



Suggestions for Benchmark Scenarios for MSSM Higgs Boson Searches at Hadron Colliders*

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Abstract

The Higgs boson search has shifted from LEP2 to the Tevatron and will subsequently move to the LHC. Due to the different initial states, the Higgs production and decay channels relevant for Higgs boson searches were different at LEP2 to what they are at hadron colliders. We suggest new benchmark scenarios for the MSSM Higgs boson search at hadron colliders that exemplify the phenomenology of different parts of the MSSM parameter space. Besides the m_h^{\max} scenario and the no-mixing scenario used in the LEP2 Higgs boson searches, we propose two new scenarios. In one the main production channel at the LHC, $gg \rightarrow h$, is suppressed. In the other, important Higgs decay channels at the Tevatron and at the LHC, $h \rightarrow b\bar{b}$ and $h \rightarrow \tau^+\tau^-$, are suppressed. All scenarios evade the LEP2 constraints for nearly the whole M_A - $\tan\beta$ -plane.

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Abstract

The Higgs boson search has shifted from LEP2 to the Tevatron and will subsequently move to the LHC. Due to the different initial states, the Higgs production and decay channels relevant for Higgs boson searches were different at LEP2 to what they are at hadron colliders. We suggest new benchmark scenarios for the MSSM Higgs boson search at hadron colliders that exemplify the phenomenology of different parts of the MSSM parameter space. Besides the m_h^{\max} scenario and the no-mixing scenario used in the LEP2 Higgs boson searches, we propose two new scenarios. In one the main production channel at the LHC, $gg \rightarrow h$, is suppressed. In the other, important Higgs decay channels at the Tevatron and at the LHC, $h \rightarrow b\bar{b}$ and $h \rightarrow \tau^+\tau^-$, are suppressed. All scenarios evade the LEP2 constraints for nearly the whole M_A - $\tan\beta$ -plane.

1 Introduction and theoretical basis

Within the MSSM the masses of the \mathcal{CP} -even neutral Higgs bosons are calculable in terms of the other MSSM parameters. The lightest Higgs boson has been of particular interest, since its mass, m_h , is bounded from above according to $m_h \leq M_Z$ at the tree level. The radiative corrections at one-loop order have been supplemented in the last years with the leading two-loop corrections, performed by renormalization group (RG) methods [1], by renormalization group improvement of the one-loop effective potential calculation [2,3], by two-loop effective potential calculations [4], and in the Feynman-diagrammatic (FD) approach [5,6]. These calculations predict an upper bound for m_h of about $m_h \lesssim 135$ GeV.¹

After the termination of LEP, the Higgs boson search has now shifted to the Tevatron and will later be continued at the LHC. Due to the large number of free parameters, a complete scan of the MSSM parameter space is too involved. Therefore at LEP the search has been performed in three benchmark scenarios [7]. Besides the m_h^{\max} scenario, which has been used to obtain conservative bounds on $\tan\beta$ [8], and the no-mixing scenario, the large- μ scenario had been designed to encourage the investigation of flavor and decay-mode independent decay channels (instead of focusing on the $h \rightarrow b\bar{b}$ channel). The investigation of these channels has lead to exclusion bounds [9] that finally completely ruled out the large- μ scenario.

The different environment at hadron colliders implies different Higgs boson production channels and also different relevant decay channels as compared to LEP. The main production modes at the Tevatron will be $V^* \rightarrow V\phi$ ($V = W, Z, \phi = h, H, A$) and also $b\bar{b} \rightarrow b\bar{b}\phi$, while the relevant decay modes will be $\phi \rightarrow b\bar{b}$ and $\phi \rightarrow \tau^+\tau^-$ [10]. At the LHC, on the other hand, the most relevant processes for a Higgs boson with $m_h \leq 135$ GeV will be $gg \rightarrow h \rightarrow \gamma\gamma$ and $t\bar{t} \rightarrow t\bar{t}h \rightarrow t\bar{t}b\bar{b}$. Also the W boson fusion channel, $WW \rightarrow h \rightarrow \tau^+\tau^-$ has been shown to be promising [11]. In order to investigate these different modes, we propose new

