Published by Institute of Physics Publishing for SISSA/ISAS

Received: *June 2, 2003*
Accepted: *July 8, 2003*

Reach of the Fermilab Tevatron for minimal supergravity in the region of large scalar masses

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Abstract: The reach of the Fermilab Tevatron for supersymmetric matter has been calculated in the framework of the minimal supergravity model in the trilepton channel. Previous analyses of this channel were restricted to scalar masses $m_0 \leq 1$ TeV. We extend the analysis to large values of scalar masses $m_0 \sim 3.5$ TeV, in order to probe the compelling hyperbolic branch/focus point (HB/FP) region, where the superpotential μ parameter becomes small, and which is one of the mSUGRA parameter space regions consistent with WMAP data. In this region, assuming a 5σ (3σ) signal with 10 (25) fb^{-1} of integrated luminosity, the Tevatron reach in the trilepton channel extends up to $m_{1/2} \sim 190$ (270) GeV independent of $\tan\beta$. This corresponds to a reach in terms of the gluino mass of $m_{\tilde{g}} \sim 575$ (750) GeV.

Keywords: Supersymmetry Phenomenology, Supersymmetric Standard Model, Hadronic Colliders.

http://jhep.sissa.it/archive/papers/jhep072003020/jhep072003020.pdf

JHEP07(2003)020

Run 2 of the Fermilab Tevatron $p\bar{p}$ collider has begun at center of mass energy $\sqrt{s} = 1.96\,\mathrm{TeV}$, and already the CDF and D0 experiments have gathered over 100 pb^{-1} of integrated luminosity. Projections are to acquire anywhere from 2-25 fb^{-1} of integrated luminosity before turn on of the CERN LHC. One prominent goal of Tevatron experiments is to discover the Higgs boson, which may well be within reach according to analyses of electroweak radiative corrections. Another prominent goal is to obtain evidence for weak scale supersymmetric matter.

The search for supersymetry is somewhat model dependent. In this paper, we adopt the paradigm minimal supergravity model (mSUGRA) [1], with parameters

$$m_0\,, \qquad m_{1/2}\,, \qquad A_0\,, \qquad \tan\beta\,, \qquad \mathrm{sign}(\mu)\,. \tag{1}$$

In models such as mSUGRA, with gaugino mass unification and a weak scale gravitino mass, the gluino to chargino mass ratio is $m_{\tilde{g}}/m_{\widetilde{W}_1} \sim 3.7$, so that bounds from LEP2 ($m_{\widetilde{W}_1} > 103.5\,\mathrm{GeV}$) [2] likely place gluino pair production out of reach of Tevatron experiments. Since squark masses are usually comparable to or greater than $m_{\tilde{g}}$, it is likely that squark pair production is beyond the Tevatron reach as well. An exception occurs for third generation squarks- the top and bottom squarks- since these might have much lower masses [3]. In addition, slepton pair production occurs at low enough rates in these models that they are unlikely to be directly observable [4].

However, charginos and neutralinos may well be within the kinematic reach of the Tevatron, and can be produced with observable cross sections. Importnat pair production reactions include

- $p\bar{p} \to \widetilde{W}_1\widetilde{Z}_1 X$,
- $p\bar{p} \to \widetilde{W}_1^+\widetilde{W}_1^- X$ and
- $p\bar{p} \to \widetilde{W}_1\widetilde{Z}_2 X$,

where X represents assorted hadronic debris. The purely hadronic final states suffer large QCD backgrounds, while the leptonic final states have more manageable electroweak backgrounds. The first of these reactions can lead to single lepton plus missing energy states, which suffer large backgrounds from $W \to \ell\nu_\ell$ production (here, $\ell = e$, μ and τ). The second chargino pair reaction suffers large backgrounds from WW and $Z \to \tau\bar{\tau}$ production. The last of these — $\widetilde{W}_1\widetilde{Z}_2$ production — can lead to clean (non-jetty) trilepton plus $\not{E}_T$ final states which can be above SM background levels for significant regions of model parameter space.

