http://www.feynhiggs.de>. To implement the new format of a Parameter table, significant internal rearrangements were necessary from which the concept of a `FeynHiggs` Record evolved.

A Record is a new data type which captures the entire content of a parameter file in the native format of `FeynHiggs`. In this respect it is akin to the SUSY Les Houches Accord Record [95], but also encodes information about parameter loops and has ‘inheritance rules’ for default values. Using the routines to manipulate a Record, the programmer can, among other things, process `FeynHiggs` parameter files independently of the front end.

In addition to containing loops over parameters, a Record can be associated with a Parameter table in such a way that values not explicitly given in the parameter file are interpolated from the table (as it can be done for the four benchmark scenarios).

The `FeynHiggs` Record is conceptually a superstructure ‘on top’ of the conventional part of `FeynHiggs`. This means that a Record can be manipulated without any influence on the computation of Higgs observables at first. Only when the `FHSetRecord` subroutine is invoked are its current values set as the inputs for the computation. So in principle, the `FeynHiggs` Record can be used without doing any computation of Higgs observables at all.

Technically, a Record is a two-dimensional real array of the form

$\text{rec}(i_{\downarrow}, j^{\rightarrow})$	iVar	iLower	iUpper	iStep
iTB	$L$	$U$	$U$	$U$
iMAO	$L$	$U$	$U$	$U$
...	...			

- The column index  $i$  specifies the parameter. The indices are labelled as in the parameter file, but prefixed with an `i` (see table 3).

- The row index  $j$  enumerates the variables that constitute the loop over a parameter, i.e. the current, lower, and upper value and the step size. The loop inferred through these parameters has the form

```
do rec(i,iVar) = rec(i,iLower), rec(i,iUpper), rec(i,iStep)
  ...
enddo
```

- $U$  entries indicate fields filled in by the user. If no loop is desired over a particular parameter, the fields `rec(i,iUpper)` and `rec(i,iStep)` can be omitted. On top of that there are also ‘inheritance rules’ (given in table 3), stating for example that M3SL defaults to MSusy if not given explicitly.
- $L$  entries indicate fields replaced by the `FHLoopRecord` routine while working off the loops over parameter space, i.e. these fields are updated automatically according to the current point in the loop. For example, if the Record contains

```
rec(iTB,iLower) = 10
rec(iTB,iUpper) = 50
rec(iTB,iStep)  = 10
```

the first call to `FHLoopRecord` will set `rec(iTB,iVar)` to 10, the next to 20, etc.

## A.1 Fortran use

### A.1.1 Declaration

Every subroutine or function which uses a Record must first include the definitions:

```
#include "FHRecord.h"
```

Records can then be declared with the preprocessor macro `RecordDecl`, which hides the declaration details. For example,

```
RecordDecl(rec)
```

declares the Record `rec(i,j)`. When declaring several records, each needs its own `RecordDecl` statement, i.e. `RecordDecl(rec1, rec2, ...)` is not permissible.

### A.1.2 Initializing a record

A FeynHiggs Record has to be brought into a defined state before its first use, either by clearing it with

```
call FHClearRecord(rec)
```

or by reading it from a file, which similarly overwrites any previous content:

```
call FHReadRecord(error, rec, "file")
if( error .ne. 0 ) stop
```

