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# Probing the Higgs Sector of High-Scale SUSY-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 note 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 (CMSSM), minimal Gauge Mediated SUSY-breaking (mGMSB), and minimal Anomaly Mediated SUSY-breaking (mAMSb). 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  $16 \text{ fb}^{-1}$  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  $16 \text{ fb}^{-1}$ , our projection shows that evidence at the  $3\sigma$  level for the light Higgs boson could be expected in extended regions of parameter space.

## I. INTRODUCTION

The Tevatron collider at Fermilab is now in its twenty-sixth 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 Large Hadron Collider (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, it is planned to run the Tevatron 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 dataset, 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 DØ 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  $\sim 135$  GeV turns out to be the most challenging one [6, 7]. At the LHC the accumulation of a significant dataset, of the order of  $10 \text{ fb}^{-1}$  [8], would be necessary for the discovery of a SM-type Higgs boson in the  $gg \rightarrow h \rightarrow \gamma\gamma$  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 exists also 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  $p\bar{p}$  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  $16 \text{ fb}^{-1}$  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 ad-

dition 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 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  $M_{\text{mess}}$  denotes the overall messenger mass scale;  $N_{\text{mess}}$  is a number called the messenger index, parameterizing the structure of the messenger sector, and  $\Lambda$  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  $M_{\text{aux}}$ , 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  $\text{sign}(\mu)$  as additional inputs (see below).

At low scales, the MSSM Higgs sector exhibits rich phenomenology. There are five physical states: the light and heavy  $\mathcal{CP}$ -even Higgs bosons<sup>1</sup>,  $h$  and  $H$ , the  $\mathcal{CP}$ -odd Higgs  $A$ , as well as the two charged states,  $H^\pm$  [25]. The lightest Higgs boson behaves 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  $\mathcal{CP}$ -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  $\mu$  denotes the Higgs mixing parameter and  $A_t$  is the stop soft trilinear coupling.

The high-scale models typically generate a SM-like lightest  $\mathcal{CP}$ -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  $\mathcal{CP}$ -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 Section 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 Section III. In Sections IV–VI we give the projected reach for each high-scale SUSY-breaking model. In Section 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 DØ 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  $m_A$  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  $t \rightarrow H^+b$ ,  $H^+ \rightarrow \tau^+\nu$  for  $\tan\beta > 1$ , and reaches maximal effect in the same parameter region

<sup>1</sup> We concentrate here on the case without  $\mathcal{CP}$ -violation.

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 2-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 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  $2\sigma$  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  $\mathcal{CP}$ -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  $10 \text{ fb}^{-1}$  and  $16 \text{ fb}^{-1}$  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  $\approx 6 \text{ fb}^{-1}$  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 has been already achieved by the 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 DØ. 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  $2\sigma$  level (corresponding to an exclusion at the 95% C.L.), once a total integrated luminosity of  $16 \text{ fb}^{-1}$  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  $m_h$ .

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

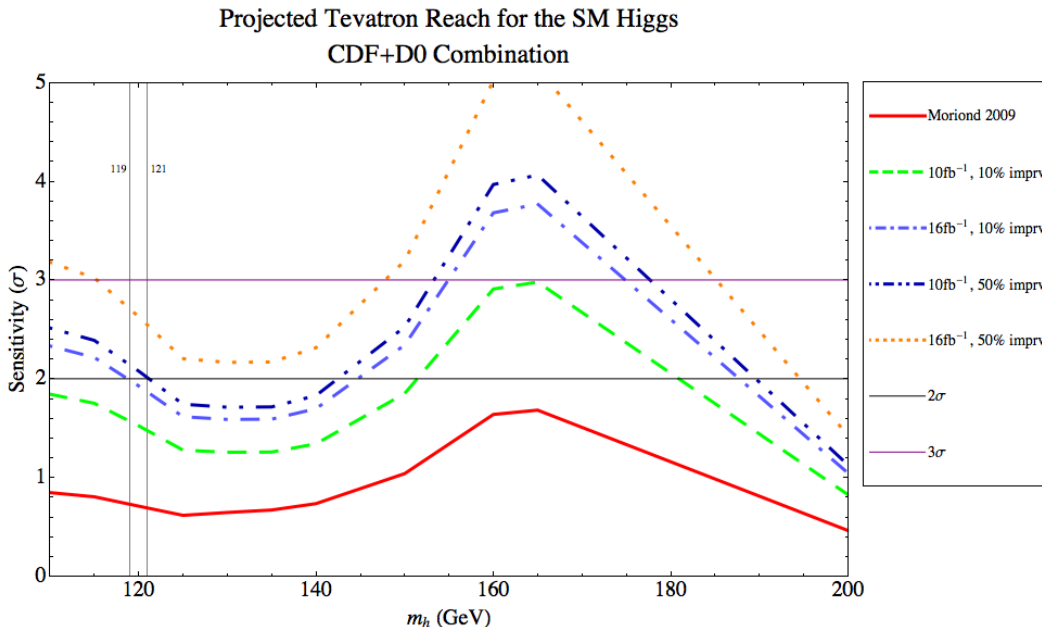


FIG. 1. Projected Tevatron coverage of SM Higgs masses for a range of final luminosities and efficiency improvements. The curve labelled “Moriond 2009” indicates the March 2009 expected limits. (color figures available online)

of the efficiency improvements for the low Higgs mass region, as presented in [62], will lead to an expected significance of  $3\sigma$  with  $16\text{fb}^{-1}$  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  $\mu$ . We fix the sign of  $\mu$  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

$$\begin{aligned} 50\text{ GeV} \leq m_0 \leq 2\text{ TeV}, \quad 50\text{ GeV} \leq m_{1/2} \leq 2\text{ TeV}, \\ -3\text{ TeV} \leq A_0 \leq 3\text{ TeV}, \quad 1.5 \leq \tan\beta \leq 60. \end{aligned} \quad (2)$$