¹ This value holds for $m_t = 175$ GeV and $M_{SUSY} = 1$ TeV. If m_t is raised by 5 GeV then the m_h limit is increased by about 5 GeV; using $M_{SUSY} = 2$ TeV increases the limit by about 2 GeV.

benchmark scenarios for the Higgs boson searches at hadron colliders. Contrary to the new “SPS” benchmark scenarios proposed in Ref. [12] for general SUSY searches, the scenarios proposed here are designed specifically to study the MSSM Higgs sector without assuming any particular soft SUSY-breaking scenario and taking into account constraints only from the Higgs boson sector itself.

The tree-level value for m_h within the MSSM is determined by $\tan\beta$, the \mathcal{CP} -odd Higgs-boson mass, M_A , and the Z -boson mass, M_Z . Beyond the tree-level, the main correction to m_h stems from the t - \tilde{t} -sector, and for large values of $\tan\beta$ also from the b - \tilde{b} -sector (see Ref. [7] for our notations). Accordingly, the most important parameters for the corrections to m_h are m_t , M_{SUSY} (in this work we assume that the soft SUSY-breaking parameters for sfermions are equal: $M_{SUSY} := M_{\tilde{t}_L} = M_{\tilde{t}_R} = M_{\tilde{b}_L} = M_{\tilde{b}_R}$), X_t ($\equiv A_t - \mu/\tan\beta$), and X_b ($\equiv A_b - \mu\tan\beta$); $A_{t,b}$ are the trilinear Higgs sfermion couplings and μ is the Higgs mixing parameter. m_h depends furthermore on the SU(2) gaugino mass parameter, M_2 (the U(1) gaugino mass parameter is given by $M_1 = 5/3 s_W^2/c_W^2 M_2$). At the two-loop level also the gluino mass, $m_{\tilde{g}}$, enters the prediction for m_h .

It should be noted in this context that the FD result has been obtained in the on-shell (OS) renormalization scheme (the corresponding Fortran code, that has been used for the analyses by the LEP collaborations, is *FeynHiggs* [13,14]), whereas the RG result has been calculated using the $\overline{\text{MS}}$ scheme; see Ref. [15] for details (the corresponding Fortran code, also used by the LEP collaborations, is *subhpole* [1,2,15]). While the corresponding shift in the parameter M_{SUSY} turns out to be relatively small in general, sizable differences can occur between the numerical values of X_t in the two schemes; see Refs. [6,15]. For this reason we specify below different values for X_t within the two approaches.

2 The benchmark scenarios

In this section we define four benchmark scenarios suitable for the MSSM Higgs boson search at hadron colliders. In these scenarios the values of the \tilde{t} and \tilde{b} sector as well as the gaugino masses will be fixed, while $\tan\beta$ and M_A are the parameters that are varied. It has been checked that the scenarios evade the LEP2 bounds [9] over a wide range of the M_A - $\tan\beta$ -plane, where the variation should be chosen according to

$$0.5 \leq \tan\beta \leq 50, \quad M_A \leq 1 \text{ TeV} . \quad (1)$$

To illustrate the effects arising in the different proposed benchmark scenarios, we have evaluated (using the results presented in Refs. [16–19])

$$\frac{[\sigma \times \text{BR}]_{\text{MSSM}}}{[\sigma \times \text{BR}]_{\text{SM}}} \quad (2)$$

for several Higgs production and decay channels for the new benchmark scenarios. Further information about the properties of these scenarios can be found at www.feynhiggs.de.

