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The 7 TeV LHC Reach for MSSM Higgs Bosons

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Abstract

The search for the Higgs boson is entering a decisive phase. The Large Hadron Collider experiments have collected more than 1 fb^{-1} of data and are now capable of efficiently probing the high Higgs mass region, $m_H > 140$ GeV. The low mass region is more challenging at the LHC, but if the Higgs has Standard Model (SM)-like properties, the LHC should find evidence for it by the end of next year. In low energy supersymmetric extensions of the SM, the situation is similar for large values of the CP-odd Higgs mass m_A, but more interesting for lower values of m_A. The ($\sqrt{s}$ =7 TeV) LHC searches for a low-mass Standard Model Higgs boson predominantly in the $h \to \gamma\gamma, WW$ decay modes, which may be suppressed by an increase in the $h \to b\bar{b}, \tau^+\tau^-$ partial widths (and thus the total h width) for $m_A \lesssim 500$ GeV. Although $h \to b\bar{b}, \tau^+\tau^-$ are sought at the LHC, these channels are not powerful enough to fully counter this suppression in the first year of running. We consider two alternative possibilities for probing the low m_A region: nonstandard Higgs boson searches at the LHC, and a statistical combination with the Tevatron, where $Vh \to b\bar{b}$ is the primary search channel for light h. We also study an MSSM scenario in which the $h \to \gamma\gamma$ rate is enhanced at low m_A to the point where discovery is possible in the near future.

1 Introduction

The Standard Model (SM) provides a very good description of experimental observables measured at high-energy colliders. The SM is a renormalizable theory and admits a perturbative description at scales of the order of the weak scale. The Higgs boson [1, 2] is the only element of the SM that has not been discovered, and plays an important role in ensuring the perturbative consistency of the theory. Within the SM, precision electroweak observables suggest a light Higgs boson, with mass below about 180 GeV. Searches for a Higgs particle are therefore some of the most important activities in high energy physics. Currently, collider searches are performed at the LHC and the Tevatron experiments, and Tevatron data has already excluded the presence of a SM-like Higgs boson with a mass in the range 158–173 GeV at the 95% confidence level [3]. At CERN, the LHC is accumulating record high luminosities, and it is expected to probe the whole SM Higgs mass region below 500 GeV by the end of 2011. The most challenging mass region for Higgs searches at the LHC is the closest to the current LEP bound of about 115 GeV. In this low mass region, the main search channel at the LHC comes from the Higgs production via gluon fusion and its rare decay into two photons [4, 5, 6, 7]. Other relevant search channels, which require higher statistics, are weak boson fusion with $h \to \tau^+\tau^-$ and Higgs associated production with weak vector bosons, with $h \to b\bar{b}$. It is expected that by the end of the year the associated production $Vh \to b\bar{b}$ channels at the Tevatron will be able to test the SM-Higgs mass region close to the present LEP bound [8].

In this note we concentrate on searches for neutral Higgs bosons in the CP-conserving Minimal Supersymmetric Standard Model (MSSM) [9]. In most of the MSSM parameter space there is a light Higgs boson with SM-like couplings to gauge bosons and a mass below 130 GeV [10, 11, 12, 13]. Additional CP-even, CP-odd, and charged Higgs bosons exist in this model and possess enhanced couplings to the third generation fermions [14]. Searches for these non-standard Higgs bosons are being performed at the Tevatron and the LHC, with the LHC rapidly surpassing the Tevatron capabilities in the main modes where neutral CP-even and CP-odd Higgs bosons decay into τ-lepton pairs [15, 16, 17].

In previous articles we have studied the reach of both the Tevatron and a 14 TeV LHC in their searches for standard and non-standard Higgs bosons of the MSSM [18, 19, 20]. Since the LHC is now operating at a center of mass energy of 7 TeV, it is important to perform a realistic estimate of its reach in the first years of running. In the course of this analysis we stress the fact that in supersymmetry, the presence of more than one Higgs doublet means that mixing between the neutral components can produce a state with SM-like gauge couplings but very different branching fractions from the SM Higgs boson. In general, the $h \to b\bar{b}$ width of the SM-like Higgs boson is increased to a degree controlled by the CP-odd mass m_A, and this effect suppresses the rates into other states such as $h \to \gamma\gamma, WW$ (the diphoton suppression was also discussed in [21], and more recently in [22]). For more specialized values of the soft supersymmetry-breaking parameters, the $h \to b\bar{b}$ width can be suppressed and the rates into other states are enhanced. We study both of these possibilities in detail and demonstrate that when the main LHC searches for h are weakened, either LHC nonstandard Higgs searches can be used to probe the parameter space, or a statistical combination with the Tevatron data may be used to provide evidence for the presence of h. On the other hand, when $h \to \gamma\gamma$ is enhanced in the MSSM, we show that the LHC will quickly reach discovery potential for the SM-like Higgs boson, while non-standard Higgs searches will provide a complementary search channel and already strongly constrain a standard benchmark scenario.

This article is organized as follows. In section 2, we discuss the statistical methods used in our analysis. In section 3 we show the LHC results in different benchmark scenarios. In section 4 we demonstrate that non-standard Higgs boson searches, as well as searches for SM-like Higgs bosons at the Tevatron, offer power complementary to that of the SM-like Higgs channels at the LHC. In section 5 we conclude.

2 Methods

Searches for SM-like Higgs bosons at hadron colliders are performed in a diverse set of channels, and the reach of SM-like Higgs bosons searches has been thoroughly studied by the experimental collaborations. We base our analysis on the results of these experimental analyses, properly interpreting them in the MSSM context and combining the significance of different channels.