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  $16\text{fb}^{-1}$  and a 50% increase in efficiency (compared to March 2009) are assumed. If these two improvements are achieved, a  $3\sigma$  sensitivity to the SM-like Higgs is reached in parts of the parameter space. On the other hand, as

shown in Fig. 3,  $16\text{fb}^{-1}$  and 30% increase in sensitivity is sufficient to achieve a  $2\sigma$  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  $2\sigma$  “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

$$m_A^2 \approx m_{H_d}^2 - m_{H_u}^2 - m_Z^2 \quad (3)$$

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 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,  $m_Q^2$ , 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  $2\sigma$  level with both  $16\text{fb}^{-1}$  and 30% improvements. These are typically models with larger values of  $m_{1/2}$ , which efficiently raises the low-scale squark masses, as well as larger negative values of  $A_0$ , which further increases 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  $10\text{fb}^{-1}$  with 50%

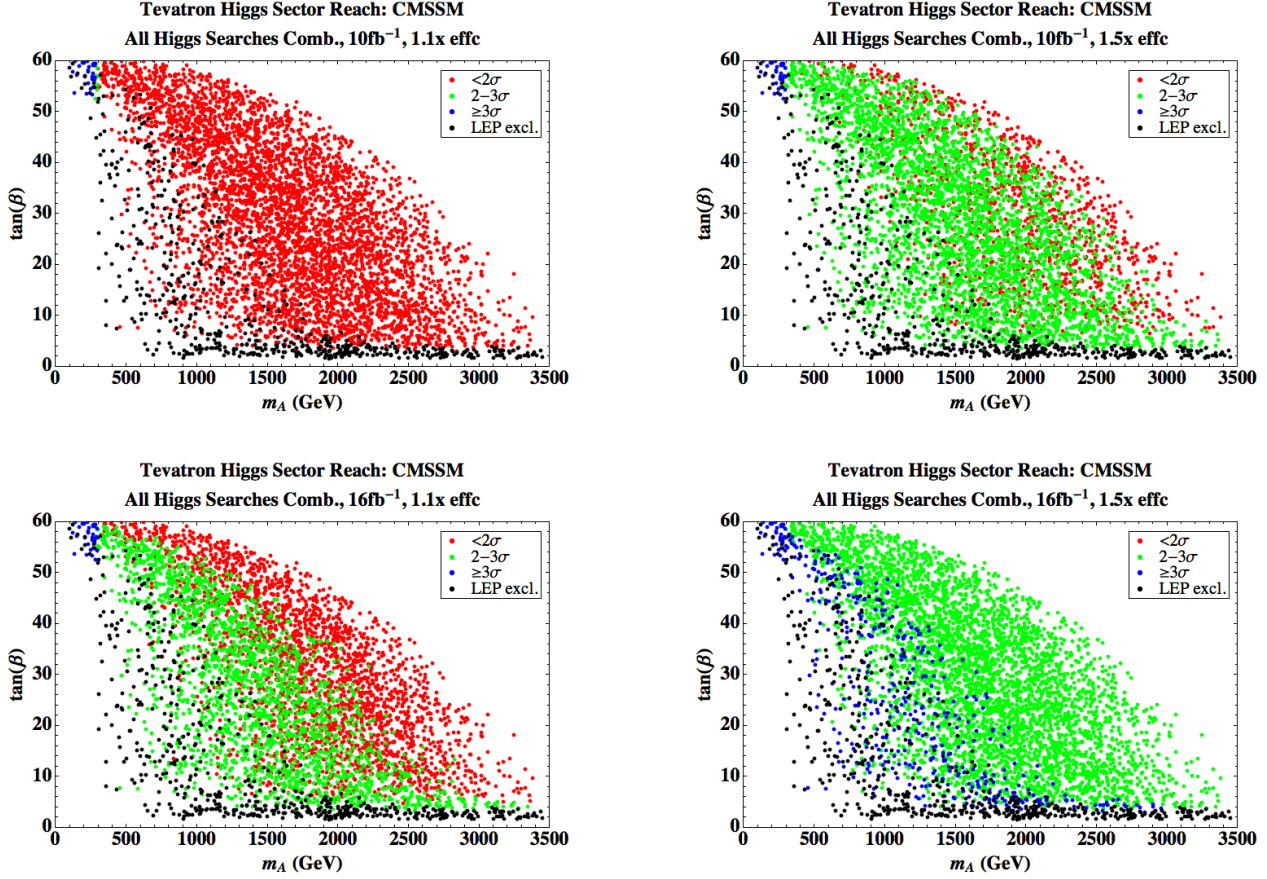


FIG. 2. Projected Tevatron coverage of the CMSSM on the  $(m_A, \tan\beta)$  plane with  $10 \text{ fb}^{-1}$  and 10% efficiency improvement (*top left*),  $10 \text{ fb}^{-1}$  and 50% improvement (*top right*),  $16 \text{ fb}^{-1}$  and 10% efficiency improvement (*bottom left*), and  $16 \text{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