2.1 The m_h^{max} scenario

This scenario is kept as presented in Ref. [7], since it allows conservative $\tan\beta$ exclusion bounds [8] (only the sign of μ is switched to a positive value). The parameters are chosen

such that the maximum possible Higgs-boson mass as a function of $\tan\beta$ is obtained (for fixed M_{SUSY} , and M_A set to its maximal value, $M_A = 1$ TeV). The parameters are²:

$$\begin{aligned} m_t &= 174.3 \text{ GeV}, & M_{SUSY} &= 1 \text{ TeV}, & \mu &= 200 \text{ GeV}, & M_2 &= 200 \text{ GeV}, \\ X_t^{\text{OS}} &= 2 M_{SUSY} \text{ (FD calculation)}, & X_t^{\overline{\text{MS}}} &= \sqrt{6} M_{SUSY} \text{ (RG calculation)} \\ A_b &= A_t, & m_{\tilde{g}} &= 0.8 M_{SUSY} . \end{aligned} \quad (3)$$

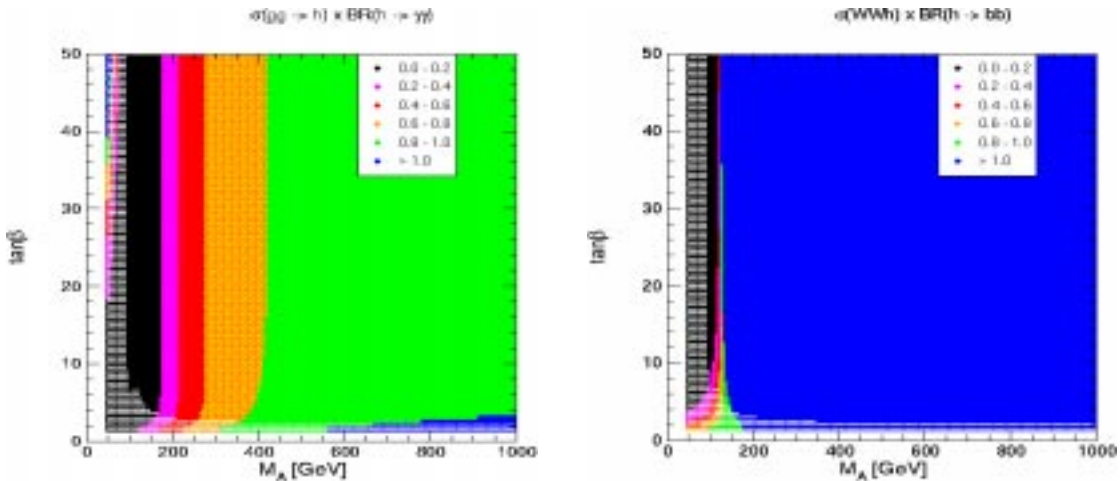


Figure 1: $[\sigma \times \text{BR}]_{\text{MSSM}}/[\sigma \times \text{BR}]_{\text{SM}}$ is shown for the channels $gg \rightarrow h \rightarrow \gamma\gamma$ (left plot) and $W^* \rightarrow Wh \rightarrow Wb\bar{b}$ (right plot) in the $M_A - \tan\beta$ -plane for the m_h^{max} scenario. The white-dotted area is excluded by LEP Higgs searches.

In Fig. 1 we show $[\sigma \times \text{BR}]_{\text{MSSM}}/[\sigma \times \text{BR}]_{\text{SM}}$ for the channels $gg \rightarrow h \rightarrow \gamma\gamma$ (left plot) and $W^* \rightarrow Wh \rightarrow Wb\bar{b}$ (right plot) in the $M_A - \tan\beta$ -plane. For low values of the \mathcal{CP} -odd Higgs boson mass, M_A , the structure of the MSSM Higgs sector leads to an enhancement with respect to the SM value of the $hb\bar{b}$ and $h\tau^+\tau^-$ coupling. The MSSM coupling possesses an additional factor of $-\sin\alpha_{\text{eff}}/\cos\beta$, where α_{eff} is the mixing angle of the neutral \mathcal{CP} -even Higgs sector, including radiative corrections (see e.g. Refs. [18,19]), and the factor of $1/\cos\beta$ can lead to an enhancement for large $\tan\beta$. The additional factor in the coupling converges very slowly to 1 for large values of M_A , and can differ significantly for low values of M_A . The branching ratio of the decay of h into other channels, in particular the $h \rightarrow \gamma\gamma$ channel, is in this case significantly suppressed. Therefore, the $gg \rightarrow h \rightarrow \gamma\gamma$ channel can be strongly suppressed for small and moderate values of M_A . The $W^* \rightarrow Wh \rightarrow Wb\bar{b}$ channel, on the other hand, is nearly always enhanced compared to the SM case, since the WW_h coupling is mostly SM-like, except for $M_A \lesssim 100$ GeV, where for intermediate and large values of $\tan\beta$ the WW_h coupling becomes small. In this parameter region, however, for very small values of M_A the heavy \mathcal{CP} -even Higgs boson, H , has SM-like couplings. As a consequence, in the parameter regions where the light Higgs boson is very difficult to observe, the search for the H should have similar prospects as the SM Higgs search.