The clean trilepton signature was suggested as long ago as 1983 [5], and explicit collider calculations for production via on-shell gauge bosons were performed in refs. [6, 7], including spin correlations between initial and final states. Arnowitt and Nath pointed out that rates may be detectable even for production via off-shell gauge bosons [8]. More detailed projections (based on partial neutralino branching fraction calculations) yielded a pessimistic assessment of the Tevatron reach [9]. Improved sparticle production and decay calculations however showed that in fact the reach of Fermilab Tevatron experiments could extend well past LEP2 for significant regions of model parameter space [10]. This was followed by a number of calculations [11] and collider simulations of clean trilepton detection rates considered against SM backgrounds arising mainly from WZ production [12, 13, 14, 15], with results being extended to large $\tan\beta$ in ref. [16]. Especially for large $\tan\beta$, it was found that the greatest reach was obtained via the inclusive trilepton channel, with jetty events allowed into the trilepton sample [17, 18]. At the Fermilab Tevatron SUSY/Higgs workshop (concluded in year 2000), it was found that in fact the largest backgrounds came from off-shell W^*Z^* and $W^*\gamma^*$ production [19]. These backgrounds were calculated, and cuts were modified to show that in fact the inclusive trilepton signal was still observable over large portions of mSUGRA model parameter space [17, 18, 20, 21, 22]. Reach calculations were made in the m_0 vs. $m_{1/2}$ plane extending out to m_0 values as high as 1 TeV.

Since these previous calculations, a greater emphasis has been placed on mSUGRA model parameter space at large m_0 values. It has been noticed that as m_0 increases, ultimately the superpotential μ parameter, as derived from radiative electroweak symmetry breaking (REWSB), becomes small in magnitude shortly before encountering the region where REWSB breaks down [23]. Chan et al. [24], adopting effectively μ^2/M_Z^2 as a fine-tuning parameter, emphasized that the entire region of small μ^2 at large m_0 may be considered to have low fine tuning; they dubbed the region as the "hyperbolic branch". Later, using more sophisticated fine tuning calculations, Feng et al. [25] showed that just the low $m_{1/2}$ portion of the hyperbolic branch has low fine tuning. The peculiar focussing behavior of the RG running of the soft breaking Higgs mass $m_{H_u}^2$ in this region led to the characterization as the "focus point" region. In this paper, we will refer to the large m_0 region with small $|\mu|$ as the hyperbolic branch/focus point (HB/FP) region.

The large m_0 region of parameter space has received renewed attention as well due to several experimental developments. First, improved evaluations of the neutralino relic density [26]–[30] show four viable regions of mSUGRA model parameter space consistent with recent WMAP and other data sets [31]. These include 1) the bulk region at low m_0 and $m_{1/2}$ where neutralinos may annihilate in the early universe via t-channel slepton exchange, 2) the stau co-annihilation region where $m_{\widetilde{Z}_1} \simeq m_{\tilde{\tau}_1}$ [26], 3) the axial Higgs A annihilation corridor at large $\tan\beta$ [27] and 4) the HB/FP region where the neutralino has a significant higgsino component and can readily annihilate to WW and ZZ pairs in the early universe [28]. A fifth region of squark-neutralino co-annihilation can exist as well for particular values of the A_0 parameter that give rise, for instance, to $m_{\tilde{t}_1} \simeq m_{\widetilde{Z}_1}$ [29].

The bulk region of relic density, which originally seemed most compelling, is difficult to reconcile with LEP2 limits on the Higgs mass, the $b \to s\gamma$ branching fraction, and for $\mu < 0$, the muon anomalous magnetic moment [32, 33]. The stau co-annihilation region is viable, but unless the parameters are just right, the relic density can become either too large or too small. The A-annihilation corridor is also viable, but requires large $\tan\beta$, and usually sparticle masses are beyond the reach of Tevatron searches. The HB/FP region remains viable for almost all $\tan\beta$ values, and since scalar sparticles are typically in the multi-TeV regime, gives a value of $b \to s\gamma$ and a_μ in close accord with SM predictions [32, 33]. Since $|\mu|$ is small in the HB/FP region, then charginos and neutralinos are expected to be light, and hence signals such as the trilepton one may be accessible to Tevatron collider searches.

