Probing the Higgs sector of high-scale supersymmetry-breaking models at the Tevatron

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A canonical signature of the minimal supersymmetric standard model (MSSM) is the presence of a neutral Higgs boson with mass bounded from above by about 135 GeV and standard model (SM)-like couplings to the electroweak gauge bosons. In this paper we investigate the reach of the Tevatron collider for the MSSM Higgs sector parameter space associated with a variety of high-scale minimal models of supersymmetry (SUSY) breaking, including the constrained MSSM, minimal gauge-mediated SUSY breaking, and minimal anomaly-mediated SUSY breaking. We find that the Tevatron can provide strong constraints on these models via Higgs boson searches. Considering a simple projection for the efficiency improvements in the Tevatron analyses, we find that with an integrated luminosity of 16 fb^{-1} per detector and an efficiency improvement of 20% compared to the present situation, these models could be probed essentially over their entire ranges of validity. With 40% analysis improvements and 16 fb^{-1}, our projection shows that evidence at the 3σ level for the light Higgs boson could be expected in extended regions of parameter space.

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I. INTRODUCTION

The Tevatron collider at Fermilab is now in its 26th year of $p\bar{p}$ collisions. Operating at a center-of-mass energy of 1.96 TeV, it is a highly productive and well-understood machine, and the rate of the delivered luminosity continues to increase. Nonetheless, with the successful collision of protons at a center-of-mass energy of 7 TeV at the LHC, the position at the energy frontier held by the Tevatron thus far is now being taken over by the LHC. According to the current schedule, the Tevatron is planned to run until the end of 2011, while recently the Fermilab Physics Advisory Committee has given the recommendation to extend the operation of the Tevatron until the end of 2014 [1]. It is therefore of interest to assess the physics reach achievable with the final Tevatron data set, based on the scenarios of running until the end of 2011 or 2014 (for a recent summary, see [2]).

One of the most important ongoing tasks of the Tevatron is the search for new particles directly associated with electroweak symmetry breaking (EWSB). Searches for the standard model (SM) Higgs boson by the CDF and D0 collaborations have excluded the fundamental scalar in the mass range 158–175 GeV at 95% C.L. via the W^+W^- decay channel [3]. The sensitivity in that region can still continue to grow as the volume of analyzed data increases. However, it is in the mass range below 135 GeV where the Tevatron achieves perhaps its greatest relevance. In this regime, Higgs production in association with an electroweak gauge boson provides the most sensitive search channels. Associated production clearly demonstrates the relationship of the scalar to the mechanism of electroweak symmetry breaking. Furthermore, access to the coupling of a light Higgs boson to bottom quarks will be a crucial input in determining the Higgs couplings to fermions and gauge bosons [4,5] and will thus be essential for establishing the Higgs mechanism as a whole. The experimental information achievable at the Tevatron will be complementary to the results of the Higgs searches at the LHC, where the low-mass region below ~135 GeV turns out to be the most challenging one [6,7]. At the LHC the accumulation of a significant data set, of the order of 10 fb^{-1} [8], would be necessary for the discovery of a SM-type Higgs boson in the $gg \to h \to \gamma\gamma$ channel. Further information at the LHC can be expected from weak boson fusion Higgs production and eventually, with sufficient luminosity, also from the associated production channels. There also exists the exciting possibility that important Higgs production channels at the LHC could arise from decays of states of new physics, such as supersymmetric particles. The LHC and the Tevatron will complement each other in the search for a light SM-like Higgs by exploiting different channels and different background levels, especially in the $b\bar{b}$ final states where the different nature of pp vs $p\bar{p}$ collisions becomes relevant.

Based on the current data acquisition rate, running the Tevatron until the end of 2011 or 2014 will yield approximately 10 or 16 fb^{-1} of analyzable data per experiment, respectively. Furthermore, a number of analysis

improvements for the Higgs searches are ongoing, and the collaborations estimate that on the order of 50% improvements (with respect to the status of March 2009) are achievable [9,10].

Low-scale minimal supersymmetry (SUSY) is a well-motivated theory of new electroweak-scale physics that resolves a number of open problems in the SM. In addition to providing a technical solution to the hierarchy problem, it offers a viable weakly interacting dark matter candidate, exhibits gauge coupling unification at high scales, and generates EWSB via radiative effects [11].

If it exists in nature, SUSY must be broken. Flavor experiments strongly suggest that the breaking of SUSY must be communicated to the MSSM fields in an approximately flavor-diagonal manner [12–17]. Three ''standard'' high-scale models with flavor-universal SUSY-breaking parameters are the constrained MSSM (CMSSM) [18,19], minimal gauge-mediated SUSY breaking (mGMSB) [20–22], and minimal anomaly-mediated SUSY breaking (mAMSB) [23,24]. Within the CMSSM the soft SUSY-breaking scalar masses are assumed to take a universal value m_0 at the grand unified theory (GUT) scale, while the soft SUSY-breaking gaugino masses take a GUT universal value of $m_{1/2}$ and the trilinear couplings take a common GUT value A_0, respectively. In mGMSB, SUSY is broken in a hidden sector that affects the MSSM only through gauge interactions, mediated via ''messenger'' particles, leading automatically to flavor-universal soft parameters in the effective theory. Here $M_{\rm mess}$ denotes the overall messenger mass scale, $N_{\rm mess}$ is a number called the messenger index, parametrizing the structure of the messenger sector, and Λ is the universal soft SUSY-breaking mass scale felt by the low-energy sector. Finally, in mAMSB the soft terms are generated by the superconformal anomaly. The overall scale of SUSY particle masses is set by $M_{\rm aux}$, which is the vacuum expectation value of the auxiliary field in the supergravity multiplet. Furthermore, a phenomenological parameter m_0 is introduced to avoid negative squared slepton mass squares. In all three models, the high-scale parameters are supplemented by $\tan\beta$ and $\mathrm{sign}(\mu)$ as additional inputs (see below).

At low scales, the MSSM Higgs sector exhibits rich phenomenology. There are five physical states: the light and heavy CP-even Higgs bosons,[1] h and H, the CP-odd Higgs A, as well as the two charged states $H^{\pm}$ [25]. The lightest Higgs boson is SM-like for $m_A \gtrsim 150$ GeV, and its mass has an upper limit of $m_h \lesssim 135$ GeV [26]. In the limit of large m_A, the H has negligible couplings of the form VVH to gauge bosons, whereas the A has vanishing VVA couplings (at tree level). Both heavy neutral Higgs bosons have $\tan\beta$-enhanced couplings to down-type fermions. The tree-level couplings and masses of the Higgs bosons are controlled entirely by two parameters, which can be taken to be the CP-odd mass m_A, and $\tan\beta$, the ratio of the vacuum expectation values of the neutral components of the two Higgs doublets. Radiative corrections introduce dependence on other MSSM parameters. This dependence is dominated by the stop masses and the stop mixing parameter $X_t = A_t - \mu\cot\beta$, where μ denotes the Higgs mixing parameter and A_t is the stop soft trilinear coupling.

The high-scale models typically generate a SM-like lightest CP-even Higgs state [27–29]. Consequently, LEP and Tevatron searches for the SM Higgs boson can be applied to the case of the lightest Higgs CP-even Higgs boson in those supersymmetric models. Conversely, in these models H and A tend to have negligible couplings to SM gauge bosons, and different searches must be used.

In this work we will examine the projected capabilities of the Tevatron to provide evidence for or exclude regions of the MSSM $(m_A, \tan\beta, m_h)$ parameter space of these three soft SUSY-breaking scenarios. We begin in Sec. II with a brief review of the calculation of combined expected statistical significances from Higgs searches. For comparison with the MSSM reach, we present the expected significance for SM Higgs searches in our approach in Sec. III. In Secs. IV, V, and VI we give the projected reach for each high-scale SUSY-breaking model. In Sec. VII we conclude.