Since the reaches for SM-like Higgs bosons at CMS and ATLAS are quite similar, for simplicity, we estimate the combined LHC reach by doubling the luminosity at the ATLAS experiment and assuming 5 fb^{-1}/channel/experiment (i.e., all channels are taken to 10 fb^{-1} with $\sqrt{\mathcal{L}}$ rescaling). Both the Gaussian scaling of the statistical significance and the 2xATLAS approximation are expected to preserve the qualitative features of the expected reach. For illustration, we also show results with 10 and 15 fb^{-1}/channel/experiment. The channels all include improvement factors as detailed in the ATLAS note [23]. In our plots we study the expected reach on the $(m_A, \tan\beta)$ plane, fixing the values of the soft parameters. At each point on the plane the Higgs spectrum, decay rates, and production cross sections are calculated with FeynHiggs [24, 25, 26], and a quantity R^{95} is calculated for each channel as the ratio of the signal (cross section times Higgs decay branching ratio) that can be probed at the 95% confidence level relative to the signal predicted by the MSSM at that point. We combine the R^{95} values from multiple channels in inverse quadrature, and the LHC is expected to have exclusion power for a point when the combined $R^{95} \leq 1$. More generally, R^{95} is related to the expected statistical significance σ of discovery or exclusion via $\sigma \approx 2/R^{95}$. In practice, the inverse quadrature combination results in a reach for the SM-like Higgs boson that is 10-20% more conservative than the more precise combination performed by ATLAS [23]. To compensate, we apply an additional 15% improvement factor. When relevant, we also show contours of 3 and 5σ reach. We expect the results presented in this analysis to give a good estimate of the MSSM bounds that would follow for a more precise combination of the ATLAS and CMS results.

Similarly to the case of the LHC, for the analysis involving Tevatron data we estimate the reach by doubling the luminosity at the CDF experiment with a luminosity of 10 fb^{-1} [8] (all channels are taken to 20 fb^{-1} with $\sqrt{\mathcal{L}}$ rescaling.) We include a 30% improvement factor to account for ongoing analysis optimizations [27] and as performed for the LHC, the R^{95} values from each channel are combined in inverse quadrature. In practice this combination is simple but effective for the Tevatron, differing for the SM Higgs by no more than about 6% from the results reported in Ref. [8]. in the low mass region, with a mean deviation of less than a percent between 110 and 130 GeV.

3 The LHC MSSM Higgs Reach

We consider first two standard benchmark scenarios, known as the maximal and minimal mixing scenarios [29], for the low-scale soft supersymmetry breaking parameters. The reach for the SM-like Higgs boson is shown in these two models on the $(m_A, \tan\beta)$ plane in Fig. 1. For illustration, we give the results for 5, 10, and 15 fb^{-1} of data per experiment.

The projected LHC reach is generally weaker in minimal mixing due to the smaller values of m_h and stronger in maximal mixing where m_h is larger. For moderate values of $\tan\beta$ and $m_A \gtrsim 150$ GeV, we obtain $m_h \sim 115-120$ GeV in the minimal mixing scenario and $m_h \sim 120-130$ GeV in the maximal mixing case. A sizable impact is had by the $h \to WW$ channel, for which projections were not provided by ATLAS below $m_h = 120$ GeV, and is thus absent in the minimal mixing plots. For low m_A, however, the vector boson fusion channel with $h \to \tau\tau$ and the associated production channel $Vh \to b\bar{b}$ provide some reach in minimal mixing. Both of these channels grow stronger with smaller m_h, so the coverage in this region is stronger than in maximal mixing. In both models, however, it is clear that overall the total reach is suppressed as m_A decreases. As mentioned in the introduction, this is due to tree-level mixing between the CP-even Higgs bosons, which can result in an enhanced decay width of the SM-like Higgs into bottom quarks. Such mixing is stronger for low values of the non-standard Higgs boson masses and tends to suppress the Higgs decay into photons and W bosons, rendering the searches at the LHC more challenging[1].

The Higgs doublet mixing decreases as $\cot\beta$ for large values of $\tan\beta$, but since the coupling of the non-standard Higgs bosons to bottom-quarks is approximately proportional to $\tan\beta$ for large values of $\tan\beta$, the mixing effects on the $BR(h \to b\bar{b})$ remain approximately constant. This property, as well as the overall magnitude of the suppression effect on the rare decays, is demonstrated in Fig. 2 for the $gg \to h \to \gamma\gamma, WW$ channels. We also display the suppression relative to the SM for the $gg \to H \to \gamma\gamma, WW$ channels, since below $m_A \sim 130$ GeV the heavy Higgs becomes SM-like in its coupling to gauge bosons, while h becomes nonstandard. However, H still retains an enhanced coupling to $b\bar{b}$ due to a small mixing with H_d^0, leading again to a suppression of the $H \to \gamma\gamma, WW$ rates.

The $b\bar{b}$ enhancement has relevant consequences for searches at the LHC. For maximal mixing, in which the SM-Higgs mass is close to 130 GeV, the most important search channel is the decay into a pair of W-gauge bosons. This decay channel is suppressed for small m_A. As shown in Fig. 1, combining the two LHC experiments at 5 fb^{-1}, for m_A below 200 GeV there are sizable regions where the LHC is not expected to probe the presence of a SM-like Higgs boson in the standard Higgs search channels.

In the minimal mixing scenario, the SM-like Higgs boson has a mass close to 115 GeV and the main decay channels are therefore into τ-leptons and b-quarks. The main searches at the LHC are through the Higgs decay into two photons, which as shown in Fig. 2, is strongly suppressed for CP-odd Higgs masses $m_A < 300$ GeV.