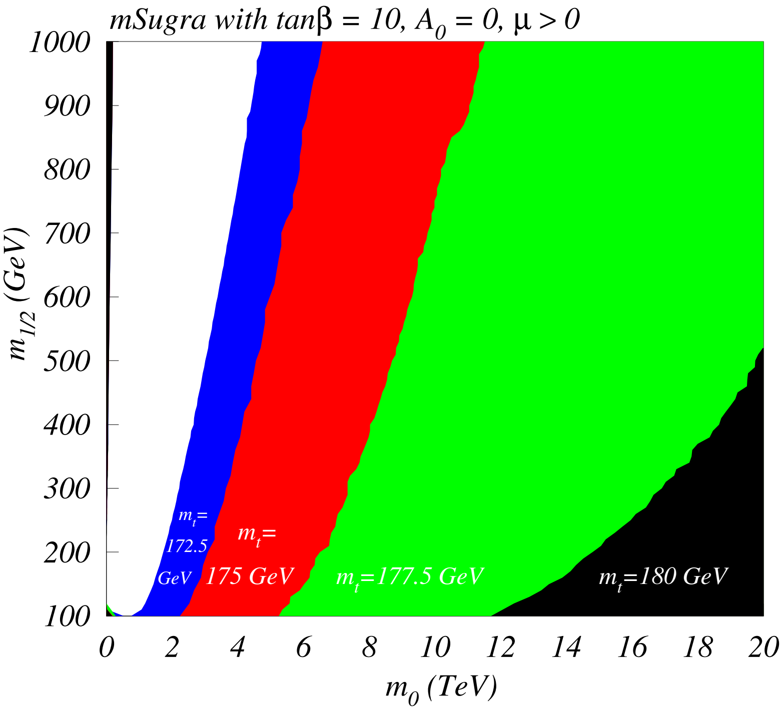

Figure 1: Boundary of the m_0 vs. $m_{1/2}$ parameter plane of the mSUGRA model, with $\tan\beta = 10$, $A_0 = 0$ and $\mu > 0$, for $m_t = 172.5$, 175, 177.5 and 180 GeV.

For these reasons, in this paper we extend the trilepton search results presented in ref. [17] to large values of $m_0 > 1$ TeV, including the HB/FP region. For our signal calculations, we use Isajet v7.66 [34]. This version of Isajet contains 1-loop corrections to all sparticle masses [35], and treats the Higgs potential in the RG-improved one loop effective potential approximation. It yields good overall agreement with other publicly available codes, as documented by Allanach et al. [36], including the location of the HB/FP region. We note, however, that the location of the HB/FP region is very sensitive to the value of m_t adopted in the calculation. To illustrate this, we show in figure 1 the boundary of parameter space in the m_0 vs. $m_{1/2}$ plane for $A_0 = 0$, $\tan\beta = 10$, $\mu > 0$, and for $m_t = 172.5$, 175, 177.5 and 180 GeV. The right-hand boundary, which dictates the location of the HB/FP region, ranges from 2-20 TeV depending on m_t and $m_{1/2}$.

We adopt the SM background calculation as presented in ref. [17]. The backgrounds evaluated include WZ ($Z \to \tau\bar{\tau}$) production, Z^*Z^* production, $t\bar{t}$ production and trilepton production through a variety of $2 \to 4$ Feynman graphs including $W^*\gamma^*$ and W^*Z^* production, as calculated using Madgraph [37]. In ref. [17], a variety of cuts were proposed to reduce background compared to signal. Here, we adopt set SC2 from ref. [17], which generally gave a reach in accord with calculations from refs. [18, 20]. For these cuts, the total $3\ell + \not{E}_T$ background level was found to be 1.05 fb.