II. EXPECTED COMBINED SIGNIFICANCES

To make our projections we follow the approach used in Refs. [30,31]. We take as input the March 2009 expected limits on Higgs signals from a number of different search channels given by the CDF and D0 experiments in Refs. [10,32–36]. The main purpose in considering the 2009 expected limits rather than the 2010 limits is to keep consistent the meaning of efficiency improvements with respect to Refs. [30,31], as we will discuss further below. Since the expected limits change primarily through efficiency and luminosity increases, the results should be insensitive to whether 2009 or 2010 limits are used as a baseline, so long as the efficiency improvements are defined relative to that baseline. It is important for projections to consider the expected reach rather than the observed, as the latter may contain fluctuations that should not be assumed in future data.

We take into account the dominant search channels for each type of Higgs boson. Tevatron searches for the SM-like neutral Higgs are performed mainly in two channels: gluon fusion production with Higgs decay to W^+W^-, which is most sensitive to Higgs masses above 135 GeV, and in the associated production with a W or Z boson and subsequent decay to $b\bar{b}$, which contributes most prominently below 135 GeV [37–40]. The neutral Higgs states with small gauge couplings (''nonstandard Higgs bosons'') are efficiently produced primarily for relatively low m_A

[1]We concentrate here on the case without CP violation.

and large $\tan\beta$ through gluon fusion via a loop of bottom quarks, or in associated production with bottom quarks, and then decay dominantly to $b\bar{b}$ and $\tau^+\tau^-$. The inclusive search for $\tau^+\tau^-$ final states and the exclusive searches for $b\tau^+\tau^-$ and $3b$ final states provide the dominant sensitivity for nonstandard Higgs bosons at the Tevatron [41–51]. Finally, the main search channel for a charged Higgs boson (if it is lighter than the top quark) at the Tevatron is $t \to H^+ b$, $H^+ \to \tau^+ \nu$ for $\tan\beta > 1$, and reaches a maximal effect in the same parameter region as the nonstandard Higgs searches [35,52].

We begin our MSSM analysis with scans over the high-scale input parameters of the CMSSM, mGMSB, and mAMSB models. The resulting MSSM soft parameters are run down to the electroweak scale with the code SOFTSUSY [53], and experimental bounds on the lightest neutralino and chargino masses are applied [54]. For points that are consistent with these bounds, the parameters are fed into the code FEYNHIGGS [26,55–57] to compute the Higgs spectrum at the two-loop order, as well as the couplings and branching ratios. Following the procedure in Refs. [30,31], the Higgs sector observables are then used to convert the expected limits on the SM Higgs given by the experimental collaborations, as well as expected limits on non-SM-like Higgs bosons into signal significances in the CMSSM, mGMSB, and mAMSB parameter spaces. As an input value for the top quark mass, we use in our analysis $m_t = 173.1$ GeV. The latest experimental value for m_t is [58]

$$m_t^{\text{exp}} = 173.3 \pm 1.1 \text{ GeV}. \quad (1)$$

Taking into account the experimental uncertainty at the 2σ level and adding the difference of 0.2 GeV between the current experimental value and the one used in our analysis, the calculated value of m_h could move upwards by $\sim$1.5 GeV (see Table 4.1 in Ref. [59] for details). Furthermore, the theoretical uncertainty from unknown higher-order corrections in the prediction for the light CP-even Higgs mass in the CMSSM, mGMSB, and mAMSB scenarios can be estimated to be about 1–2 GeV [29]. Combining the parametric uncertainty from m_t quadratically with a theory uncertainty of $\sim$1.5 GeV results in a possible upward shift of m_h of up to 2.2 GeV. We discuss below the effects of these uncertainties.

In the $B \gg S$ (B = background, S = signal) Gaussian approximation, the significances scale with the square root of the luminosity and linearly with increases in signal efficiency. This approximation was shown in Ref. [30] to match well with more precise combinations of Tevatron Higgs limits, and we use it in the present work. We analyze the Tevatron potential for the cases of 10 fb^{-1} and 16 fb^{-1} of final integrated luminosity per experiment, and 10% to 50% efficiency improvements. We emphasize that the analysis improvements examined in this work are taken with respect to the March 2009 Tevatron expected limits (following exactly the approach in Refs. [30,31]). A comparison of the projections for the SM Higgs given in Ref. [30] with the expected limits for ≈ 6 fb^{-1} presented in Ref. [3] indicates that effectively 10% improvements have already been achieved in the low-mass region and 20% improvements have been achieved in the high-mass region between March 2009 and summer 2010. As the low-mass searches are most relevant for the SM-like Higgs in the MSSM, the universal 10% improvement gives an estimated MSSM reach, assuming *no further* improvements beyond what was already achieved by summer 2010.

In our figures we present the estimated maximal reach for any given point in model space, obtained by combining in quadrature the expected significance for each individual search channel, including those that search for SM-like, nonstandard, and charged Higgs bosons from both CDF and D0. In the Gaussian approximation, $S/\sqrt{B}$ can be interpreted either as the exclusion or the discovery power. In other words, a point marked as "$n\sigma$" can be excluded at the $n\sigma$ level if the signatures in the Higgs sector corresponding to this point are excluded at this level of confidence, or one could obtain an $n\sigma$ "evidence" if signatures compatible with a corresponding signal were observed. For reference, we also shade LEP-excluded regions as derived from Ref. [60]. For each soft SUSY-breaking scenario we also present the minimum required improvement in efficiency for all points to be probed at the 2σ level (corresponding to an exclusion at the 95% C.L.), once a total integrated luminosity of 16 fb^{-1} per experiment is analyzed.

III. THE SM

Before analyzing the Tevatron reach for the MSSM Higgs sector, it is useful to briefly review the reach for the SM Higgs, which can then be used to understand some features of the MSSM plots in the subsequent sections. In Fig. 1 we give the projections for the two luminosity and efficiency improvement assumptions as a function of m_h.

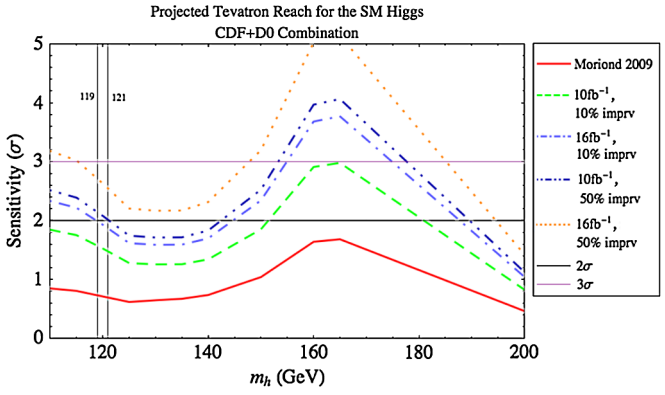

FIG. 1 (color online). Projected Tevatron coverage of SM Higgs masses for a range of final luminosities and efficiency improvements. The curve labeled "Moriond 2009" indicates the March 2009 expected limits.

Three features are immediately apparent. First, for low $m_h \sim 115$ GeV, the Tevatron is expected to achieve 3σ sensitivity with 16 fb^{-1} and 50% analysis improvements. Second, even with 50% improvements, more than 10 fb^{-1} is necessary to cover the entire low-mass range at more than the 2σ level. Finally, for the high-mass range, 3σ sensitivity is expected in a broad range, from 185 GeV to below 150 GeV, with 16 fb^{-1} and 50% analysis improvements.

We note that these projections are somewhat weaker than those presented in [61] and have a slightly different shape in the low-mass region. The primary reason for the difference is that we have assumed a rate of efficiency improvement independent of the Higgs mass, while the Tevatron experiments expect additional gains in efficiency improvement in certain mass regions. In particular, they expect efficiency improvements larger than 50% (40% with respect to today's analyses) to be possible in the mass region between 120 and 140 GeV (see, e.g., [62]). In our analysis we use flat improvement factors, as presented in Fig. 1, since they allow a simpler analytical treatment and understanding of the Higgs reach projections. Since in most of the parameter space the MSSM Higgs reach is controlled by SM Higgs searches, the extrapolation of our results to different values of the efficiency improvements can be performed in a straightforward way using the curves presented in Fig. 1. We expect that a detailed mass-dependent implementation of the efficiency improvements for the low Higgs mass region, as presented in [62], will lead to an expected significance of 3σ with 16 fb^{-1} over nearly the whole parameter space in the models under study.