Consequently, in both scenarios, the searches for a MSSM light SM-like Higgs boson

[1] Note that although the $h \to b\bar{b}$ partial width can easily increase by an order of magnitude, since it is the dominant contributor to the total Higgs width, the $h \to b\bar{b}$ branching fraction is only increased by a factor $\lesssim 2$. For this reason $Vh \to b\bar{b}$ does not compensate for the $h \to \gamma\gamma, WW$ channels, where the branching ratios can experience the full order of magnitude suppression.

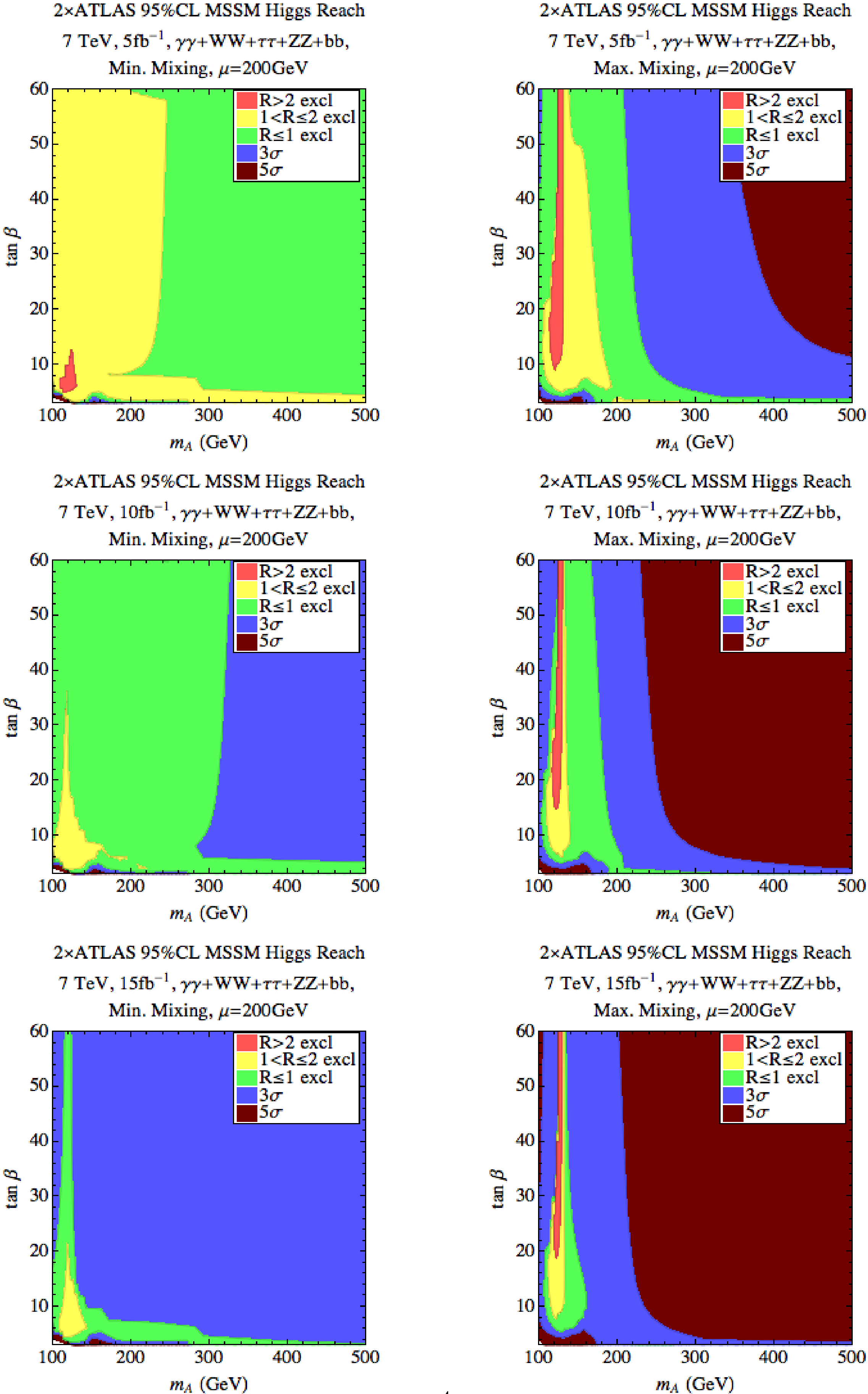

Figure 1: Top row: Estimated median LHC reach for the light, SM-like Higgs boson in the minimal mixing (*left*) and maximal mixing (*right*) benchmark scenarios of the MSSM with 5 fb^{-1}/experiment. Middle (Bottom) row: same, with 10 (15) fb^{-1}/experiment.

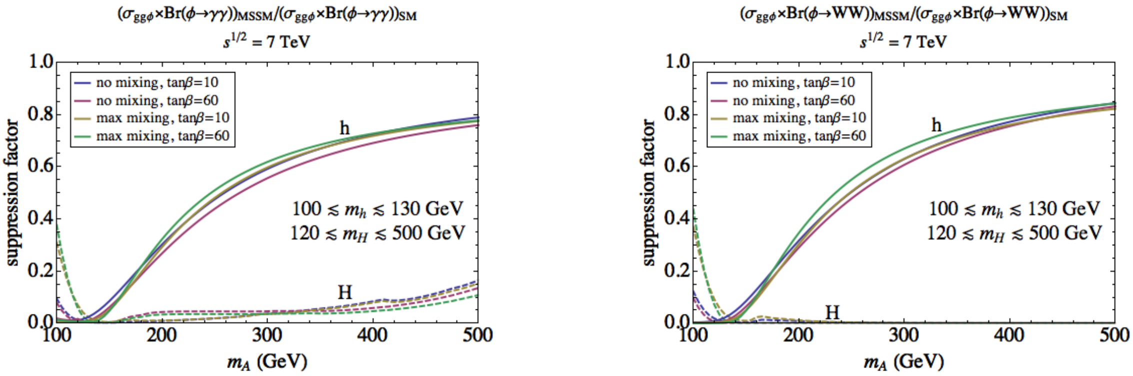

Figure 2: Rates for $gg \to h \to \gamma\gamma, WW$ (solid) and $gg \to H \to \gamma\gamma, WW$ (dashed) in the MSSM, relative to the rates in the SM for a Higgs of mass m_h or m_H, respectively. Four different curves are shown for each particle, demonstrating the relatively model-independent nature of the suppression.