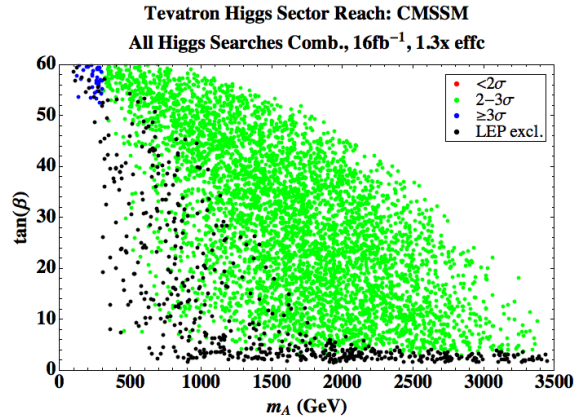


FIG. 3. Projected Tevatron coverage of the CMSSM on the  $(m_A, \tan\beta)$  plane with  $16 \text{ fb}^{-1}$  and 30% efficiency improvement (w.r.t. March 2009), which is the approximate threshold for full coverage at the  $2\sigma$  level. (color figures available online)

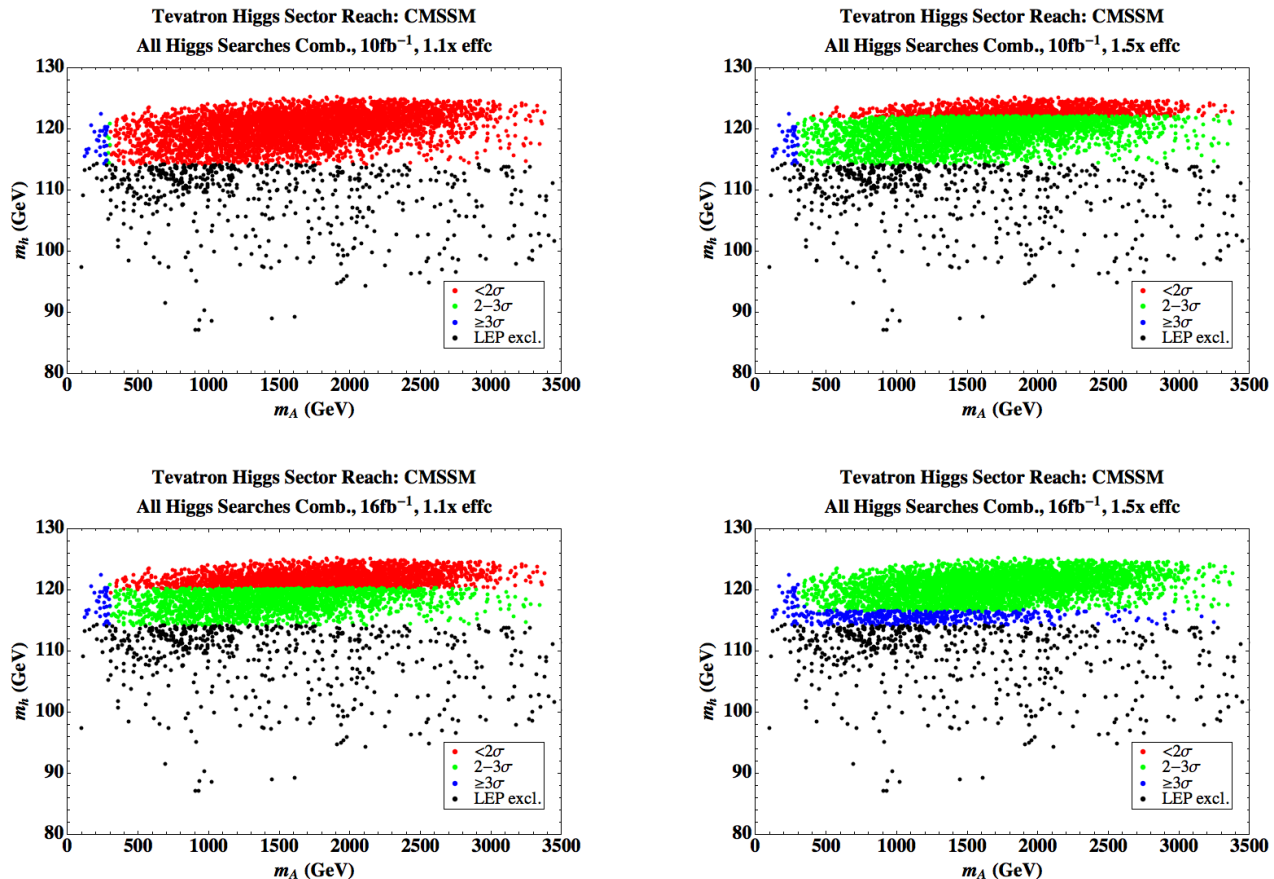


FIG. 4. Projected Tevatron coverage of the CMSSM on the  $(m_A, m_h)$  plane with  $10\text{ fb}^{-1}$  and 10% efficiency improvement (*top left*),  $10\text{ fb}^{-1}$  and 50% improvement (*top right*),  $16\text{ fb}^{-1}$  and 10% efficiency improvement (*bottom left*), and  $16\text{ fb}^{-1}$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