IV. THE CONSTRAINED MSSM

In the CMSSM, the messenger scale is taken to be the unification scale, $\approx 2 \times 10^{16}$ GeV. At this scale the sfermions and Higgs bosons are assigned a common soft mass m_0, the gauginos share a soft mass $m_{1/2}$, and the soft trilinear couplings are set to a value A_0. The low-energy inputs are $\tan\beta$ and the sign of μ. We fix the sign of μ to be positive to give a positive contribution to the anomalous magnetic moment of the muon, $(g-2)_\mu$, thus not worsening the SM prediction [29,63–65]. The remaining parameters are scanned over the ranges

$$50\ \text{GeV} \le m_0 \le 2\ \text{TeV}, \qquad 50\ \text{GeV} \le m_{1/2} \le 2\ \text{TeV},$$
$$-3\ \text{TeV} \le A_0 \le 3\ \text{TeV}, \qquad 1.5 \le \tan\beta \le 60. \tag{2}$$

The resulting expected significances on the $(m_A, \tan\beta)$ plane are given in Figs. 2 and 3, for values of the luminosity and signal efficiency in each panel as given in the figure captions. The results of Fig. 2 are also projected onto the (m_A, m_h) plane in Fig. 4. The most important feature can be seen in the lower right plot of Fig. 2, where 16 fb^{-1} and a 50% increase in efficiency (compared to March 2009) are assumed. If these two improvements are achieved, a 3σ sensitivity to the SM-like Higgs is reached in parts of the parameter space. On the other hand, as shown in Fig. 3, 16 fb^{-1} and a 30% increase in sensitivity are sufficient to achieve a 2σ sensitivity over the whole parameter space. Consequently, the complete model could be excluded at the 95% C.L. in this case, or it would yield at least a 2σ "excess" in the Higgs boson searches.

Examining Figs. 2 and 3 in more detail, the scatter points exhibit a characteristic curve bounding the upper value of m_A for a given value of $\tan\beta$. This behavior can be understood from the dependence of the low-scale value of m_A^2 on the splitting between two soft SUSY-breaking parameters in the MSSM Higgs sector, $m_{H_u}^2$ and $m_{H_d}^2$, given by

$$m_A^2 \approx m_{H_d}^2 - m_{H_u}^2 - m_Z^2 \tag{3}$$

in the large $\tan\beta$ limit [66]. At the electroweak scale, the splitting approaches zero as $\tan\beta$ increases, because the $\tan\beta$-enhanced bottom Yukawa coupling approaches the top Yukawa coupling and uniformizes the renormalization group (RG) evolution of $m_{H_d}^2$ and $m_{H_u}^2$. The splitting generated by RG running is also roughly proportional to the squark masses squared, $m_{\tilde{Q}}^2$, times a logarithm, so the points that saturate the boundary curve are typically those for which the squarks are heavy. Heavy squarks also generate a larger m_h, so most of the CMSSM points near the boundary represent models that can only be probed at the 2σ level with both 16 fb^{-1} and 30% improvements. These are typically models with larger values of $m_{1/2}$, which efficiently raise the low-scale squark masses, as well as larger negative values of A_0, which further increase the SM-like Higgs mass. Note that in such cases the squarks and gluino are typically beyond the kinematic reach of the LHC. For low values of m_A, large $\tan\beta$, and either 10 fb^{-1} with 50% analysis improvements or 16 fb^{-1} with only 10% analysis improvements, the nonstandard Higgs searches in the $\tau\tau$ and $3b$ channels provide the only expected 3σ significance. In contrast, for 16 fb^{-1} with 50% improvements, models with lighter squarks can give rise to a 3σ excess in the $b\bar{b}$ search channels for a light SM-like Higgs.

To understand clearly the strong correlation between the expected reach and m_h, in Fig. 4 we plot the scan points on the (m_A, m_h) plane, with luminosity and efficiency improvements in each panel as in Fig. 2. As expected, the sensitivity is well controlled by m_h, reflecting the SM-like nature of h for most points. Indeed, the qualitative behavior discussed above can be understood from the projected search reach for a light SM Higgs in Fig. 1. For 10 fb^{-1} with 10% analysis improvements the expected limit in the searches for a light SM-like Higgs at the Tevatron stays below the LEP 95% C.L. observed limit of 114.4 GeV [67]. As a consequence, in the upper left plots of Figs. 2 and 4 the points outside of the region of very small m_A and large $\tan\beta$ are either excluded by the LEP Higgs searches or they show a sensitivity below the 2σ level. For 16 fb^{-1} and 10%

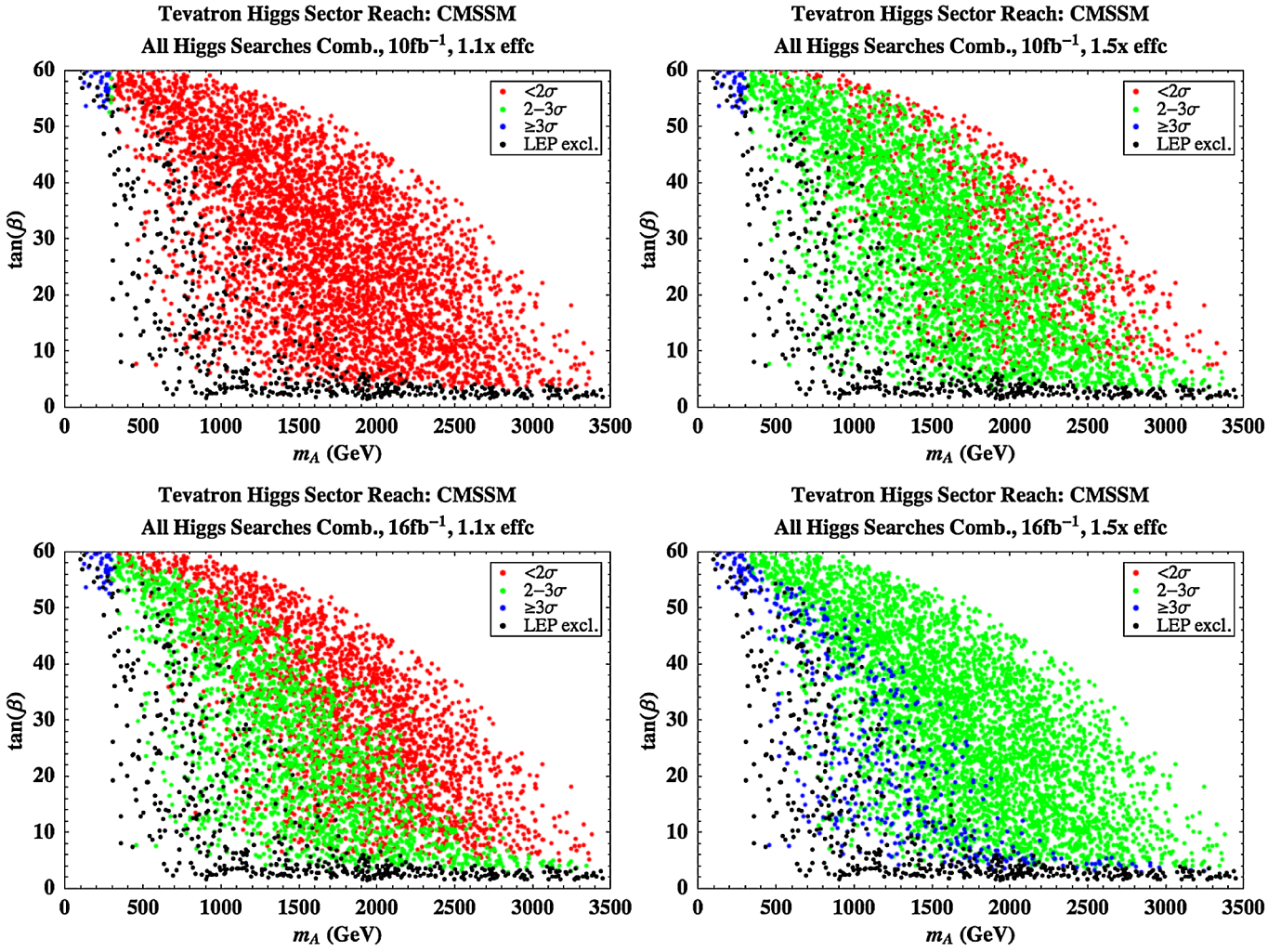

FIG. 2 (color online). Projected Tevatron coverage of the CMSSM on the $(m_A, \tan\beta)$ plane with 10 fb^{-1} and 10% efficiency improvement (top left panel), 10 fb^{-1} and 50% improvement (top right panel), 16 fb^{-1} and 10% efficiency improvement (bottom left panel), and 16 fb^{-1} with 50% improvement (bottom right panel). The efficiency improvements are given relative to the March 2009 expected limits.