Index name	Parameter	Default value	Index name	Parameter	Default value
iAlfasMZ	$\alpha_s(M_Z^2)$	-1	iM1	$M_1$	0
iMC	$m_c$	-1	iM2	$M_2$	
iMT	$m_t$		iM3	$M_3$	
iMB	$m_b$ (on-shell)	-1	iAt	$A_t$	
iMW	$M_W$	-1	iAc	$A_c$	iAt
iMZ	$M_Z$	-1	iAu	$A_u$	iAc
TB	$\tan\beta$		iAb	$A_b$	iAt
MA0	$M_{A^0}$		iAs	$A_s$	iAb
MHp	$M_{H^+}$		iAd	$A_d$	iAs
iMSusy	$M_{\text{SUSY}}$		iAtau	$A_\tau$	iAb
iM3SL	$M_L^3$	iMSusy	iAmu	$A_\mu$	iAtau
iM2SL	$M_L^2$	iM3SL	iAe	$A_e$	iAmu
iM1SL	$M_L^1$	iM2SL	ideltaLLuc	$\delta_{uc}^{LL}$	0
iM3SE	$M_E^3$	iMSusy	ideltaLRuc	$\delta_{uc}^{LR}$	0
iM2SE	$M_E^2$	iM3SE	ideltaRLuc	$\delta_{uc}^{RL}$	0
iM1SE	$M_E^1$	iM2SE	ideltaRRuc	$\delta_{uc}^{RR}$	0
iM3SQ	$M_Q^3$	iMSusy	ideltaLLct	$\delta_{ct}^{LL}$	0
iM2SQ	$M_Q^2$	iM3SQ	ideltaLRct	$\delta_{ct}^{LR}$	0
iM1SQ	$M_Q^1$	iM2SQ	ideltaRLct	$\delta_{ct}^{RL}$	0
iM3SU	$M_U^3$	iMSusy	ideltaRRct	$\delta_{ct}^{RR}$	0
iM2SU	$M_U^2$	iM3SU	ideltaLLut	$\delta_{ut}^{LL}$	0
iM1SU	$M_U^1$	iM2SU	ideltaLRut	$\delta_{ut}^{LR}$	0
iM3SD	$M_D^3$	iMSusy	ideltaRLut	$\delta_{ut}^{RL}$	0
iM2SD	$M_D^2$	iM3SD	ideltaRRut	$\delta_{ut}^{RR}$	0
iM1SD	$M_D^1$	iM2SD	ideltaLLds	$\delta_{ds}^{LL}$	0
iQtau	$Q_\tau$	0	ideltaLRds	$\delta_{ds}^{LR}$	0
iQt	$Q_t$	0	ideltaRLds	$\delta_{ds}^{RL}$	0
iQb	$Q_b$	0	ideltaRRds	$\delta_{ds}^{RR}$	0
iCKMtheta12	$\theta_{12}$	-1	ideltaLLsb	$\delta_{sb}^{LL}$	0
iCKMtheta23	$\theta_{23}$	-1	ideltaLRsb	$\delta_{sb}^{LR}$	0
iCKMtheta13	$\theta_{13}$	-1	ideltaRLsb	$\delta_{sb}^{RL}$	0
iCKMdelta13	$\delta_{13}$	-1	ideltaRRsb	$\delta_{sb}^{RR}$	0
			ideltaLLdb	$\delta_{db}^{LL}$	0
			ideltaLRdb	$\delta_{db}^{LR}$	0
			ideltaRLdb	$\delta_{db}^{RL}$	0
			ideltaRRdb	$\delta_{db}^{RR}$	0

**Table 3:** The parameter index names of a FeynHiggs Record. Indices of real parameters are listed in the left, of complex ones in the right column. Complex quantities, e.g.  $A_t$ , can be accessed either through  $\text{Re}(\text{iAt})$  and  $\text{Im}(\text{iAt})$ , or  $\text{Abs}(\text{iAt})$  and  $\text{Arg}(\text{iAt})$ , with  $\text{iAt}$  alone as a synonym for  $\text{Re}(\text{iAt})$ . In cases where both  $\text{Re}/\text{Im}$  and  $\text{Abs}/\text{Arg}$  are given, the latter take precedence. Please consult the FeynHiggs(1) manual page for more details.

where `file` is the name of a parameter file in FeynHiggs' native format.

Fields can be set or read out using ordinary Fortran array access, e.g.

```

    rec(iTB,iLower) = 10
or   print *, "At = ", rec(Re(iAt),iVar), rec(Im(iAt),iVar)

```

The ‘current value’ field (`iVar`) should not be set explicitly, as it is updated automatically by `FHLoopRecord`.

### A.1.3 Looping over a record/setting the FeynHiggs input

The loops over parameters contained in a `Record` are worked off through calls to `FHLoopRecord`, which update the `Record`’s ‘current value’ fields (`iVar`). `FHLoopRecord` is thus usually invoked in the context of a looping construct, such as

```

    call FHLoopRecord(error, rec)
    do while( error .eq. 0 )
        \ldots
        call FHLoopRecord(error, rec)
    enddo

```

The subroutine `FHSetRecord` can be used to set the ‘current value’ fields (`iVar`) as input parameters for `FeynHiggs`. This works effectively as a combination of `FHSetPara`, `FHSetCKM`, and `FHSetNMFV`, except that the parameters are taken from the `Record`. In a typical application the above loop would be extended to

```

    call FHLoopRecord(error, rec)
    do while( error .eq. 0 )
        call FHSetRecord(error, rec, 1D0)
        if( error .ne. 0 ) stop
        call FHHiggsCorr(error, MHiggs, SAeff, UHiggs, ZHiggs)
        if( error .ne. 0 ) stop
        \ldots
        call FHLoopRecord(error, rec)
    enddo

```

The third argument in `FHSetRecord` is the same scale factor which appears in `FHSetPara` and which determines the renormalization scale as a multiple of the top mass.

### A.1.4 Associating a record with a table

The `FeynHiggs` `Record` allows one to interpolate parameters from a data table. The table is interpolated in two user-selectable variables which can be chosen identical if interpolation in only one variable is desired.

The table first needs to be loaded into internal storage. At the moment `FeynHiggs` has a static allocation for one table of at most 2400 lines. This allows the complete implementation in Fortran and seems sufficient for all present applications. The table’s format is rather straightforward: the first line contains the column names (same identifiers as in the `FeynHiggs` input file), followed by the data rows. All items are separated by whitespace.

Loading the table can either be done through the input file and is thus automatically performed in `FHReadRecord`. To this end one has to add a line

```
table file var1 var2
```

to the parameter file. For example, “`table mytable TB MA0`” reads the file `mytable` into memory and sets `TB` and `MA0` as input variables for the interpolation. The table must obviously contain columns for the input variables.