Our first results are shown in figure 2, where we show the m_0 vs. $m_{1/2}$ plane for $\tan\beta = 10$, $A_0 = 0$ and $\mu > 0$. Here, and in the rest of this paper, we fix $m_t = 175$ GeV. The red regions are excluded by lack of REWSB (right side) and presence of a stau LSP (left side). The magenta shaded regions are excluded by the LEP2 bound $m_{\widetilde{W}_1} > 103.5\,\mathrm{GeV}$.[1] In addition, the region below the magenta contour has $m_h < 114.1\,\mathrm{GeV}$, in violation of LEP2 limits on the search for a SM Higgs boson. We also show the Tevatron reach contours requiring a 5σ signal for $10\,\mathrm{fb}^{-1}$ of integrated luminosity (solid contour), and a more optimistic contour for a 3σ signal for $25\,\mathrm{fb}^{-1}$ (dashed contour). These correspond to signal cross sections rates of 1.62 fb and 0.61 fb, respectively, after application of cuts SC2 of ref. [17].

The first feature to note is that the LEP2 bound on m_h now excludes essentially all the region that was previously mapped out in refs. [17, 18, 20]. There is some uncertainty of a few GeV with respect to the calculation of m_h (see e.g. ref. [36]), so the magenta contour is not a solid bound on mSUGRA parameter space. In any case, the reach region of the Fermilab Tevatron separates into two regions. The first, for very low m_0 values where sleptons are light, has the $\widetilde{Z}_2 \to \tilde{\ell}\ell$ and $\widetilde{W}_1 \to \tilde{\ell}\nu$ two body decay modes allowed, which dominate the $\widetilde{Z}_2$ and $\widetilde{W}_1$ branching fractions. The large leptonic branching fractions give rise to high rates for trileptons. The second region occurs for $m_0 \gtrsim 300\,\mathrm{GeV}$. As m_0 increases, the slepton masses also increase so that two-body chargino and neutralino decay modes become forbidden. In the region of moderate $m_0 \sim 200\,\mathrm{GeV}$, three-body decays such as $\widetilde{Z}_2 \to \ell\bar{\ell}\widetilde{Z}_1$ can occur, but interference between slepton- and Z-mediated decay graphs give rise [10] to a very tiny leptonic branching fraction for the $\widetilde{Z}_2$, and hence a sharp drop in the Tevatron reach for SUSY via trileptons. As m_0 increases further, the slepton mediated decay diagrams for $\widetilde{Z}_2$ three-body decay are increasingly suppressed, and the decay rate becomes dominated by the Z exchange graph. Ultimately, the branching fraction $\widetilde{Z}_2 \to e^+e^-\widetilde{Z}_1$ increases to $\sim 3\%$, i.e. the same as the Z branching fraction to electrons. Thus the reach of Fermilab Tevatron experiments increases and levels off as m_0 becomes large. However, for very large m_0 values, then we enter the HB/FP region, where $|\mu|$ become small. In this case, chargino and neutralino masses decrease, and the production cross sections rise, yielding an increased reach at very large m_0. From figure 2, we see that the 5σ reach for $10\,\mathrm{fb}^{-1}$ reaches $m_{1/2} \sim 175\,\mathrm{GeV}$ for $m_0 \sim 1000 - 2000\,\mathrm{GeV}$, corresponding to a reach in $m_{\widetilde{W}_1}$ ($m_{\tilde{g}}$) of 125 (525) GeV. The observability of the 3σ signal for $25\,\mathrm{fb}^{-1}$ of integrated luminosity extends to values of $m_{1/2} \sim 210\,\mathrm{GeV}$, corresponding to values of $m_{\widetilde{W}_1}$ ($m_{\tilde{g}}$) ~ 150 (600) GeV. In the HB/FP region, this extends to $m_{1/2} \sim 270\,\mathrm{GeV}$, corresponding to a reach in $m_{\tilde{g}} \sim 750\,\mathrm{GeV}$.

To gain a better understanding of what's happening in the HB/FP region, in figure 3*a* we plot the masses of various charginos and neutralinos and the μ parameter as a function of m_0 for fixed $m_{1/2} = 225\,\mathrm{GeV}$, $A_0 = 0$, $\tan\beta = 30$ and $\mu > 0$. Initially, for $m_0 \sim 1500 - 1700\,\mathrm{GeV}$, the $\widetilde{W}_1$, $\widetilde{Z}_1$ and $\widetilde{Z}_2$ masses are essentially constant with m_0, as might be expected. As we approach the large m_0 HB/FP region, the value of μ drops, and consequently the light chargino and neutralino masses drop, as they become increasingly higgsino-like. As $\mu \to 0$, $m_{\widetilde{W}_1} - m_{\widetilde{Z}_1}$ also approaches zero. However, the LEP2 limit of $m_{\widetilde{W}_1} = 103.5$ is reached before the $\widetilde{W}_1$ and $\widetilde{Z}_1$ become nearly degenerate.