analysis improvements, the projected SM limit is about 119 GeV, while for 10 fb^{-1} and 50% analysis improvements, the SM limit rises to about 121 GeV. Comparison of the corresponding plots in Figs. 2 and 4 shows that the parameter regions displaying a 2σ sensitivity are characterized by m_h values bounded from above by approximately the projected SM limits. (The MSSM reach is slightly stronger due to the combination with nonstandard channels and the mild increase in the $h \to b\bar{b}$ branching fraction in the MSSM relative to the SM. These differences also explain why the minimal improvement to achieve 2σ coverage in the CMSSM is 30%, whereas this improvement yields slightly less than 2σ significance for a relevant mass range around 125 GeV in the SM.) Finally, for 16 fb^{-1} and 50% analysis improvements the search for the SM Higgs gives rise to a sensitivity above the 2σ level over the whole range of m_h values allowed in the supersymmetric models. This feature is visible in the lower right

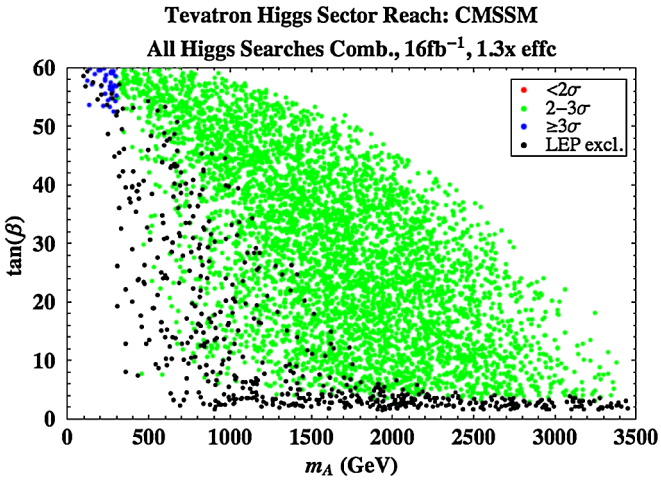

FIG. 3 (color online). Projected Tevatron coverage of the CMSSM on the $(m_A, \tan\beta)$ plane with 16 fb^{-1} and 30% efficiency improvement (w.r.t. March 2009), which is the approximate threshold for full coverage at the 2σ level.

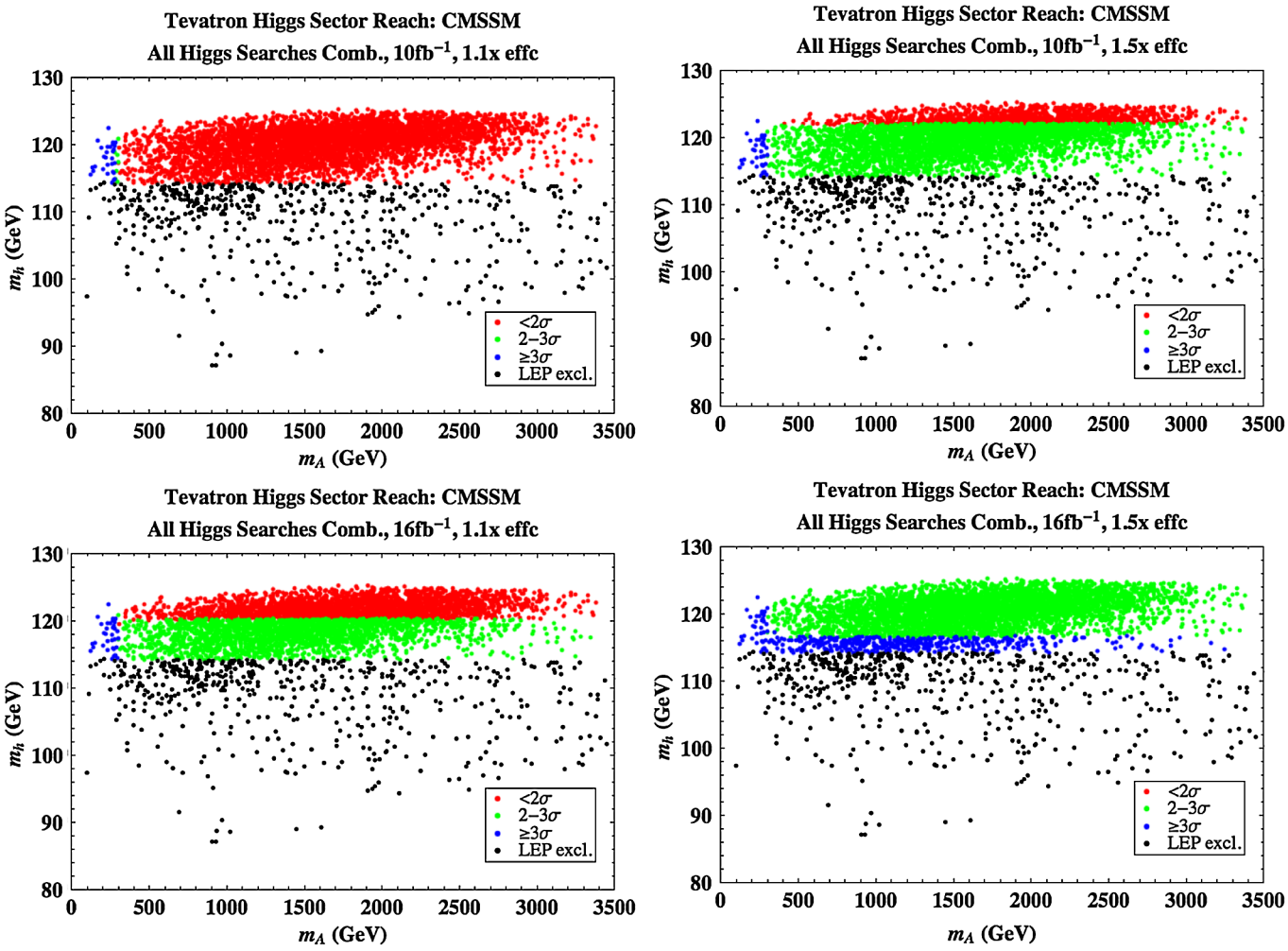

FIG. 4 (color online). Projected Tevatron coverage of the CMSSM on the (m_A, m_h) plane with 10 fb^{-1} and 10% efficiency improvement (top left panel), 10 fb^{-1} and 50% improvement (top right panel), 16 fb^{-1} and 10% efficiency improvement (bottom left panel), and 16 fb^{-1} with 50% improvement (bottom right panel). The efficiency improvements are given relative to the March 2009 expected limits.

plots of Figs. 2 and 4. Furthermore, we find a 3σ median sensitivity for $m_h \lesssim 116$ GeV in this case.

We note that the results of Fig. 4 allow one to read off the upper bound on the lightest *CP*-even Higgs boson mass in the CMSSM obtained for $m_t = 173.1$ GeV with state-of-the-art theoretical predictions. We find an upper bound of $m_h \leq 125.2$ GeV in the CMSSM in the case where m_t is kept fixed and no uncertainties from unknown higher-order corrections are taken into account. If the theory and parametric uncertainties are included as described in Sec. II, we find an upper value for m_h of 127.4 GeV. Saturating the bound on m_h would still require an improvement of 30% in the signal efficiency to be fully tested at the 2σ level; the fact that the minimal improvement is the same for both mass values reflects the flatness of the SM projection curves starting near 125 GeV in Fig. 1. Including the theoretical errors could push some points below the 2σ threshold in the cases of 16 fb^{-1} with 10% improvements or 10 fb^{-1} with 50% improvements, or below the 3σ thresholds in the case of 16 fb^{-1} with 50% improvements, as is most evident from the results of Fig. 4. However, the curves in Fig. 1 imply that the theory errors of $\sim$2 GeV in m_h shift the expected sensitivities by very small amounts ($\sim 0.2\sigma$), and therefore the reach remains close to the sensitivity shown in our figures.