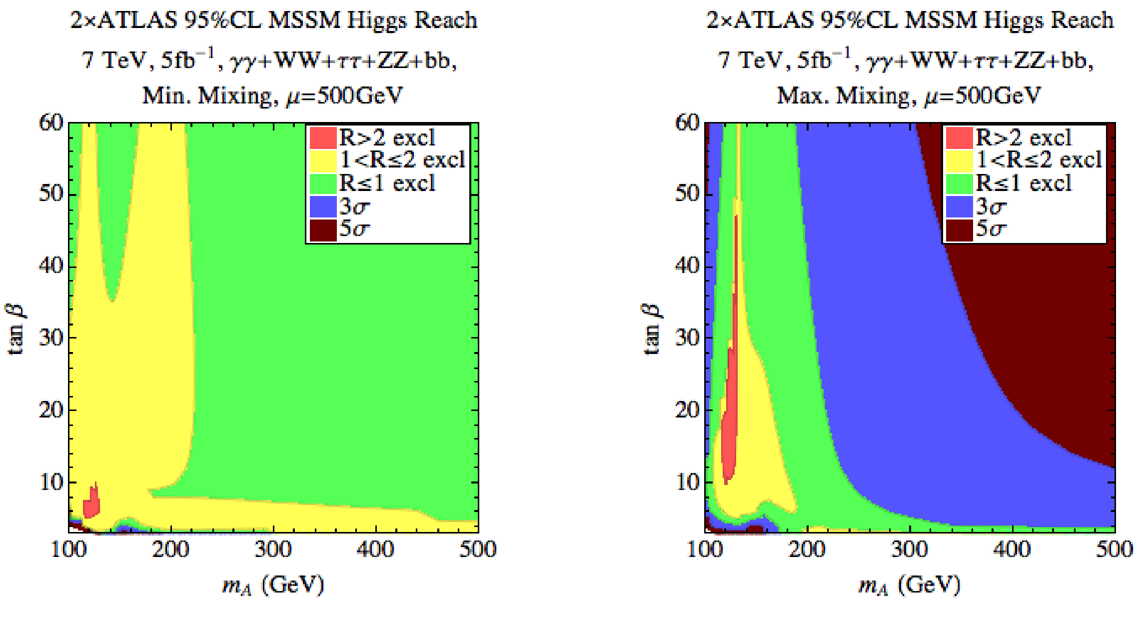

Figure 3: Estimated median LHC reach for the light, SM-like Higgs boson in the minimal mixing (*left*) and maximal mixing (*right*) benchmark scenarios of the MSSM with 5 fb^{-1}/experiment and an increase in the standard benchmark value of μ from 200 GeV (as in Fig. 1) to 500 GeV.

at the LHC will depend critically on the performances of the VBF,$h \to \tau\tau$ and $Vh \to b\bar{b}$ modes for low values of m_A. The reach for SM-like Higgs bosons in these two channels improves for smaller values of the Higgs mass, and in combination with the WW and $\gamma\gamma$ channels, we find that the LHC can test the low m_A region in both scenarios at the 2σ level with 10 fb^{-1} and find 3σ evidence of the SM-like Higgs boson at 15 fb^{-1} in the majority of the low m_A parameter space.

We note that in the near future the LHC dataset will be large enough to begin performing searches for the electroweak production of neutralinos and charginos [28]. These searches may provide direct probes of other MSSM parameters, in particular the value of the Higgsino mass parameter μ. In both of our benchmark scenarios μ is fixed at 200 GeV; however, we stress that the Higgs sector reach presented here is relatively insensitive to moderate increases in μ, which enters mainly through the $hb\bar{b}$ effective coupling. For comparison, the 5 fb^{-1} LHC reach for $\mu = 500$ GeV is given in Fig. 3. The primary change as μ is increased is a strengthening of the reach for low m_A and large $\tan\beta$, which is due to a small suppression of the $hb\bar{b}$ effective coupling relative to the tree level value in this region (although it is still enhanced relative to the SM for the reasons discussed above.) As we will discuss further below, this region is already disfavored by searches for non-standard Higgs bosons.

On the other hand, it is also possible to achieve an *increase* in the rates for the $h \to \gamma\gamma, WW$ decay channels sought at the LHC, relative to the SM. Such effects are also achieved through Higgs mixing: for sufficiently large values of $\tan\beta$, one-loop corrections to the mixing angle may be as important as the tree-level effects. Indeed, the enhancement of the bottom-quark coupling may be avoided in limited regions of parameter space, in which the stop mixing parameter A_t and the Higgsino mass parameter μ are larger than the characteristic stop mass scale. For negative values of the product μA_t, the one-loop corrections may cancel the tree-level mixing effects, and the SM-like Higgs boson becomes almost purely H_u^0. Under these conditions, a large suppression of the b-quark coupling of the SM-like Higgs may be obtained[2]. This possibility has been named small α_{eff} scenario [29], since the fraction of the SM-like Higgs composed of the neutral field coupling to down-quarks and leptons is small. As shown in Fig. 4, the suppression of the Higgs decay width leads to an enhancement of the photon branching ratio.