[1] LEP experiments exclude charginos up to 91.9 GeV even if $m_{\widetilde{W}_1} - m_{\widetilde{Z}_1}$ is as small as 3 GeV, so that the LEP excluded region is unlikely to be much altered even in the FP/HB part of parameter space.

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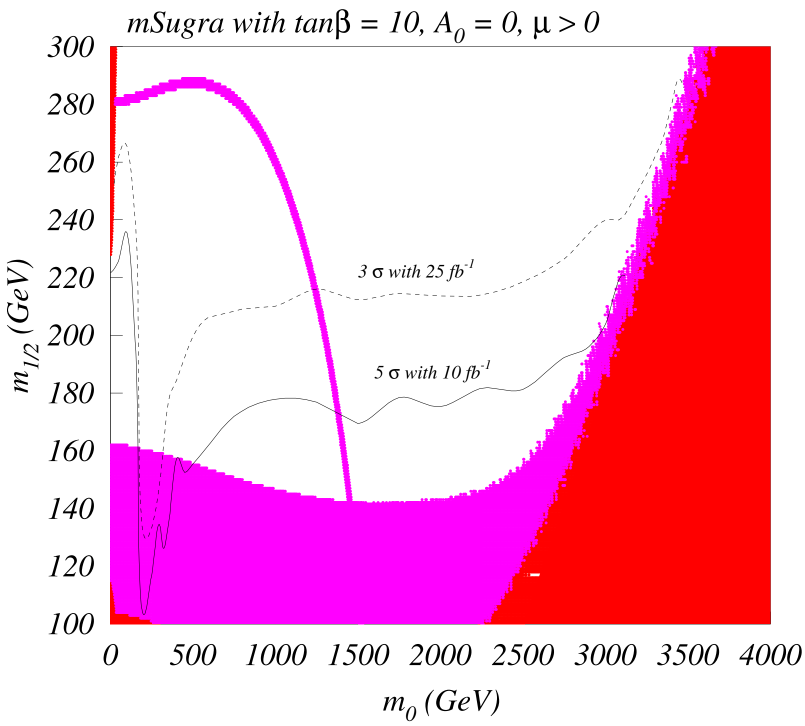

Figure 2: The reach of Fermilab Tevatron in the m_0 vs. $m_{1/2}$ parameter plane of the mSUGRA model, with $\tan\beta = 10$, $A_0 = 0$ and $\mu > 0$, assuming a 5σ signal at $10\,\mathrm{fb}^{-1}$ (solid) and a 3σ signal with $25\,\mathrm{fb}^{-1}$ of integrated luminosity (dashed). The red (magenta) region is excluded by theoretical (experimental) constraints. The region below the magenta contour has $m_h < 114.1\,\mathrm{GeV}$, in violation of Higgs mass limits from LEP2.

In figure 3b, we also show various chargino and neutralino cross sections versus m_0 for the same parameters as in figure 3a. For intermediate values of m_0, $\sigma(\widetilde{W}_1\widetilde{Z}_2)$ and $\sigma(\widetilde{W}_1^+\widetilde{W}_1^-)$ are dominant. As one increases m_0 and approaches the HB/FP region, the various chargino and neutralino masses drop, and the production cross sections increase, giving rise to an increased reach by Tevatron experiments. At the highest m_0 values, actually $\sigma(\widetilde{W}_1\widetilde{Z}_1)$ production has become dominant. In addition, a variety of cross sections such as $\sigma(\widetilde{Z}_1\widetilde{Z}_3)$, $\sigma(\widetilde{Z}_2\widetilde{Z}_3)$, $\sigma(\widetilde{W}_2\widetilde{Z}_4)$, ... are increasing, and their sum can be non-negligible. These heavier -ino states in general have lengthier cascade decays, and can lead to complicated signals including multileptons which may be at the edge of observability.