V. MINIMAL GAUGE-MEDIATED SUSY BREAKING

In the so-called minimal gauge mediation model, the SUSY-breaking effects are transmitted to the MSSM through loops of heavy messenger particles that are charged under the MSSM gauge groups. The MSSM soft masses are generated by integrating out the messengers at their mass scale $M_{\rm mess}$, which is not tied to the GUT scale, in general, and evolving the parameters down to the weak

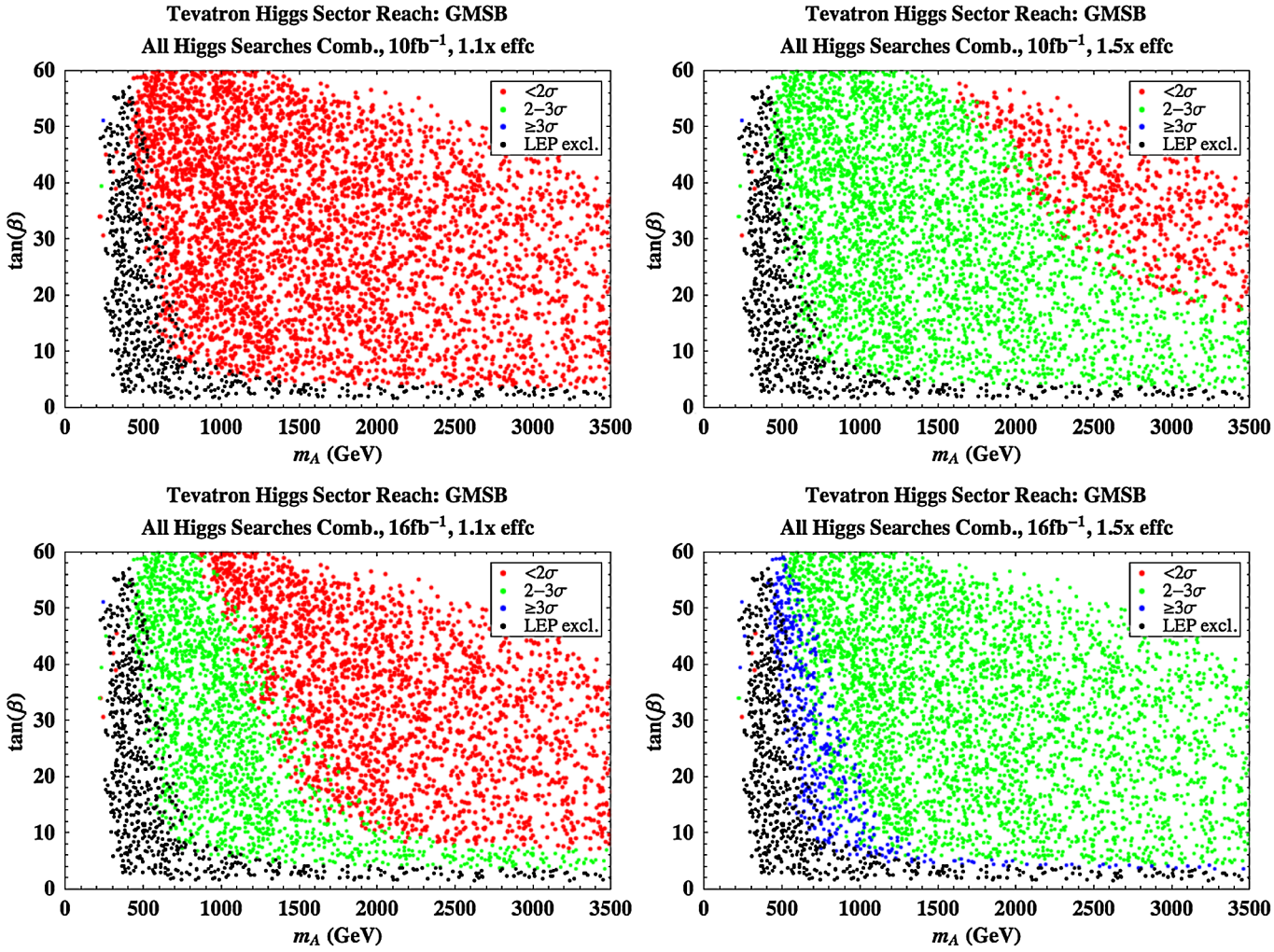

FIG. 5 (color online). Projected Tevatron coverage of mGMSB on the $(m_A, \tan\beta)$ plane with 10 fb^{-1} and 10% efficiency improvement (top left panel), 10 fb^{-1} and 50% improvement (top right panel), 16 fb^{-1} and 10% efficiency improvement (bottom left panel), and 16 fb^{-1} with 50% improvement (bottom right panel). The efficiency improvements are given relative to the March 2009 expected limits.

scale. At $M_{\rm mess}$ the soft masses are controlled by gauge couplings, the number of complete $SU(5)$ $5 + \bar{5}$ messenger representations $N_{\rm mess}$, and a parameter Λ which is proportional to the SUSY-breaking F-term expectation value in the hidden sector. Soft trilinear couplings are generated only at higher order and therefore achieve nonzero values at the weak scale only through RG evolution. We scan the input parameters in the ranges

$$10\ \text{TeV} \le \Lambda \le 200\ \text{TeV}, \qquad \Lambda \le M_{\rm mess} \le 10^5 \times \Lambda,$$
$$1 \le N_{\rm mess} \le 8, \qquad 1.5 \le \tan\beta \le 60. \tag{4}$$

The Tevatron Higgs reach for the mGMSB scenario is given in Figs. 5 and 6 on the $(m_A, \tan\beta)$ plane. The panels of Fig. 5 assume the same increases in luminosity and signal efficiency as in Fig. 2, but Fig. 6 assumes 16 fb^{-1} and a 25% gain in efficiency. In Fig. 7 we project the reach onto the (m_A, m_h) plane with the same parameters for each panel as in Fig. 5.

As explained above, for 10 fb^{-1} and no further analysis improvements beyond what has already been achieved (i.e., a 10% improvement compared to March 2009), the sensitivity of the Tevatron searches for a light SM-like Higgs boson does not exceed the sensitivity of the LEP Higgs searches, giving rise to the results displayed in the upper left plots of Figs. 5 and 7 (and in the corresponding plots for the mAMSB scenario shown below).

For the analyses with 16 fb^{-1} and/or further analysis improvements, two main features emerge. First, for the upper bound on the lightest CP-even Higgs boson mass in the mGMSB scenario, we find $m_h \le 122.6$ GeV (for $m_t = 173.1$ GeV; the value moves up to $m_h = 124.9$ GeV if all theory uncertainties as described in Sec. II are taken into account), which is about 2.5 GeV lower than in the

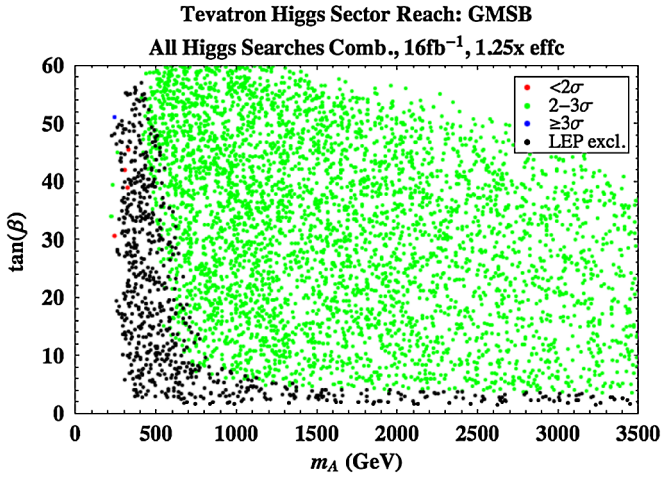

FIG. 6 (color online). Projected Tevatron coverage of mGMSB on the $(m_A, \tan\beta)$ plane with 16 fb^{-1} and 25% efficiency improvement (w.r.t. March 2009), which is the approximate threshold for full coverage at the 2σ level.