² Better agreement with $\text{BR}(b \rightarrow s\gamma)$ constraints is obtained for the other sign of X_t (called the “constrained m_h^{max} ” scenario). However, this lowers the maximum m_h values by ~ 5 GeV.

The channels presented in Fig. 1 show the complementarity between Tevatron and LHC for the search for the lightest MSSM Higgs boson. It is worth to notice as well that the LHC itself will exhibit a similar complementary behavior in this benchmark scenario between the $gg \rightarrow h \rightarrow \gamma\gamma$ process and the other two search channels, $t\bar{t}h \rightarrow t\bar{t}b\bar{b}$ and $WW \rightarrow h \rightarrow \tau^+\tau^-$.

2.2 The no-mixing scenario

This benchmark scenario is the same as the m_h^{\max} scenario, but with vanishing mixing in the \tilde{t} sector and with a higher SUSY mass scale to avoid the LEP Higgs bounds:

$$m_t = 174.3 \text{ GeV}, \quad M_{SUSY} = 2 \text{ TeV}, \quad \mu = 200 \text{ GeV}, \quad M_2 = 200 \text{ GeV}, \\ X_t = 0 \text{ (FD/RG calculation)}, \quad A_b = A_t, \quad m_{\tilde{g}} = 0.8 M_{SUSY}. \quad (4)$$

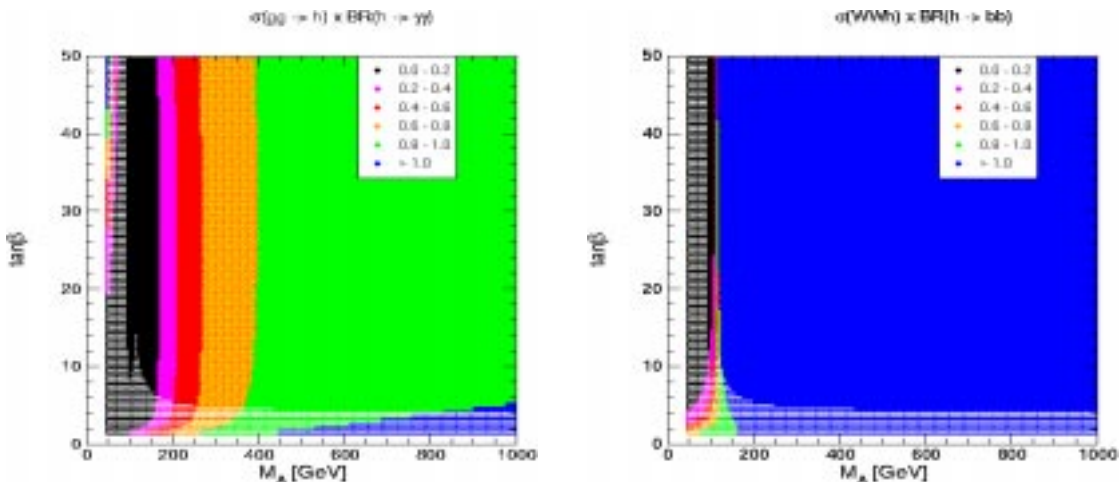


Figure 2: $[\sigma \times \text{BR}]_{\text{MSSM}}/[\sigma \times \text{BR}]_{\text{SM}}$ is shown for the channels $gg \rightarrow h \rightarrow \gamma\gamma$ (left plot) and $W^* \rightarrow Wh \rightarrow Wb\bar{b}$ (right plot) in the $M_A - \tan\beta$ -plane for the no-mixing scenario. The white-dotted area is excluded by LEP Higgs searches.