analysis improvements or  $16\text{ fb}^{-1}$  with only 10% analysis improvements, the nonstandard Higgs searches in the  $\tau\tau$  and  $3b$  channels provide the only expected  $3\sigma$  significance. In contrast, for  $16\text{ fb}^{-1}$  with 50% improvements, models with lighter squarks can give rise to a  $3\sigma$  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  $10\text{ fb}^{-1}$  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 Fig. 2 and Fig. 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 be-

low the  $2\sigma$  level. For  $16\text{ fb}^{-1}$  and 10% analysis improvements, the projected SM limit is about 119 GeV, while for  $10\text{ fb}^{-1}$  and 50% analysis improvements the SM limit raises to about 121 GeV. Comparison of the corresponding plots in Fig. 2 and Fig. 4 shows that the parameter regions displaying a  $2\sigma$  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  $h \rightarrow b\bar{b}$  branching fraction in the MSSM relative to the SM. These differences also explain why the minimal improvement to achieve  $2\sigma$  coverage in the CMSSM is 30%, whereas this improvement yields slightly less than  $2\sigma$  significance for a relevant mass range around 125 GeV in the SM.) Finally, for  $16\text{ fb}^{-1}$  and 50% analysis improvements the search for the SM Higgs gives rise to a sensitivity above the  $2\sigma$  level over the whole range of  $m_h$  values allowed in the supersymmetric models. This feature is visible in the lower right plots of Fig. 2 and Fig. 4. Furthermore, we find a  $3\sigma$  median sensitivity for  $m_h \lesssim 116\text{ GeV}$  in this case.



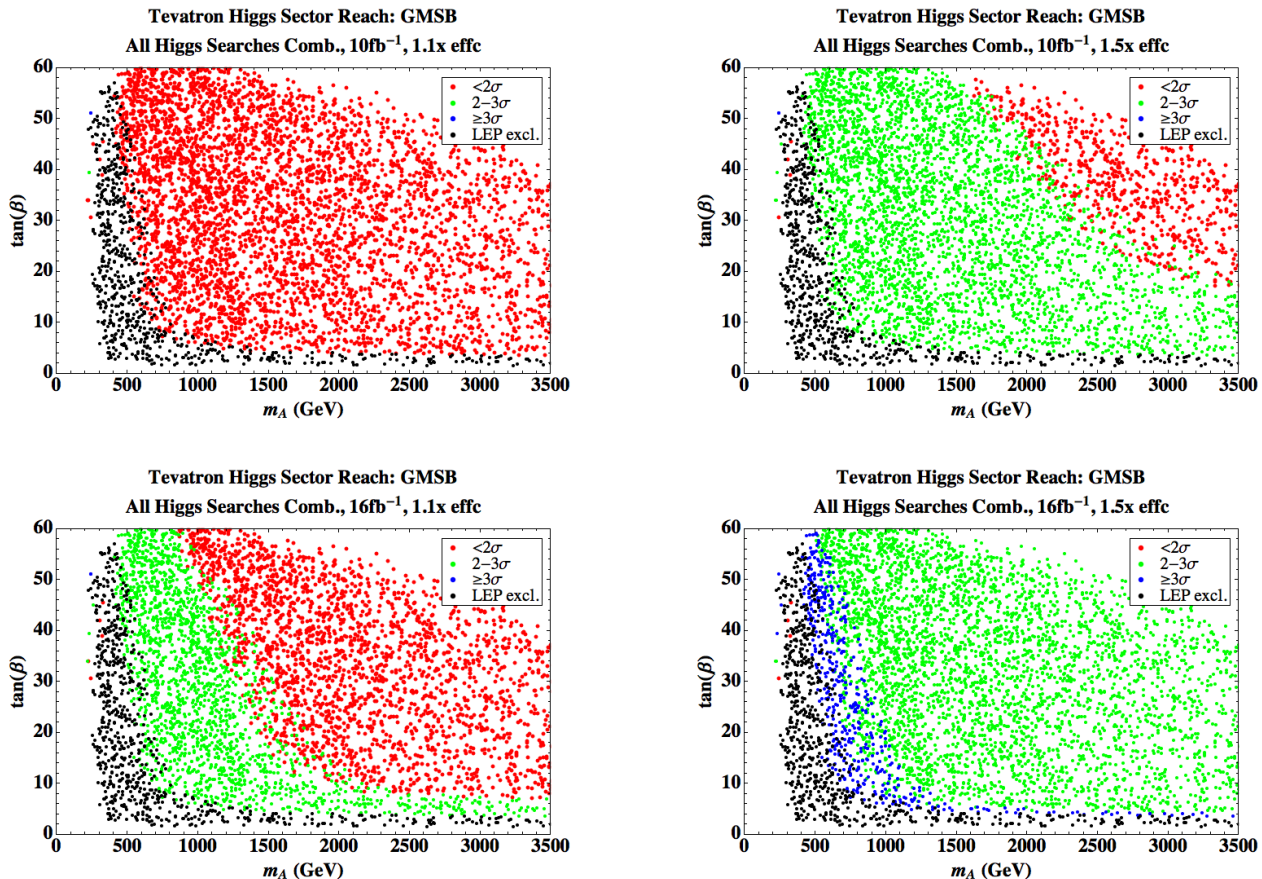


FIG. 5. Projected Tevatron coverage of mGMSB on the  $(m_A, \tan\beta)$  plane with  $10\text{ fb}^{-1}$  and 10% efficiency improvement (*top left*),  $10\text{ fb}^{-1}$  and 50% improvement (*top right*),  $16\text{ fb}^{-1}$  and 10% efficiency improvement (*bottom left*), and  $16\text{ fb}^{-1}$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