CMSSM, implying a larger coverage from the Tevatron searches compared to the CMSSM case. The reduction of the upper bound on m_h relative to the CMSSM case can be traced to the stop trilinear coupling, which maximizes the radiative contributions to m_h for $A_t^2 \approx 4m_{\tilde{t}}^2$ at large $\tan\beta$ (note that the factor of 4 is due to the on-shell renormalization scheme used in FEYNHIGGS; in the modified minimal subtraction scheme, the relation is instead $A_t^2 \approx 6m_{\tilde{t}}^2$ [68]). Because A_t is generated by two-loop diagrams at the messenger scale in mGMSB, it is typically smaller than $m_{\tilde{t}}$ at the electroweak scale. Therefore m_h tends to be less than about 120 GeV, close to the LEP limit [28,69–71]. The Tevatron reach in the $b\bar{b}$ channel is thus significant: most points are reached at the 2σ level with 10 fb^{-1} and 50% analysis improvements (and all points are covered at 90% C.L.). It should be noted that for 16 fb^{-1}, 50% improvements, and $m_A \lesssim 500$ GeV, 3σ evidence is expected. This can be understood as follows. The direct dependence of m_h

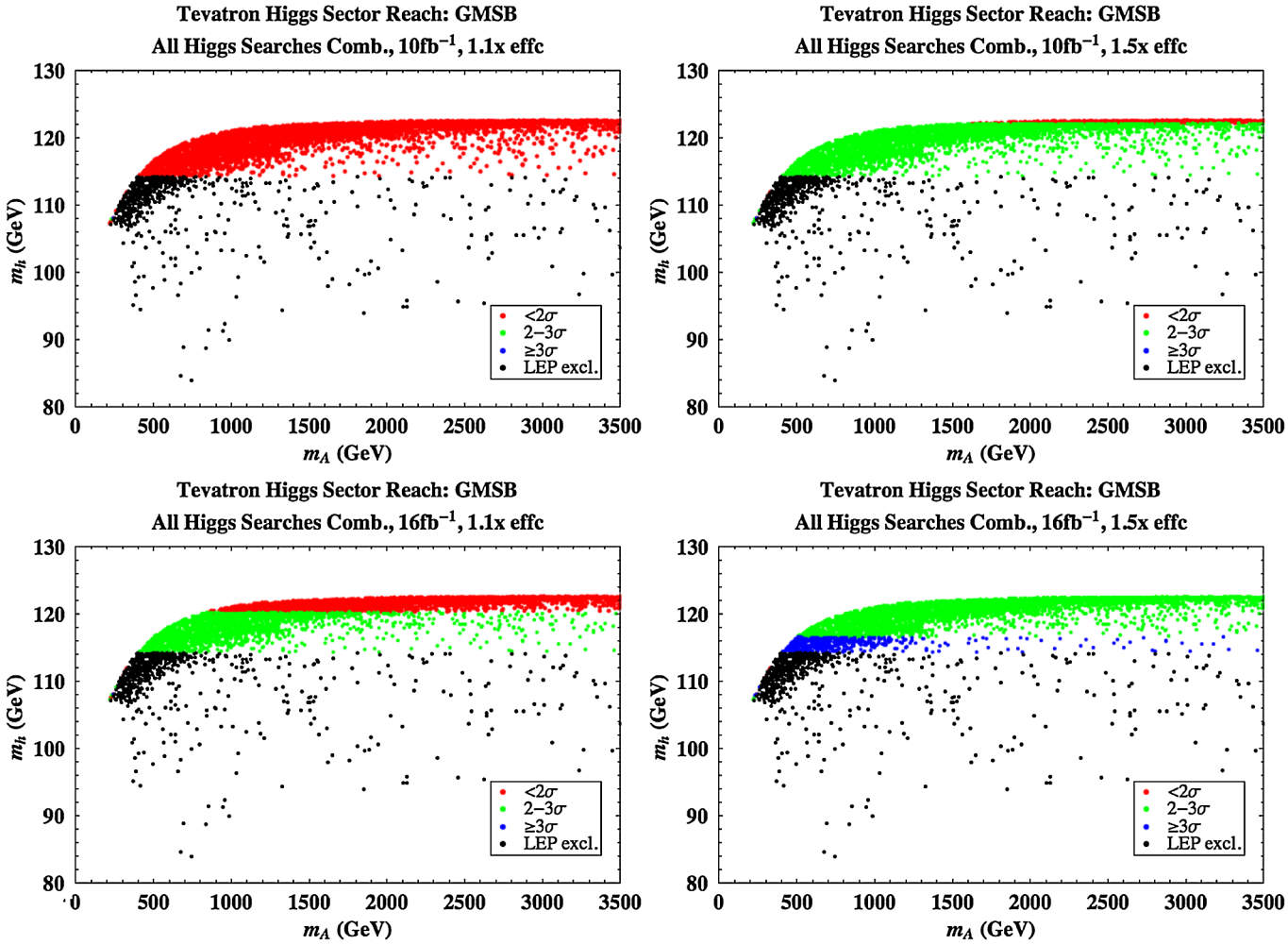

FIG. 7 (color online). Projected Tevatron coverage of mGMSB on the (m_A, m_h) plane with 10 fb^{-1} and 10% efficiency improvement (top left panel), 10 fb^{-1} and 50% improvement (top right panel), 16 fb^{-1} and 10% efficiency improvement (bottom left panel), and 16 fb^{-1} with 50% improvement (bottom right panel). The efficiency improvements are given relative to the March 2009 expected limits.

on m_A is minimal for such large values of m_A, but in mGMSB m_A and the squark masses are both controlled by Λ. Consequently, lower values of m_A are typically correlated with lighter squarks. In addition to the reduction in m_h from small A_t, the lower stop masses in this region of parameters also reduce m_h, so that the Tevatron Higgs searches have a high sensitivity. Again we note that as with the CMSSM, it is only with a combination of increased luminosity and refinements in the signal extraction that 3σ sensitivity is obtained. However, we stress that, as shown in Fig. 6, only 15% improvement is necessary [i.e., 25% improvement with respect to (w.r.t.) March 2009] to achieve the sensitivity to exclude any model point at the 95% C.L. with 16 fb^{-1} and therefore to completely rule out this widely studied SUSY scenario. Increasing m_h by the theory uncertainties discussed in Sec. II requires an improvement of 20% (30% w.r.t. March 2009) in the signal efficiency to fully cover mGMSB at 2σ.

The second important feature apparent in our analysis for the mGMSB model is the absence of a 3σ reach in the nonstandard channels at large $\tan\beta$ and low m_A. More precisely, such points do not arise at all in the scan, because they are associated with slepton masses below the experimental limit. Unlike in the CMSSM, the boundary values for the slepton masses are suppressed relative to the squarks by factors of the electroweak gauge couplings, and at large $\tan\beta$ and low Λ, the τ Yukawa coupling is sufficiently enhanced to drive the squared slepton masses to small or even negative values at the electroweak scale. Thus it can be expected that the primary signal of a mGMSB Higgs sector at the Tevatron (with 16 fb^{-1} and 50% analysis improvements) will be 2σ–3σ evidence for a SM-like state in the associated production channel with $m_h < 125$ GeV (including, in this upper bound, possible contributions from both the theoretical and parametric uncertainties).