In Fig. 2 we show $[\sigma \times \text{BR}]_{\text{MSSM}}/[\sigma \times \text{BR}]_{\text{SM}}$ for the channels $gg \rightarrow h \rightarrow \gamma\gamma$ (left plot) and $W^* \rightarrow Wh \rightarrow Wb\bar{b}$ (right plot) in the $M_A - \tan\beta$ -plane. As in the m_h^{\max} scenario, the branching ratio for $h \rightarrow b\bar{b}$ and $h \rightarrow \tau^+\tau^-$ is significantly enhanced for low values of M_A . Therefore, also in the no-mixing scenario the $gg \rightarrow h \rightarrow \gamma\gamma$ channel can be strongly suppressed for not too large values of M_A . The $W^* \rightarrow Wh \rightarrow Wb\bar{b}$ channel is nearly always enhanced compared to the SM case for the same reasons as in the m_h^{\max} scenario (except for $M_A \lesssim 100 \text{ GeV}$).

2.3 The gluophobic Higgs scenario

In this scenario the main production cross section for the light Higgs boson at the LHC, $gg \rightarrow h$, is strongly suppressed. This can happen due to a cancellation between the top quark and the stop quark loops in the production vertex (see Ref. [20]). This cancellation

is more effective for small \tilde{t} masses and hence for relatively large values of the \tilde{t} mixing parameter, X_t . The partial width of the most relevant decay mode, $\Gamma(h \rightarrow \gamma\gamma)$, is affected much less, since it is dominated by the W boson loop. The parameters are:

$$\begin{aligned}
m_t &= 174.3 \text{ GeV}, & M_{SUSY} &= 350 \text{ GeV}, & \mu &= 300 \text{ GeV}, & M_2 &= 300 \text{ GeV}, \\
X_t^{\text{OS}} &= -750 \text{ GeV (FD calculation)}, & X_t^{\overline{\text{MS}}} &= -770 \text{ GeV (RG calculation)} \\
A_b &= A_t, & m_{\tilde{g}} &= 500 \text{ GeV}.
\end{aligned} \tag{5}$$