It is also possible to integrate the table file into the parameter file. The `table` statement then takes the form

```
table - var1 var2
```

and must be the last statement in the parameter file, followed immediately by the table data.

Alternately, the table is loaded by

```
call FHLoadTable(error, "file", 5)
if( error .ne. 0 ) stop
```

The table is read from `file`, unless that equals “-”, in which case the table is read from the Fortran unit given in the third argument (unit 5 is Fortran’s equivalent of `stdin` and hence a good default argument here).

The table is associated with the record through

```
call FHTableRecord(error, rec, var1, var2)
if( error .ne. 0 ) stop
```

where `var1` and `var2` are the indices of the input variables, e.g. `iTB` and `iMA0`. To translate parameter names (strings) into indices, one can use the `FHRecordIndex` subroutine, as in:

```
call FHRecordIndex(index, name)
```

## A.2 Mathematica use

Using FeynHiggs Records in Mathematica is for the larger part very similar to doing so in Fortran. The main difference is that one does not have to declare a Record. Rather, both initialization routines ‘create’ the Record:

```
rec = FHClearRecord[]
or  rec = FHReadRecord["file"]
```

The Record is represented as an `FHRecord` object in Mathematica. Access to fields is very similar to the Fortran case, e.g.

```
rec[[iTB,iLower]] = 10
or  Print["At = ", rec[[Re[iAt],iVar]], rec[[Im[iAt],iVar]]]
```

So is the use of `FHLoopRecord`, except that the updated Record is returned, rather than modified in situ. In other words, `FHLoopRecord` returns an `FHRecord` as long as the loop continues. The loop would thus look like

```
While[ Head[rec = FHLoopRecord[rec]] === FHRecord,
  \ldots
]
```

The other routines are used straightforwardly, for example:

```
FHSetRecord[rec, 1]
FHLoadTable["file"]
rec = FHTableRecord[rec, var1, var2]
index = FHRecordIndex[name]
```

### A.3 Examples

#### A.3.1 Command-line mode with parameter table

In the simplest case, a Parameter table can be processed through an input file with a `table` statement:

```
MA0 203
TB 5.7
table file.dat MA0 TB
```

The Parameter table is read from `file.dat` in a format like

```
MT MSusy MA0 TB At MUE \ldots
171.4 500 200 5 1000 761
171.4 500 210 5 1000 753
\ldots
171.4 500 200 6 1000 742
171.4 500 210 6 1000 735
\ldots
```

Alternately, the table can be integrated into the parameter file, as in

```
MA0 203
TB 5.7
table - MA0 TB
MT MSusy MA0 TB At MUE \ldots
171.4 500 200 5 1000 761
171.4 500 210 5 1000 753
\ldots
171.4 500 200 6 1000 742
171.4 500 210 6 1000 735
\ldots
```

This minimal setup assumes that all parameters are contained in the table. More generally, the ones not contained in the table have to be given in the parameter file. The interpolation for the parameters given (here MA0 and TB) is performed automatically by FeynHiggs.

### A.3.2 Using a record with table in Fortran

In Fortran, the same example might be coded as

```
program record_test
  implicit none

#include "FHRecord.h"

  RecordDecl(rec)
  integer error
  double precision MHiggs(4)
  double complex SAeff, UHiggs(3,3), ZHiggs(3,3)

  call FHClearRecord(rec)
  rec(iMA0,iLower) = 203
  rec(iTB,iLower) = 5.7

  call FHLoadTable(error, "file.dat", 5)
  if( error .ne. 0 ) stop

  call FHTableRecord(error, rec, iTB, iMA0)
  if( error .ne. 0 ) stop

  call FHSetFlags(4, 0, 0, 3, 0, 2, 1, 1, 3)

  call FHLoopRecord(error, rec)
  do while( error .eq. 0 )
    call FHSetRecord(error, rec, 1D0)
    if( error .ne. 0 ) stop

    call FHHiggsCorr(error, MHiggs, SAeff, UHiggs, ZHiggs)
    if( error .ne. 0 ) stop

    print *, "TB, Mh1 = ", rec(iTB,iVar), MHiggs(1)

    call FHLoopRecord(error, rec)
  enddo
end
```

### A.3.3 Using a record with table in Mathematica

In Mathematica, the structure and syntax is very similar to Fortran (mainly round brackets have to be converted into square ones):

```
Install["MFeynHiggs"]

rec = FHClearRecord[]

rec[[iMA0,iLower]] = 203;
rec[[iTB,iLower]] = 5.7

FHLoadTable["file.dat"]

rec = FHTableRecord[rec, iTB, iMA0]

FHSetFlags[4, 0, 0, 3, 0, 2, 1, 1, 3]

While[ Head[rec = FHLoopRecord[rec]] === FHRecord,
  FHSetRecord[rec, 1];
  res = FHHiggsCorr[];
  Print["TB, Mh1 = ", rec[[iTB,iVar]], (MHiggs /. res)[[1]] ];
]
```

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