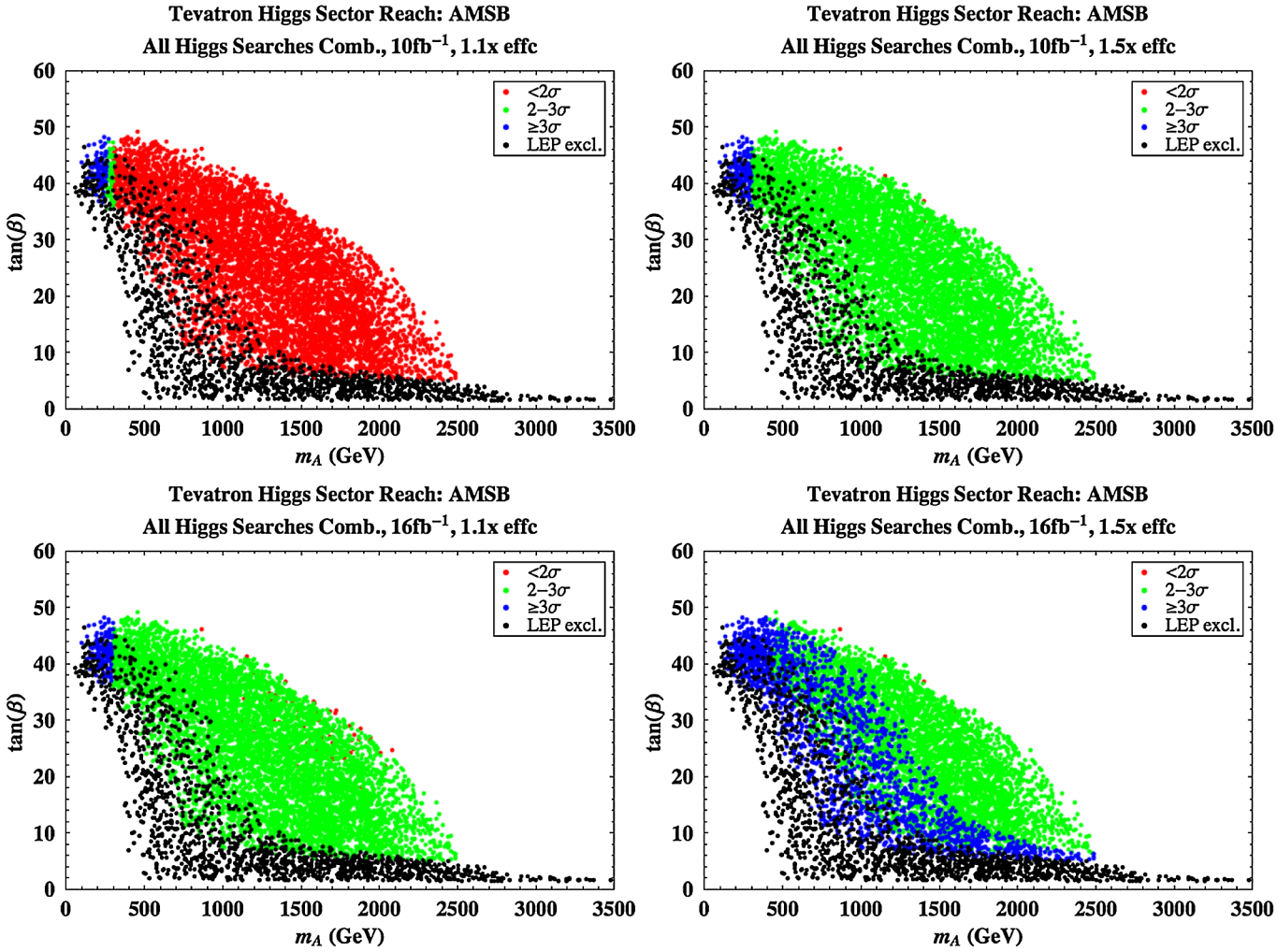

FIG. 8 (color online). Projected Tevatron coverage of mAMSB on the $(m_A, \tan\beta)$ plane with 10 fb^{-1} and 10% efficiency improvement (top left panel), 10 fb^{-1} and 50% improvement (top right panel), 16 fb^{-1} and 10% efficiency improvement (bottom left panel), and 16 fb^{-1} with 50% improvement (bottom right panel). The efficiency improvements are given relative to the March 2009 expected limits.

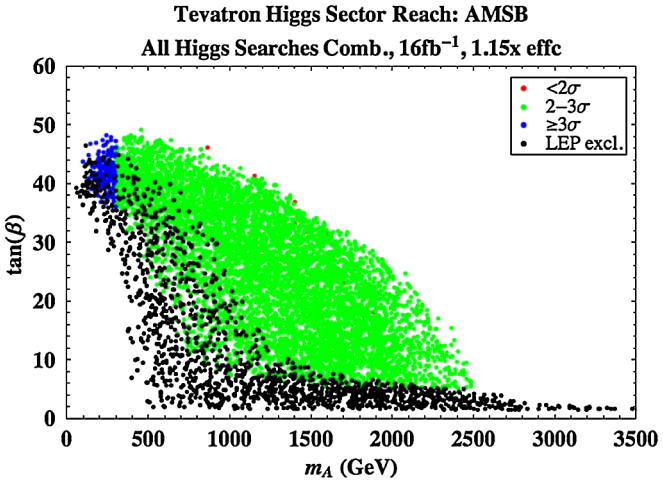

FIG. 9 (color online). Projected Tevatron coverage of mAMSB on the $(m_A, \tan\beta)$ plane with 16 fb^{-1} and 15% efficiency improvement (w.r.t. March 2009), which is the approximate threshold for full coverage at the 2σ level.

VI. ANOMALY-MEDIATED SUSY BREAKING

SUSY breaking in the simplest phenomenologically acceptable realization of the mAMSB scenario is governed by two parameters: an F-term $M_{\rm aux}$, to which all MSSM soft parameters are proportional, and an explicit universal sfermion mass m_0. The soft masses at all scales are given by simple functions of the gauge and Yukawa β functions and the anomalous dimensions of the fields. We scan in the ranges

$$0 \leq m_0 \leq 2 \text{ TeV}, \qquad 20 \text{ TeV} \leq M_{\rm aux} \leq 100 \text{ TeV},$$
$$1.5 \leq \tan\beta \leq 60. \tag{5}$$

The Higgs sector reach is given in Figs. 8 and 9 on the $(m_A, \tan\beta)$ plane. As before, the panels of Fig. 8 assume increases in luminosity and signal efficiency as in Fig. 2, but Fig. 9 assumes 16 fb^{-1} and a 15% gain in efficiency (i.e., about a 5% gain w.r.t. the present situation). The reach on the (m_A, m_h) plane is given in Fig. 10 with the same