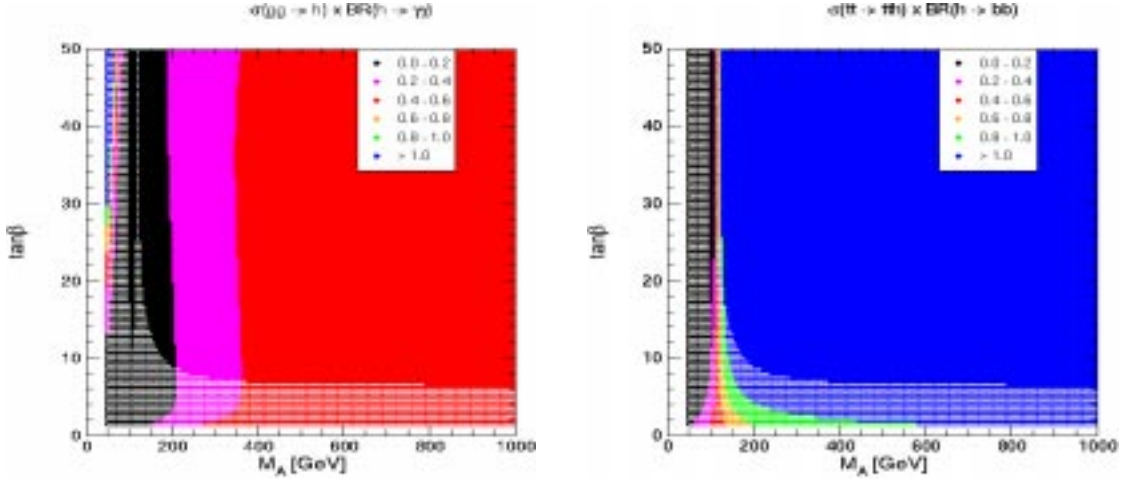


Figure 3: $[\sigma \times \text{BR}]_{\text{MSSM}}/[\sigma \times \text{BR}]_{\text{SM}}$ is shown for the channels $gg \rightarrow h \rightarrow \gamma\gamma$ (left plot) and $t\bar{t} \rightarrow t\bar{t}h \rightarrow t\bar{t}b\bar{b}$ (right plot) in the $M_A - \tan\beta$ -plane for the gluophobic Higgs scenario. The white-dotted area is excluded by LEP Higgs searches.

In Fig. 3 we show $[\sigma \times \text{BR}]_{\text{MSSM}}/[\sigma \times \text{BR}]_{\text{SM}}$ for the channels $gg \rightarrow h \rightarrow \gamma\gamma$ (left plot) and $t\bar{t} \rightarrow t\bar{t}h \rightarrow t\bar{t}b\bar{b}$ (right plot) in the $M_A - \tan\beta$ -plane. The $gg \rightarrow h \rightarrow \gamma\gamma$ channel can be strongly suppressed over the whole $M_A - \tan\beta$ -plane, rendering this detection channel difficult. The $t\bar{t} \rightarrow t\bar{t}h \rightarrow t\bar{t}b\bar{b}$ channel, on the other hand, is always enhanced compared to the SM case (except for $M_A \lesssim 100$ GeV). The same qualitative behavior holds for the WW fusion channel with subsequent decay to $b\bar{b}$ or $\tau^+\tau^-$.

2.4 The small α_{eff} scenario

Besides the channel $gg \rightarrow h \rightarrow \gamma\gamma$ at the LHC, the other channels for light Higgs searches at the Tevatron and at the LHC mostly rely on the decays $h \rightarrow b\bar{b}$ and $h \rightarrow \tau^+\tau^-$, see Sect. 2.1. If α_{eff} is small, these two decay channels can be heavily suppressed in the MSSM due to the additional factor $-\sin\alpha_{\text{eff}}/\cos\beta$ compared to the SM coupling. ($h \rightarrow b\bar{b}$ can also receive large corrections from $\tilde{b}-\tilde{g}$ loops [17, 18].) Such a suppression occurs for large $\tan\beta$ and not too large M_A (in a similar way as in the large- μ scenario [7]) for the following parameters:

$$\begin{aligned}
m_t &= 174.3 \text{ GeV}, & M_{SUSY} &= 800 \text{ GeV}, & \mu &= 2.5 M_{SUSY}, & M_2 &= 500 \text{ GeV}, \\
X_t^{\text{OS}} &= -1100 \text{ GeV (FD calculation)}, & X_t^{\overline{\text{MS}}} &= -1200 \text{ GeV (RG calculation)} \\
A_b &= A_t, & m_{\tilde{g}} &= 500 \text{ GeV}.
\end{aligned} \tag{6}$$