Figure 4 shows the Tevatron reach in the m_0 vs. $m_{1/2}$ plane for $\tan\beta = 30$, $A_0 = 0$ and $\mu > 0$. In this case, the reach at large m_0 remains large as in the $\tan\beta = 10$ case from figure 2. However, the reach at low m_0 has diminished somewhat, which is an effect of large $\tan\beta$ where the τ and b Yukawa couplings become large, and the $\tilde{\tau}_1$ mass becomes lighter than that of other sleptons. The enhanced chargino and neutralino decays to taus in this region comes at the expense of decays to es and μs, so that the low m_0 3ℓ reach is diminished [16].

The m_0 vs. $m_{1/2}$ plane is shown for $\tan\beta = 45$, with $\mu < 0$ in figure 5. The plot shows even greater reach suppression at low m_0 due to the increase in $\tan\beta$, where an even

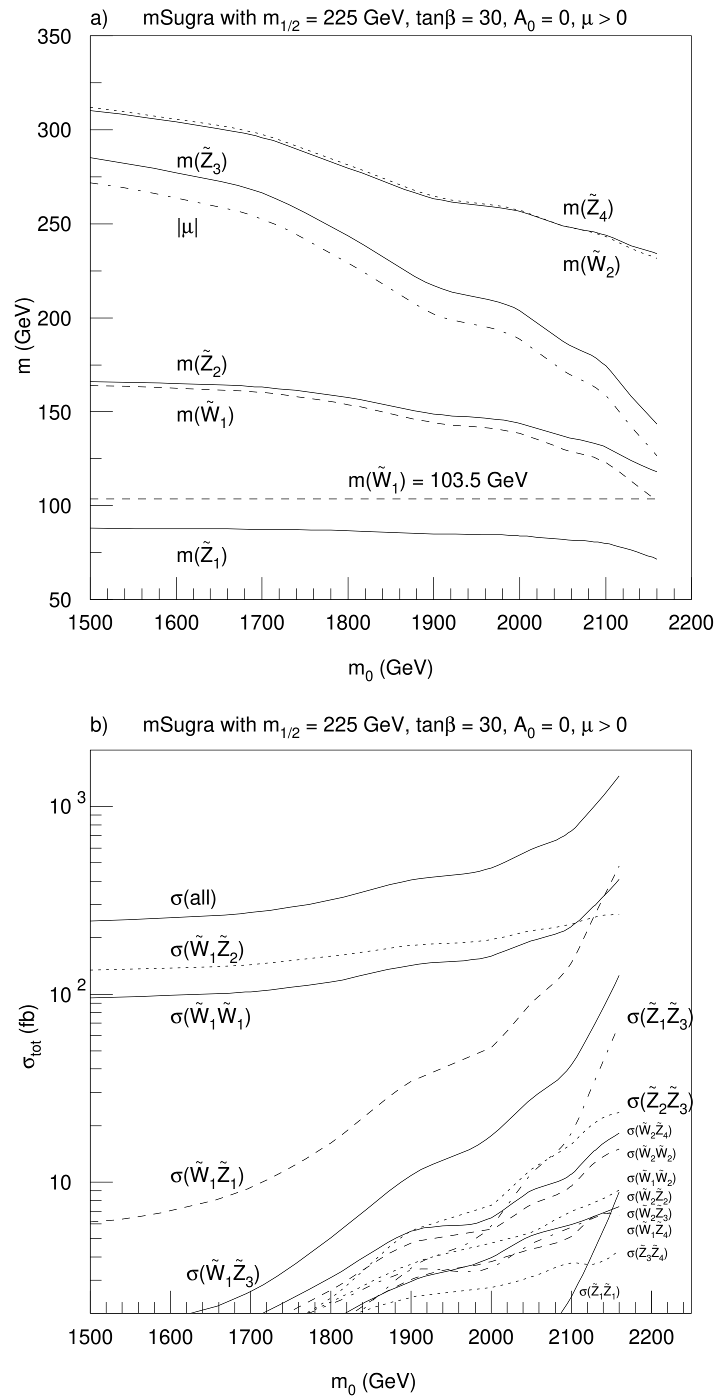

Figure 3: In (a), we show selected sparticle masses versus m_0 in the HB/FP region. In (b), the corresponding total cross sections are shown.

greater suppression of chargino and neutralino decays to es and μs occurs at the expense of decays to τs. Irregardless, as m_0 increases, sleptons, smuons and staus all decouple from the decay calculations, so that results are relatively insensitive to $\tan\beta$, and the reach remains large in the HB/FP region.