We note that the results of Fig. 4 allow one to read off the upper bound on the lightest  $\mathcal{CP}$ -even Higgs boson mass in the CMSSM obtained for  $m_t = 173.1\text{ GeV}$  with state-of-the-art theoretical predictions. We find an upper bound of  $m_h \leq 125.2\text{ GeV}$  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 Sect. II, we find an upper value for  $m_h$  of  $127.4\text{ GeV}$ . Saturating the bound on  $m_h$  would still require an improvement of 30% in the signal efficiency to be fully tested at the  $2\sigma$  level; the fact that the minimal improvement is the same for both mass values reflects the flatness of the SM projection curves starting near  $125\text{ GeV}$  in Fig. 1. Including the theoretical errors could push some points below the  $2\sigma$  threshold in the cases of  $16\text{ fb}^{-1}$  with 10% improvements or  $10\text{ fb}^{-1}$  with 50% improvements, or below the  $3\sigma$  thresholds in the case of  $16\text{ fb}^{-1}$  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  $\sim 2\text{ GeV}$  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  $M_{\text{mess}}$ , which is not tied to the GUT scale in general, and evolving the parameters down to the weak scale. At  $M_{\text{mess}}$  the soft masses are controlled by gauge couplings, the number of complete  $SU(5)$   $5 + \bar{5}$  messenger representations  $N_{\text{mess}}$ , and a parameter  $\Lambda$  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



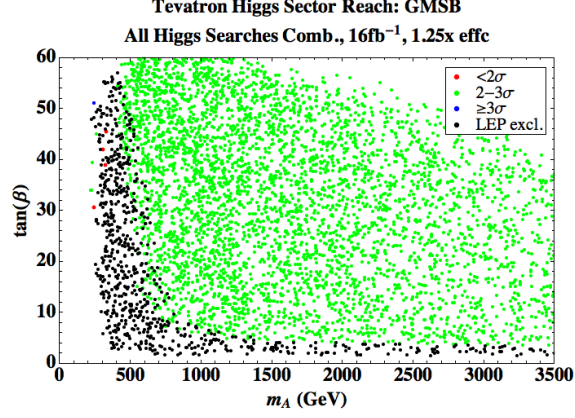


FIG. 6. Projected Tevatron coverage of mGMSB on the  $(m_A, \tan \beta)$  plane with  $16 \text{ fb}^{-1}$  and 25% efficiency improvement (w.r.t. March 2009), which is the approximate threshold for full coverage at the  $2\sigma$  level. (color figures available online)