In the region of parameters where the $h \to \gamma\gamma$ decay rate is enhanced, the LHC has the possibility of a 5σ discovery in the near future. This is shown in the left panel of Fig. 5 for 5 fb^{-1}/experiment, and in the right panel for 10 fb^{-1}/experiment.

4 Combination with other Higgs searches at the Tevatron and the LHC

In the last section, we showed that for low values of m_A searches for the SM-like Higgs boson at the LHC may become challenging. We consider two routes to covering the low m_A parameter space. First, because the main Tevatron search mode for light Higgs states

[2]Similar suppression occurs for the $h\tau\tau$ coupling, although for slightly different values of the parameters due to large quantum corrections to the $hb\bar{b}$ coupling that are absent for the τ. This would also suppress the VBF,$h \to \tau\tau$ channel.

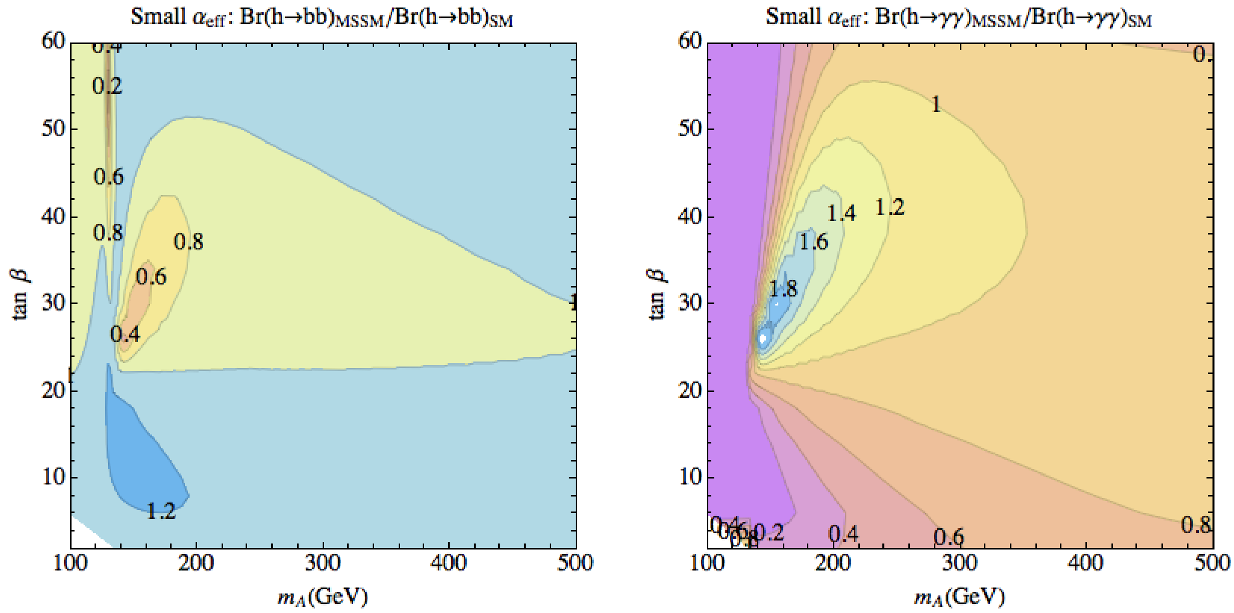

Figure 4: Enhancement of the $h \to bb$ decay branching ratio (left panel) and enhancement of the $h \to \gamma\gamma$ decay branching ratio (right panel) in the small α scenario of the MSSM.

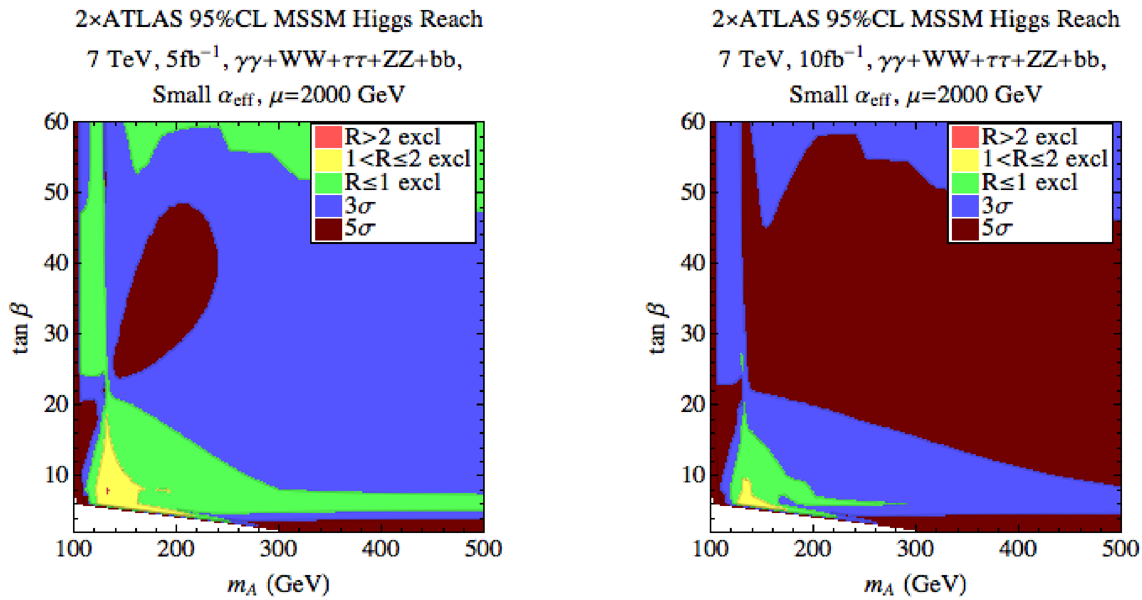

Figure 5: LHC reach for the light, SM-like Higgs boson in the small α_{eff} benchmark scenario of the MSSM. Left: 5 fb^{-1}/experiment; Right: 10 fb^{-1}/experiment.