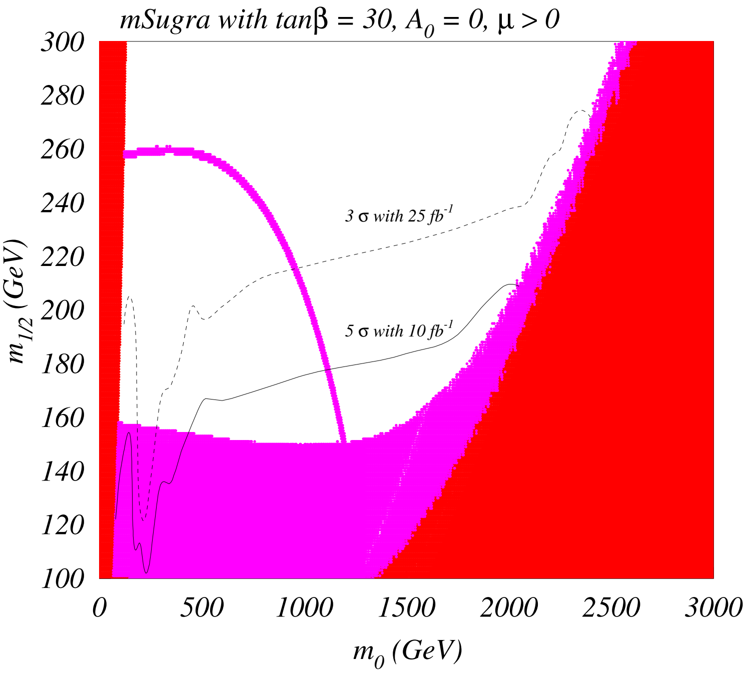

Figure 4: The reach of Fermilab Tevatron in the m_0 vs. $m_{1/2}$ parameter plane of the mSUGRA model, with $\tan\beta = 30$, $A_0 = 0$ and $\mu > 0$. The red (magenta) region is excluded by theoretical (experimental) constraints. The region below the magenta contour has $m_h < 114.1$ GeV, in violation of Higgs mass limits from LEP2.