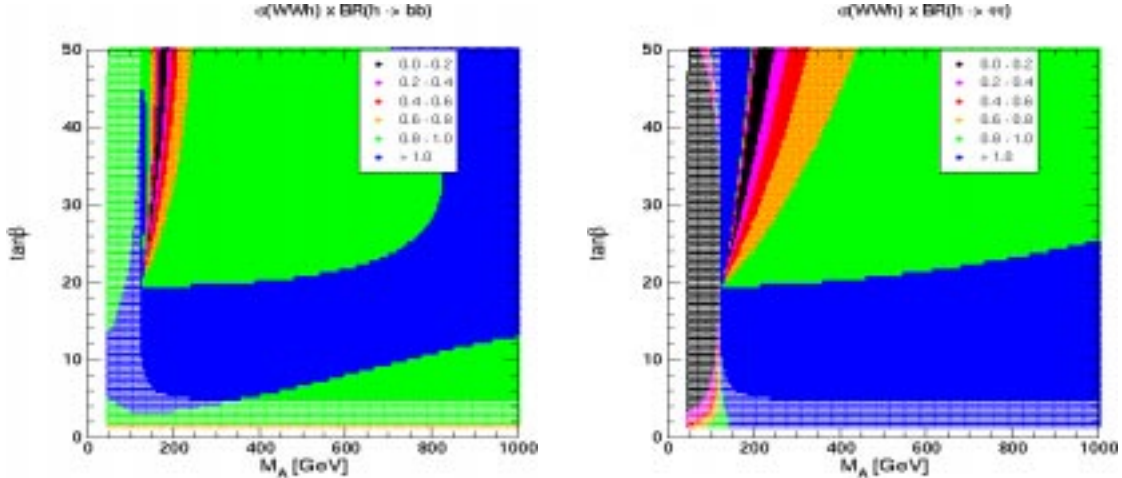


Figure 4: $[\sigma \times \text{BR}]_{\text{MSSM}}/[\sigma \times \text{BR}]_{\text{SM}}$ is shown for the channels $W^* \rightarrow Wh \rightarrow Wb\bar{b}$ (left plot) and $W^* \rightarrow Wh \rightarrow W\tau^+\tau^-$ (right plot) in the $M_A - \tan\beta$ -plane for the small α_{eff} scenario. The white-dotted area is excluded by LEP Higgs searches.

In Fig. 4 we show $[\sigma \times \text{BR}]_{\text{MSSM}}/[\sigma \times \text{BR}]_{\text{SM}}$ for the channels $W^* \rightarrow Wh \rightarrow Wb\bar{b}$ (left plot) and $W^* \rightarrow Wh \rightarrow W\tau^+\tau^-$ (right plot) in the $M_A - \tan\beta$ -plane. Significant suppression occurs for large $\tan\beta$, $\tan\beta \gtrsim 20$, and small M_A , $M_A \lesssim 250, 400$ GeV, for $h \rightarrow b\bar{b}$ and $h \rightarrow \tau^+\tau^-$, respectively. Thus, Higgs boson search via the W production channel and the WW fusion channel (see also Ref. [11]) will be difficult in these parts of the parameter space. The same applies for the channel $t\bar{t}h \rightarrow t\bar{t}b\bar{b}$. The complementary channel, $h \rightarrow \gamma\gamma$, is unsuppressed compared to the SM case for large parts of the $M_A - \tan\beta$ -plane.

3 Conclusions

We have presented four benchmark scenarios for the MSSM Higgs boson search at hadron colliders, evading the exclusion bounds obtained at LEP2. The different scenarios exemplify different features of the MSSM parameter space, such as large m_h values and significant $gg \rightarrow h$ or $h \rightarrow b\bar{b}$, $h \rightarrow \tau^+\tau^-$ suppression. In the benchmark scenarios proposed above, we have briefly analyzed the possible suppression of several Higgs production and decay channels, showing possible “problematic” regions of the MSSM parameter space.

With the exception of the gluon fusion mediated process, which is significantly suppressed in the gluophobic Higgs scenario, the production processes at the Tevatron and the LHC considered here, $W^* \rightarrow Wh$, $t\bar{t} \rightarrow t\bar{t}h$, $WW \rightarrow h$ and $gg \rightarrow h$, are close to their SM values for most of the allowed parameter space of the benchmark scenarios. Hence, deviations of the rate of the Higgs search processes at hadron colliders compared to the SM case are mainly due to the SUSY corrections affecting the Higgs decay modes.

In all the cases analyzed in this note, we have found a complementarity between the $h \rightarrow b\bar{b}$, $h \rightarrow \tau^+\tau^-$ and the $h \rightarrow \gamma\gamma$ channels, i.e. in the parameter regions where the search for the Higgs in one of these channels becomes problematic, in at least one of the other channels it becomes easier than in the SM case. It is difficult to find exceptions to this

rule in the MSSM parameter space. Therefore in analyzing the new benchmark scenarios, it will be helpful to make use of the complementarity of different channels accessible at the Tevatron and the LHC (see e.g. Ref. [18] for details).

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