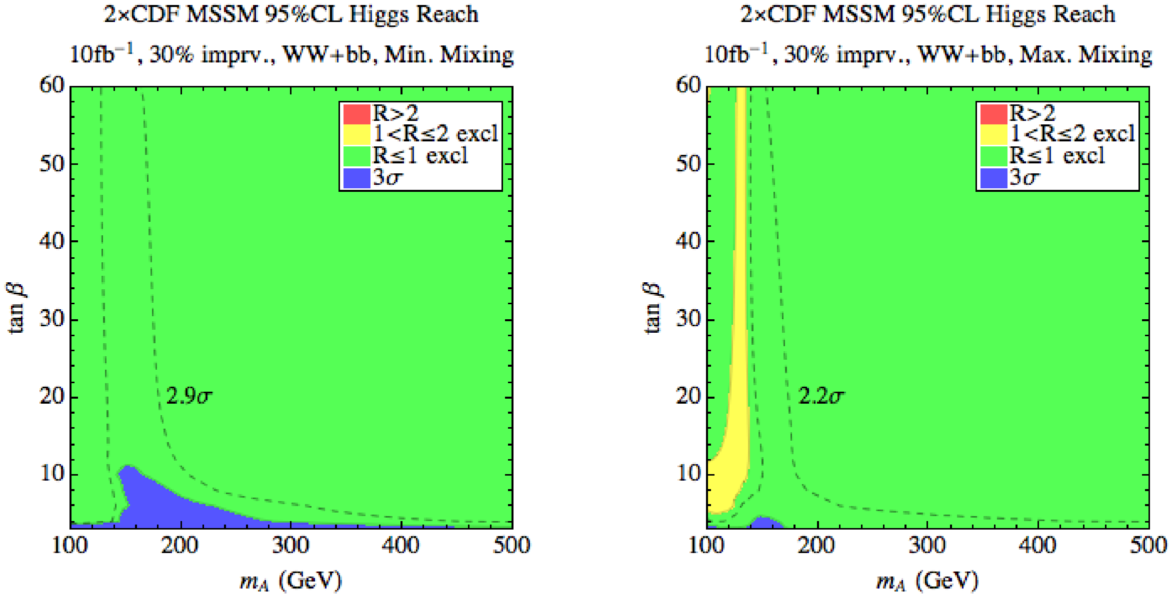

Figure 6: Estimated median Tevatron reach for the light, SM-like Higgs boson in the minimal mixing (*left*) and maximal mixing (*right*) benchmark scenarios of the MSSM.

is through $h \to b\bar{b}$ decays, a statistical combination of the datasets may be well-motivated. In Fig. 6, we give the estimated Tevatron reach in maximal and minimal mixing. It is clear that the Tevatron should have nearly full exclusion coverage of the MSSM Higgs sector by the time it shuts down. In fact, for low values of m_A the Tevatron has of order 20% greater reach than at large m_A, because as m_A decreases the Higgs mass is reduced and the rate into bottom quarks increases. (This feature is not visible in the colors of Fig. 6 because of the coarse contours in R^{95}, which we chose for consistency with the previous LHC figures. To illustrate the behavior we add dashed contours at lower values of m_A, inside of which the Tevatron power is higher.) In any case, Fig. 6 demonstrates that searches for the SM-like Higgs at the Tevatron and the LHC become of similar power and complementary in the early LHC phase. Therefore, it is worth considering the utility of combining the analyses of the data from both colliders.

Any effort to precisely quantify the result of a Tevatron+LHC combination would require a detailed analysis of combining the systematic uncertainties of the different experiments, an exercise which is already highly nontrivial for the two experiments at each machine alone. In our work we shall limit ourselves to analyzing the possible effects of such combination by presenting estimates based on the naive combination of purely statistical uncertainties.

In Fig. 7 we show the combination of the estimated reaches of the LHC and the Tevatron, using 5 fb^{-1}/experiment for the LHC. Most notably the combination may lead to evidence for a SM-like Higgs in both the minimal mixing as well as the maximal mixing scenario for most of the parameter space, including the low m_A region. This stresses the importance of achieving the efficiency improvements on the search for SM-like Higgs bosons at the Tevatron, and suggests that an effort to perform a combination of the data from the four experiments after the first year of LHC running may be justified.