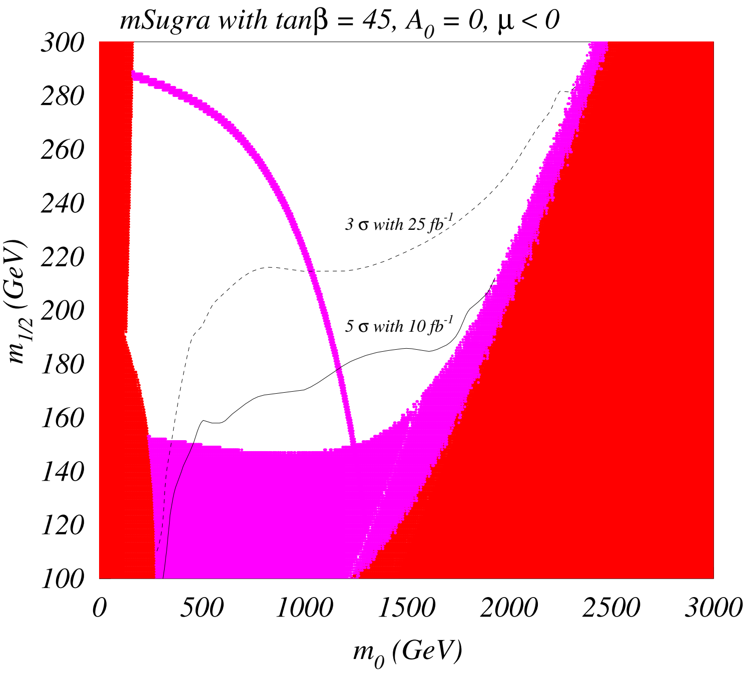

Figure 5: The reach of Fermilab Tevatron in the m_0 vs. $m_{1/2}$ parameter plane of the mSUGRA model, with $\tan\beta = 45$, $A_0 = 0$ and $\mu < 0$. The red (magenta) region is excluded by theoretical (experimental) constraints. The region below the magenta contour has $m_h < 114.1$ GeV, in violation of Higgs mass limits from LEP2.

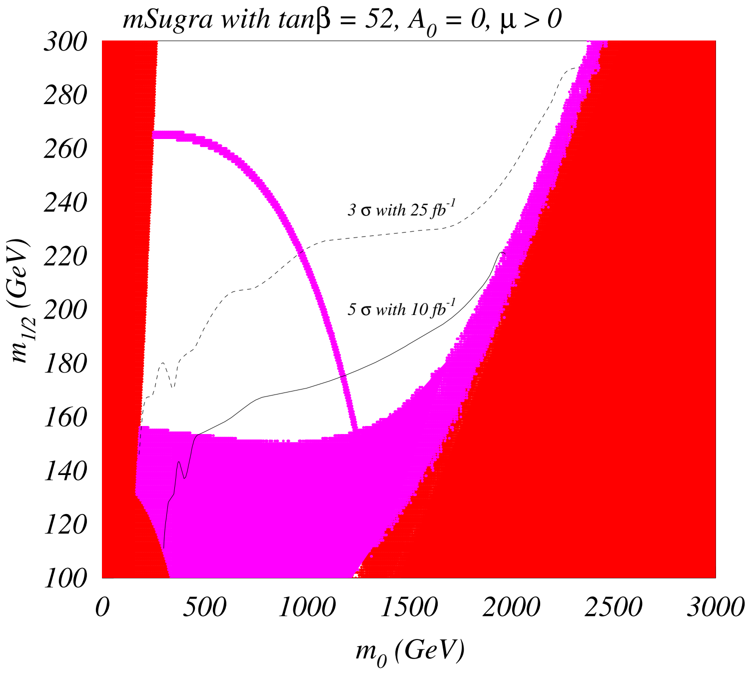

Figure 6: The reach of Fermilab Tevatron in the m_0 vs. $m_{1/2}$ parameter plane of the mSUGRA model, with $\tan\beta = 52$, $A_0 = 0$ and $\mu > 0$. The red (magenta) region is excluded by theoretical (experimental) constraints. The region below the magenta contour has $m_h < 114.1$ GeV, in violation of Higgs mass limits from LEP2.

Finally, in figure 6, we show the mSUGRA plane for $\tan\beta = 52$, $A_0 = 0$ and $\mu > 0$. Again, the reach is diminished for low m_0, but remains substantial for large m_0, especially in the HB/FP region. As with the previous figures, the reach extends to $m_{1/2} \sim 270$ GeV, corrresponding to a value of $m_{\tilde{g}} \sim 750$ GeV.

Summary. In summary, we have evaluated the reach of the Fermilab Tevatron collider for supersymmetry in the framework of the mSUGRA model. The best signature for SUSY appears to be trilepton events orginating from chargino/neutralino production, with subsequent leptonic decays. We have extended previous analyses into the large m_0 region, where significant regions of parameter space are accessible to Tevatron search experiments. This region includes the intriguing HB/FP region, where squarks and sleptons are heavy (thus ameliorating the SUSY flavor and CP problems), while possibly maintaining naturalness [25]. In this region, since μ is decreasing, sparticle production cross sections increase, and Tevatron experiments may be able to find evidence for SUSY out to $m_{1/2}$ values as high as 200-280 GeV depending on the ultimate integrated luminosity which is achieved.

Acknowledgments

We thank K. Matchev for discussions. This research was supported in part by the U.S. Department of Energy under contracts number DE-FG02-97ER41022 and DE-FG03-94ER40833.

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