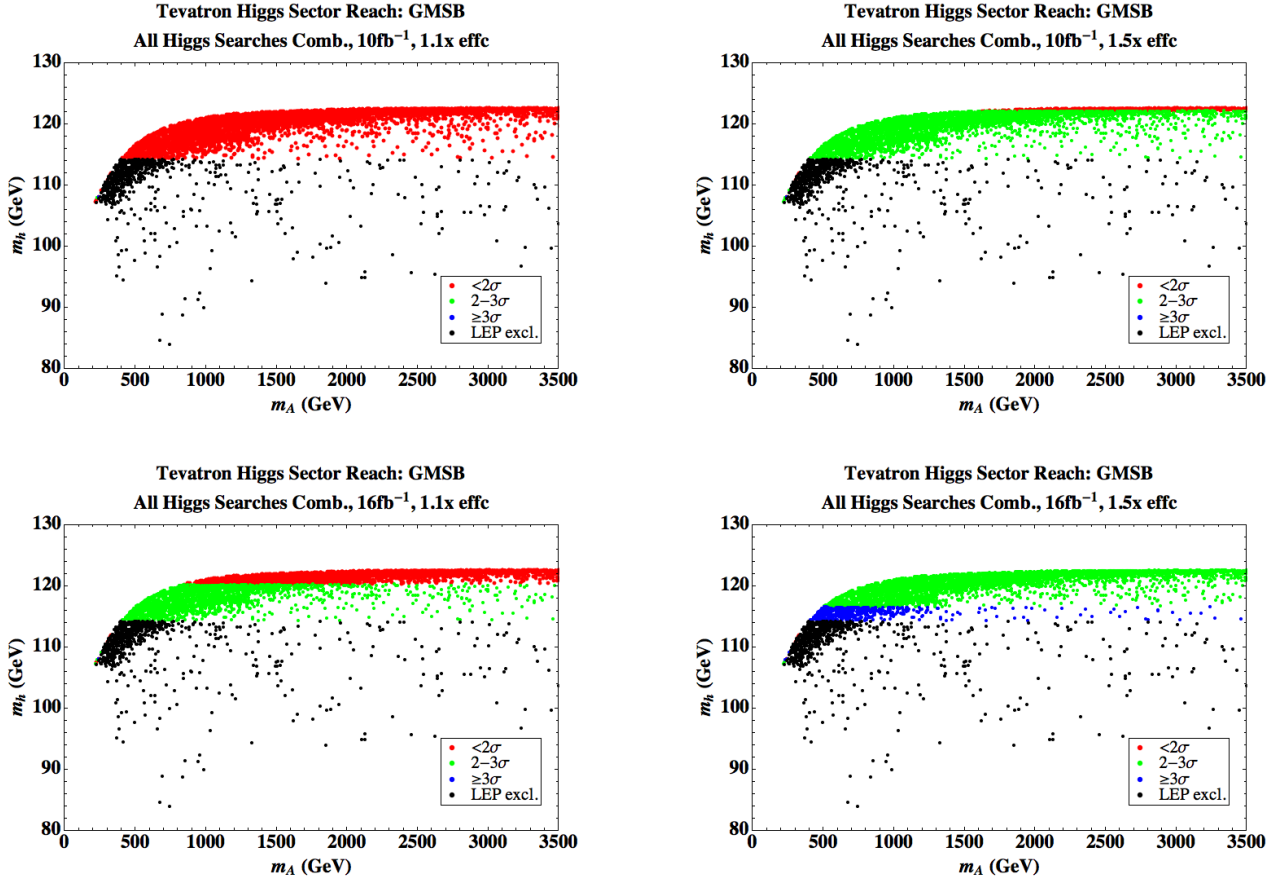


FIG. 7. Projected Tevatron coverage of mGMSB on the  $(m_A, m_h)$  plane with  $10 \text{ fb}^{-1}$  and 10% efficiency improvement (*top left*),  $10 \text{ fb}^{-1}$  and 50% improvement (*top right*),  $16 \text{ fb}^{-1}$  and 10% efficiency improvement (*bottom left*), and  $16 \text{ fb}^{-1}$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

therefore achieve nonzero values at the weak scale only through RG evolution. We scan the input parameters in the ranges

$$10 \text{ TeV} \leq \Lambda \leq 200 \text{ TeV}, \quad \Lambda \leq M_{\text{mess}} \leq 10^5 \times \Lambda, \\ 1 \leq N_{\text{mess}} \leq 8, \quad 1.5 \leq \tan \beta \leq 60. \quad (4)$$

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  $16 \text{ fb}^{-1}$  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  $10 \text{ fb}^{-1}$  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 Fig. 5 and Fig. 7 (and in the corresponding plots for the mAMSB scenario shown below).

For the analyses with  $16 \text{ fb}^{-1}$  and/or further analysis improvements, two main features emerge. Firstly, for the upper bound on the lightest  $\mathcal{CP}$ -even Higgs boson mass in the mGMSB scenario we find  $m_h \leq 122.6 \text{ GeV}$  (for  $m_t = 173.1 \text{ GeV}$ ; the value moves up to  $m_h = 124.9 \text{ GeV}$  if all theory uncertainties as described in Sect. II are taken into account), which is about 2.5 GeV lower than in the 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  $A_t^2 \approx 4m_t^2$  at large  $\tan \beta$  (note that the factor of 4 is due to the on-shell renormalization scheme used in FeynHiggs; in the  $\overline{\text{MS}}$  scheme, the relation is instead  $A_t^2 \approx 6m_t^2$  [68]). Because  $A_t$  is generated by 2-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  $2\sigma$  level with  $10 \text{ fb}^{-1}$  and 50% analysis improvements (and all points are covered at 90% C.L.). It should be noted that for  $16 \text{ fb}^{-1}$ , 50% improvements, and  $m_A \lesssim 500 \text{ GeV}$ ,  $3\sigma$  evidence is expected. This can be understood as follows. The direct dependence of  $m_h$  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  $\Lambda$ . 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  $3\sigma$  sensitivity is obtained. However, we stress that, as shown in Fig. 6, only 15% improvement is necessary (i.e., 25% improvement w.r.t. March 2009) to

achieve the sensitivity to exclude any model point at the 95% C.L. with  $16 \text{ fb}^{-1}$  and therefore to completely rule out this widely studied SUSY scenario. Increasing  $m_h$  by the theory uncertainties discussed in Section II requires an improvement of 20% (30% w.r.t. March 2009) in the signal efficiency to fully cover mGMSB at  $2\sigma$ .

The second important feature apparent in our analysis for the mGMSB model is the absence of a  $3\sigma$  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  $\Lambda$ , the  $\tau$  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 an mGMSB Higgs sector at the Tevatron (with  $16 \text{ fb}^{-1}$  and 50% analysis improvements) will be  $2$ – $3\sigma$  evidence for an SM-like state in the associated production channel with  $m_h < 125 \text{ GeV}$  (including in this upper bound possible contributions from both the theoretical and parametric uncertainties.)

## 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  $M_{\text{aux}}$ , 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  $\beta$ -functions and the anomalous dimensions of the fields. We scan in the ranges

$$0 \leq m_0 \leq 2 \text{ TeV}, \quad 20 \text{ TeV} \leq M_{\text{aux}} \leq 100 \text{ TeV}, \\ 1.5 \leq \tan \beta \leq 60. \quad (5)$$

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  $16 \text{ fb}^{-1}$  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 parameters for each panel as in Fig. 8. For the upper bound on the lightest  $\mathcal{CP}$ -even Higgs boson mass in the mAMSB scenario we find  $m_h \leq 120.5 \text{ GeV}$  (for  $m_t = 173.1 \text{ GeV}$ ; the value moves up to  $m_h = 122.5 \text{ GeV}$  if all theory uncertainties as described in Sect. 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  $16 \text{ fb}^{-1}$  and as little as 5% increase in efficiency (i.e., 15%