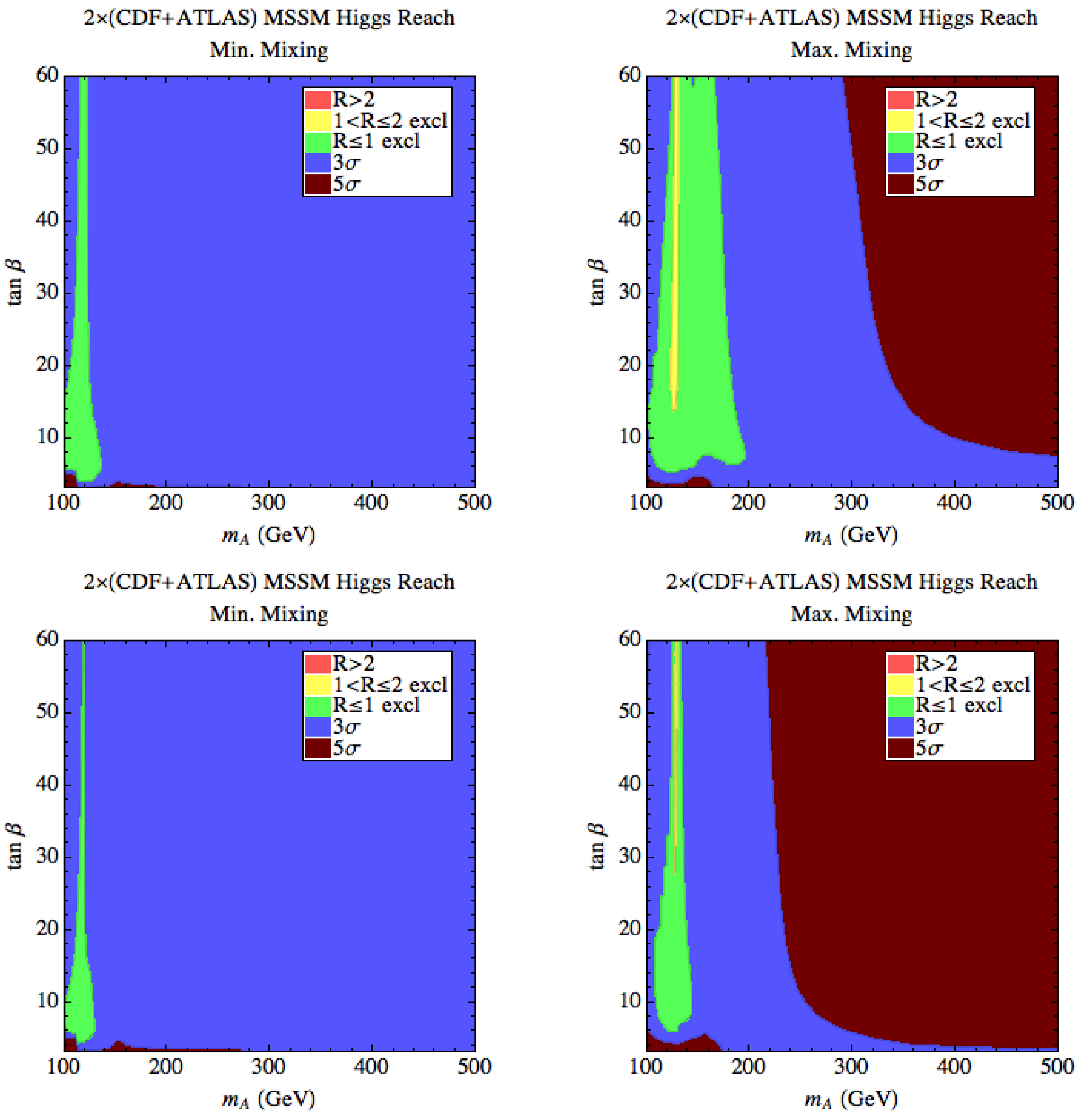

Figure 7: Estimated median combined Tevatron+LHC reach for the light, SM-like Higgs boson in the minimal mixing (*left*) and maximal mixing (*right*) benchmark scenarios of the MSSM. Top: 5 fb^{-1}/experiment for the LHC, 10 fb^{-1}/experiment for the Tevatron; Bottom: 10 fb^{-1}/experiment for both the Tevatron and LHC.

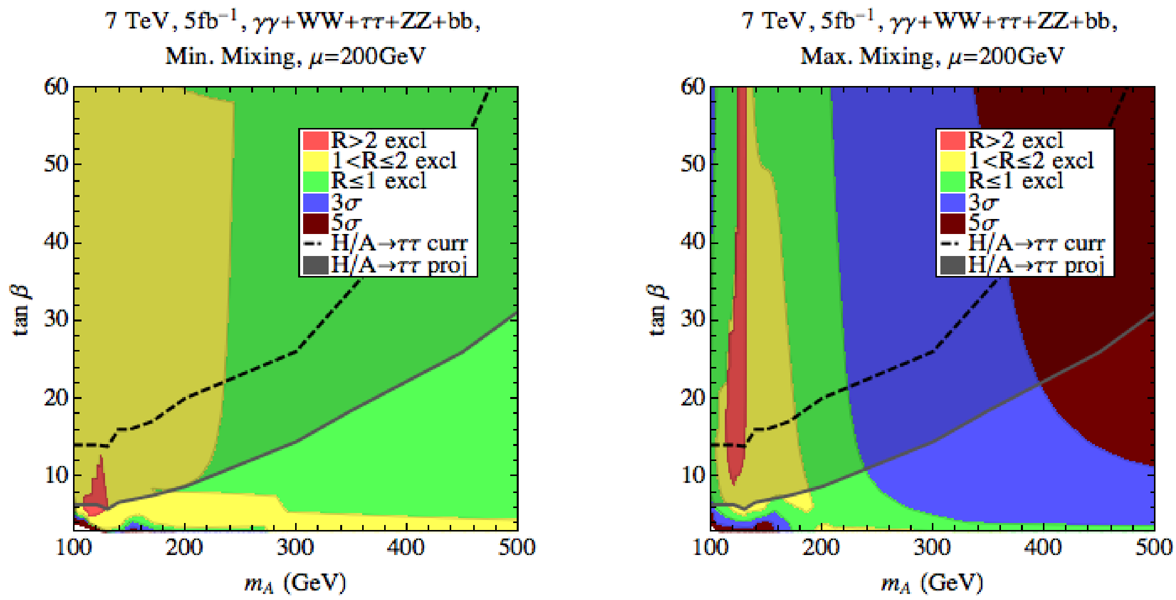

Figure 8: LHC reach for the light, SM-like Higgs boson and the nonstandard Higgs states in the minimal mixing (*left*) and maximal mixing (*right*) benchmark scenarios of the MSSM.