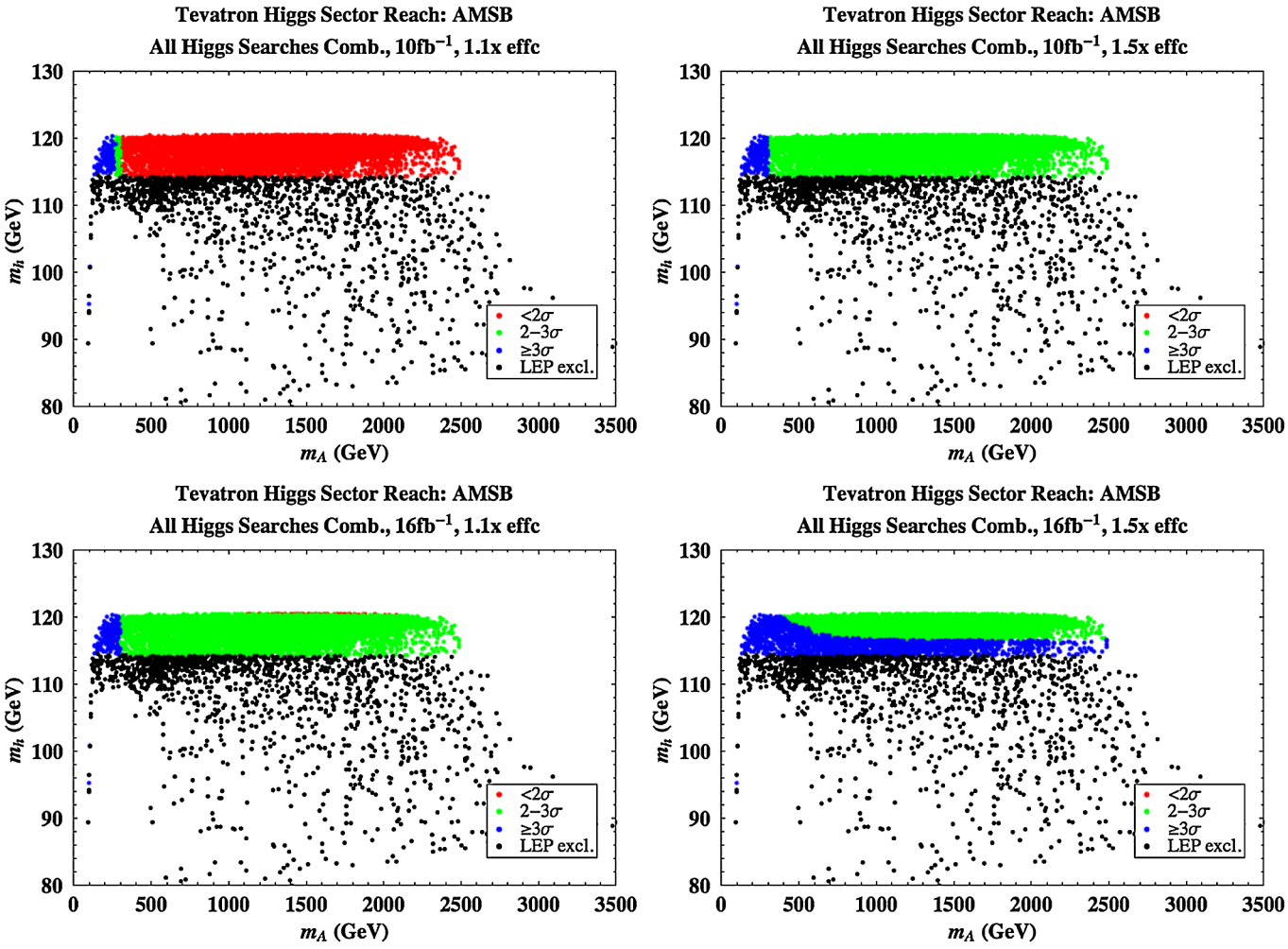

FIG. 10 (color online). Projected Tevatron coverage of mAMSB on the (m_A, m_h) plane with 10 fb^{-1} and 10% efficiency improvement (top left panel), 10 fb^{-1} and 50% improvement (top right panel), 16 fb^{-1} and 10% efficiency improvement (bottom left panel), and 16 fb^{-1} with 50% improvement (bottom right panel). The efficiency improvements are given relative to the March 2009 expected limits.

parameters for each panel as in Fig. 8. For the upper bound on the lightest *CP*-even Higgs boson mass in the mAMSB scenario, we find $m_h \leq 120.5$ GeV (for $m_t = 173.1$ GeV; the value moves up to $m_h = 122.5$ GeV if all theory uncertainties as described in Sec. II are taken into account), which is about 2.1 GeV lower than in the mGMSB case, and about 4.7 GeV lower than in the CMSSM case. Thus, among the scenarios considered here, the potential of the Tevatron Higgs searches to completely cover the whole parameter space of the model will be highest in the mAMSB scenario. Accordingly, for 16 fb^{-1} and as little as 5% increase in efficiency (i.e., 15% increase as compared to March 2009) there will be 2σ exclusion power for all scan points. Taking into account the theory uncertainties for m_h discussed above requires an increase of 25% w.r.t. 2009 in the experimental efficiency to fully cover mAMSB at 2σ. For 16 fb^{-1} and a 50% increase in efficiency w.r.t. 2009, there is a broad potential for 3σ evidence. The former is demonstrated in Fig. 9 (with the exception of points at the boundary of the parameter space that will be discussed below).

The Tevatron reach can be understood from arguments similar to the previous two models. In the absence of m_0 the sleptons would always be tachyonic, but the introduction of this parameter allows positive masses squared even for large $\tan\beta$. Therefore, as in the CMSSM, the sensitivity to the nonstandard Higgs in the $\tau\tau$ and $3b$ channels is high for low m_A. The reduced upper bound on m_h as compared to the CMSSM and the mGMSB scenario is attributable to the stop trilinear coupling, which is proportional to $M_{\rm aux}$ and the β function of the top Yukawa coupling, and is generically of the same order or smaller than $m_{\tilde{t}}$. As a consequence of the relatively low upper bound on m_h, a large fraction of the parameter space is reachable at the 2σ level with luminosity gains alone, and the 3σ reach for the light Higgs is significant, with 16 fb^{-1} and 50% improvements.

However, near the largest values of m_0 and smallest values of $M_{\rm aux}$, a few points avoid even 2σ sensitivity. In these models the squarks are heavy, pushing up m_h, while the gaugino masses are light, opening the decay channel $h \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$. Although we did not treat this case specially in our projections, the analysis of Ref. [72] indicates that evidence for an invisibly decaying SM-like Higgs may be achievable at the Tevatron by combining searches in the weak boson fusion and associated production channels with 12 fb^{-1}, and that discovery may occur at the LHC with 10 fb^{-1} and $\sqrt{s} = 14$ TeV in the Zh channel alone.

VII. CONCLUSIONS

In this paper we have analyzed the physics potential of the Tevatron collider in the context of the MSSM Higgs sector, based on 10 fb^{-1} or 16 fb^{-1} of analyzable data per experiment, corresponding to Tevatron operation until the end of 2011 or 2014, respectively. For the projections, we have also studied the impact of possible improvements in the efficiencies of the Tevatron analyses (an extended running time and higher accumulated statistics should of course be helpful for achieving such efficiency improvements, as some uncertainties in Higgs analyses can be sensitive to statistical uncertainties in other measurements). We have investigated the most commonly considered high-scale models for the communication of SUSY breaking to the MSSM, in which predictions for the low-scale spectra and the collider reach are given in terms of relatively few free parameters. As a result, we have provided projections for the constrained MSSM, the minimal gauge mediation of SUSY breaking, and minimal anomaly mediation.

For 10 fb^{-1}, i.e. Tevatron running until the end of 2011, and no further improvements in the analysis efficiency compared to the present situation, the sensitivity of the Tevatron searches for a light SM-like Higgs would not exceed the sensitivity of the Higgs searches at the LEP. Thus, the impact of the Tevatron Higgs searches in the different SUSY scenarios would be rather limited in this case, with the best prospects in the parameter region of small m_A and very large $\tan\beta$ for nonstandard Higgs searches in the $\tau\tau$ and $3b$ channels.

If 16 fb^{-1} can be analyzed at each Tevatron experiment, as expected from running the Tevatron for three additional years beyond 2011, and the analysis efficiency can be improved by 30% with respect to the status of March 2009 (where 10% between March 2009 and summer 2010 has been realized already), a 2σ (or higher) sensitivity is expected over the whole parameter space in all three models. Consequently, all three different types of SUSY-breaking models considered here could be excluded at the 95% C.L., or would yield at least a 2σ excess in the Higgs boson searches. It should be noted that an exclusion of those SUSY scenarios, which up to now have been used for defining the benchmarks for SUSY searches at the LHC and elsewhere, could have profound consequences on the possible interpretation of SUSY searches at the LHC.

With an integrated luminosity of 16 fb^{-1} per experiment and a 50% improvement in the signal efficiency with respect to the status of March 2009, the opportunity for 3σ evidence for a SM-like Higgs will open up in significant parts of the parameter space of the most prominent SUSY-breaking scenarios. We also stress that our projections could be considered conservative in the sense that we have used a flat efficiency improvement profile that is weaker in the low-mass region than the improvements projected by the Tevatron collaborations. Using the efficiency improvements presented in [62] would result in widespread 3σ coverage in all of the models we considered for 16 fb^{-1} of data.

Perhaps the most exciting possibility is that indications of a Higgs signal would build up simultaneously at the Tevatron and LHC in their respective search channels. The $gg \to h \to \gamma\gamma$ channel will eventually provide a discovery channel at the LHC and will allow a precise mass measurement, while the simultaneous observation of the Higgs in the associated production channel at the Tevatron will strengthen the link to EWSB and will provide direct information on its coupling to weak gauge bosons and to bottom quarks. The combination of the LHC and Tevatron channels can thus be important input for a Higgs boson coupling determination. The combined significance of the LHC and Tevatron channels can also be helpful in the observation of a Higgs in the near future in cases in which the production cross sections in one or more of the channels are suppressed with respect to the SM expectations.

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