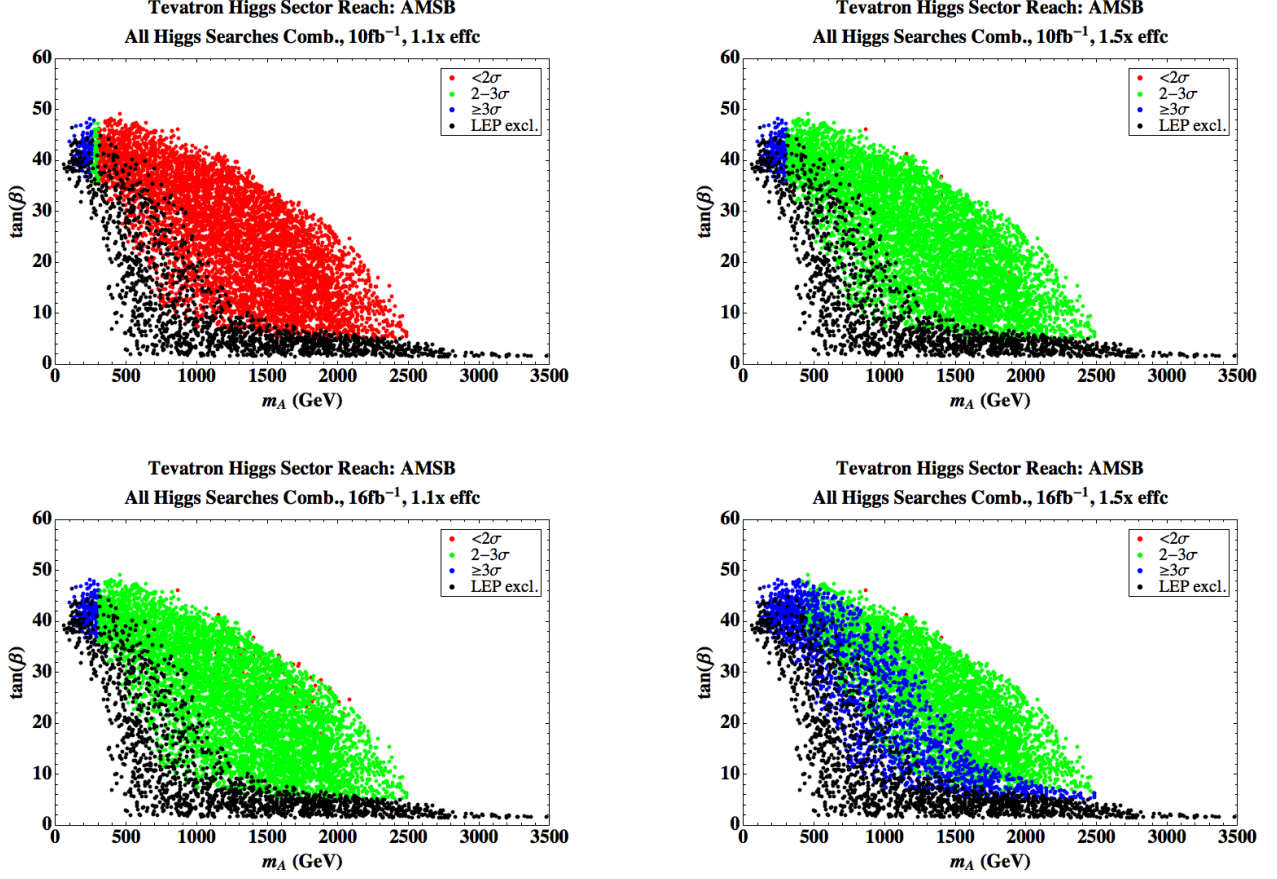


FIG. 8. Projected Tevatron coverage of mAMS B on the  $(m_A, \tan\beta)$  plane with  $10\text{fb}^{-1}$  and 10% efficiency improvement (*top left*),  $10\text{fb}^{-1}$  and 50% improvement (*top right*),  $16\text{fb}^{-1}$  and 10% efficiency improvement (*bottom left*), and  $16\text{fb}^{-1}$ 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

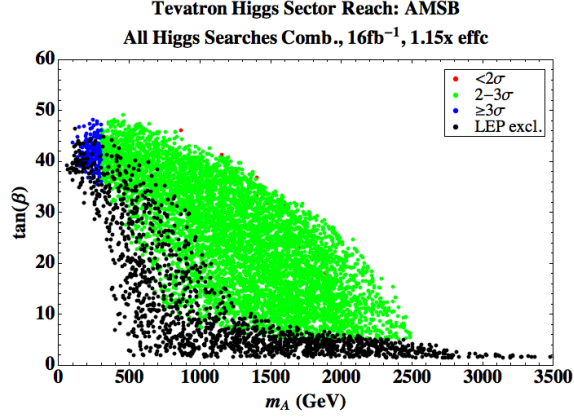


FIG. 9. Projected Tevatron coverage of mAMS B on the  $(m_A, \tan\beta)$  plane with  $16\text{fb}^{-1}$  and 15% efficiency improvement (w.r.t. March 2009), which is the approximate threshold for full coverage at the  $2\sigma$  level. (color figures available online)