A second approach to studying the low m_A parameter space is given by the LHC searches for the nonstandard Higgs bosons H and A in their decays to τ leptons [16, 17]. These channels are most effective at low m_A, where both H and A are lighter and easier to produce, and at large $\tan\beta$ where the production in association with bottom quarks is proportional to $\tan^2\beta$.

In Fig. 8 we overlay the estimated reach for the neutral MSSM Higgs bosons with nonstandard gauge couplings in the maximal and minimal mixing scenarios. The 95% CL limit is derived from the expected limits given in the recent CMS $H/A \to \tau\tau$ search [17] with 1.1 fb^{-1}, using the tree-level approximation that the reach in $\tan\beta$ scales like $\mathcal{L}^{1/4}$ and the useful property that the nonstandard Higgs expected reach is robust against changes in the soft parameters and μ [30] (although some weak dependence on μ can appear for large values of μ [31].) This demonstrates the complementarity of the two types of Higgs searches at the LHC: a statistical combination of the channels should be able to test the parameter space of the model, even though none of the particles h, H, A can necessarily be probed on all of the model space.

In the regions of parameter space for which the SM-like Higgs bottom and tau couplings are suppressed, analyzed in the small-α_{eff} scenario of Fig. 5, the LHC will also be able to test the nonstandard Higgs sector. In fact, almost all of the interesting parameter space of this particular model is already ruled out with the first 1.1 fb^{-1} of data. This is shown in Fig. 9, where the current CMS 95% CL limit on the CP-odd Higgs mass is drawn as a dashed line. For the specific point we analyzed, the current bounds already heavily constrain the region of parameters for which the branching ratio $BR(h \to \gamma\gamma)$ may be enhanced, leaving only a small window around $\tan\beta \sim 10$ and $m_A \sim 100$ GeV. This is a generic feature. In Fig. 9 we also show the projected reach of the $H/A \to \tau\tau$ channel with 5 fb^{-1} per experiment. Based on these results, we find that with the acquisition

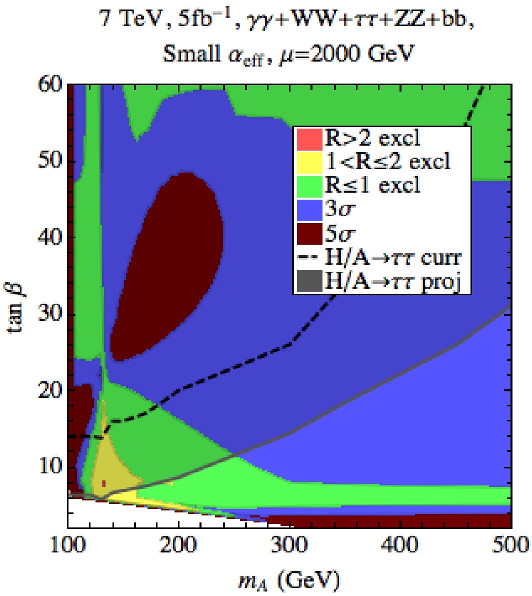

Figure 9: Same as Fig. 5, but with nonstandard searches overlaid, showing both the current limits from $H/A \to \tau\tau$ (dashed curve) and the projected reach with 5 fb^{-1} (shaded region).

of 5 fb^{-1}/experiment, either the LHC will find both the SM-like Higgs and evidence of non-standard Higgs bosons, or the region in which the photon pair production is enhanced will be ruled out by both channels.

5 Conclusions

In this article we have analyzed the 7 TeV LHC capabilities to exclude, provide evidence for, or discover neutral Higgs bosons in the MSSM. At $m_A \gtrsim 300$ GeV, in the maximal mixing scenario, for which the Higgs mass is about 125-130 GeV, the LHC is expected to discover or find evidence of a SM-like Higgs boson (the state provided by the doublet that is primarily responsible for electroweak symmetry breaking) in a combination of the WW and $\gamma\gamma$ channels with 5 fb^{-1}/experiment. In the same region of m_A, evidence for h is expected in the diphoton channel with $\gtrsim 10$ fb^{-1}/experiment in the minimal mixing scenario, for which the Higgs mass is about 115-120 GeV. At lower values of m_A, we have emphasized that the SM-like Higgs can generically exhibit branching ratios different from those of the SM Higgs in decays relevant for the main LHC search channels. In the most generic models for the soft parameters, the $h \to \gamma\gamma, WW$ modes are suppressed at low to moderate m_A by a large increase in the $h \to b\bar{b}$ width, an effect that is due to mixing between the two Higgs doublets. In such cases we have shown that combinations with Tevatron results and with nonstandard Higgs boson searches at the LHC can provide an experimental handle on the parameter space. Furthermore, with other specific choices of the soft parameters, the mixing can be such that the $h \to b\bar{b}$ width is strongly suppressed, leading to an enhancement in the $h \to \gamma\gamma, WW$ branching ratios, allowing the discovery of the SM-like Higgs at 5 fb^{-1}. Because this feature is present at low m_A and large

$\tan\beta$ such models are already constrained by the LHC, and will be fully probed in the near future by the searches for standard and nonstandard Higgs bosons. Recently, a number of authors have studied the possibility of searching for Higgs production in SUSY decay chains [32, 33, 34]. Although the rates in these channels are more sensitive to the structure of the soft parameters, they may provide additional complementarity to the direct-production channels considered in this paper. We leave an analysis of the combined reach of such channels to the future.

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