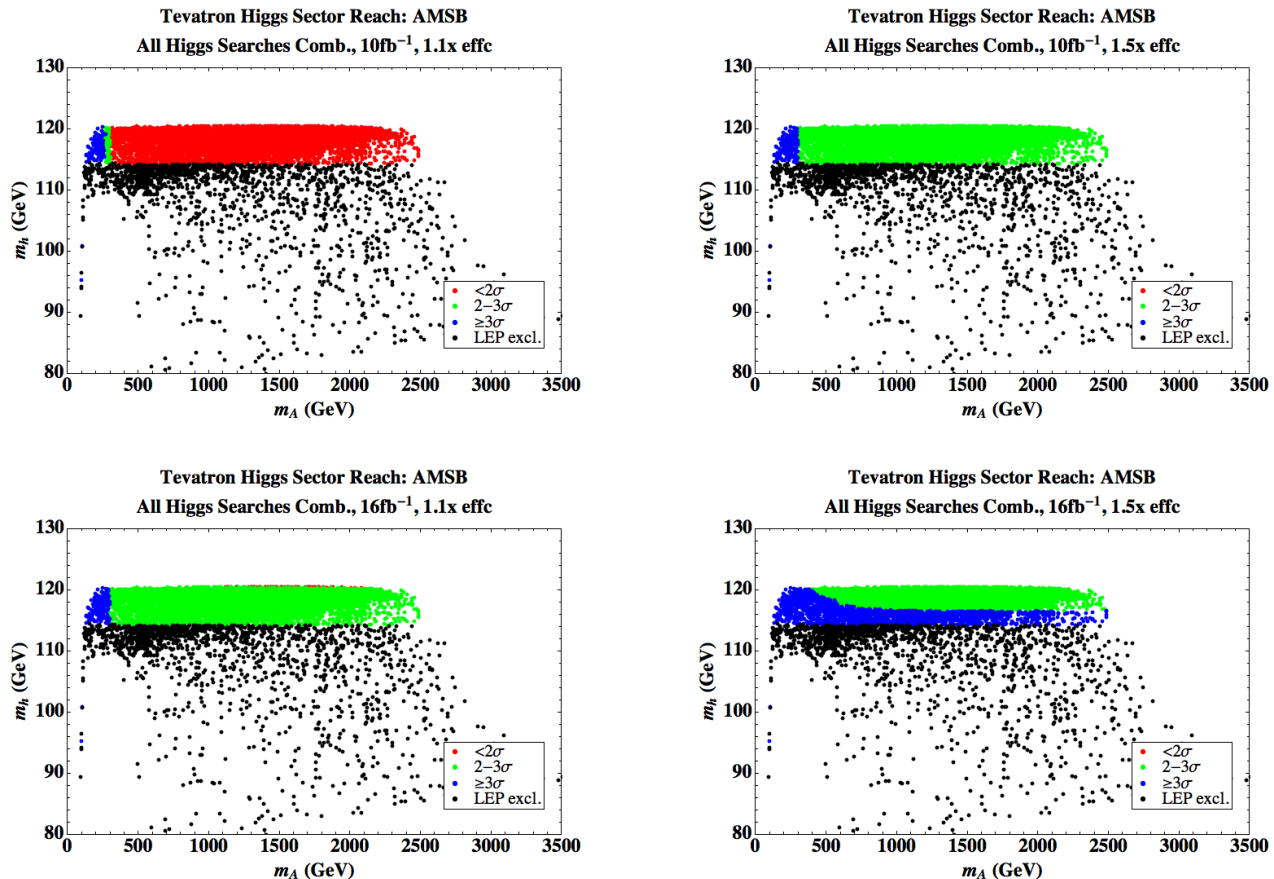


FIG. 10. Projected Tevatron coverage of mAMS B on the  $(m_A, m_h)$  plane with  $10 \text{ fb}^{-1}$  and 10% efficiency improvement (*top left*),  $10 \text{ fb}^{-1}$  and 50% improvement (*top right*),  $16 \text{ fb}^{-1}$  and 10% efficiency improvement (*bottom left*), and  $16 \text{ fb}^{-1}$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

increase as compared to March 2009) there will be  $2\sigma$  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 mAMS B at  $2\sigma$ . For  $16 \text{ fb}^{-1}$  and a 50% increase in efficiency w.r.t. 2009, there is a broad potential for  $3\sigma$  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  $M_{\text{aux}}$  and the  $\beta$ -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  $2\sigma$  level with luminosity gains alone, and the  $3\sigma$  reach for the light Higgs is significant with  $16 \text{ fb}^{-1}$  and 50% improvements.

However, near the largest values of  $m_0$  and smallest values of  $M_{\text{aux}}$ , a few points avoid even  $2\sigma$  sensitivity. In these models the squarks are heavy, pushing up  $m_h$ , while the gaugino masses are light, opening the decay channel  $h \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0$ . 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  $12 \text{ fb}^{-1}$ , and that discovery may occur at the LHC with  $10 \text{ fb}^{-1}$  and  $\sqrt{s} = 14 \text{ TeV}$  in the  $Zh$  channel alone.

## VII. CONCLUSIONS

In this note we have analyzed the physics potential of the Tevatron collider in the context of the MSSM

Higgs sector, based on  $10\text{ fb}^{-1}$  or  $16\text{ fb}^{-1}$  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  $10\text{ fb}^{-1}$ , 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 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  $16\text{ fb}^{-1}$  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  $2\sigma$  (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  $2\sigma$  “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  $16\text{ fb}^{-1}$  per experiment and a 50% improvement in the signal efficiency with respect to the status of March 2009, the opportunity for  $3\sigma$  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  $3\sigma$  coverage in all of the models we considered for  $16\text{ fb}^{-1}$  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  $gg \rightarrow h \rightarrow \gamma\gamma$  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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