THE REACH OF THE FERMILAB TEVATRON  
AND CERN LHC FOR  
GAUGINO MEDIATED SUSY BREAKING MODELS

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Abstract

In supersymmetric models with gaugino mediated SUSY breaking (ino\textit{MSB}), it is assumed that SUSY breaking on a hidden brane is communicated to the visible brane via gauge superfields which propagate in the bulk. This leads to GUT models where the common gaugino mass $\tilde{m}_1/2$ is the only soft SUSY breaking term to receive contributions at tree level. To obtain a viable phenomenology, it is assumed that the gaugino mass is induced at some scale $M_c$ beyond the GUT scale, and that additional renormalization group running takes place between $M_c$ and $M_{\text{GUT}}$ as in a SUSY GUT. We assume an SU(5) SUSY GUT above the GUT scale, and compute the SUSY particle spectrum expected in models with ino\textit{MSB}. We use the Monte Carlo program ISAJET to simulate signals within the ino\textit{MSB} model, and compute the SUSY reach including cuts and triggers appropriate to Fermilab Tevatron and CERN LHC experiments. We find no reach for SUSY by the Tevatron collider in the trilepton channel. At the CERN LHC, values of $\tilde{m}_1/2 = 1000$ (1160) GeV can be probed with 10 (100) fb$^{-1}$ of integrated luminosity, corresponding to a reach in terms of $m_{\tilde{g}}$ of 2150 (2500) GeV. The ino\textit{MSB} model and mSUGRA can likely only be differentiated at a linear $e^+e^-$ collider with sufficient energy to produce sleptons and charginos.

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I. INTRODUCTION

Supersymmetric models with weak scale supersymmetric matter are very compelling for a variety of reasons, most important of which is that they solve the gauge hierarchy problem [1]. However, it is safe to say that a compelling model for supersymmetry breaking has yet to emerge. Supergravity models based on SUSY breaking in a hidden sector [2] can give rise to weak scale soft SUSY breaking (SSB) terms with SUSY breaking communicated via gravitational interactions. However, there exists no compelling mechanism in supergravity to suppress the generation of non-universal SSB parameters that lead to unacceptably large flavor violation, sometimes in $CP$-violating processes. Alternatively, in models with gauge mediated SUSY breaking [3], universality of scalars with the same quantum numbers occurs naturally, but at the expense of the introduction of a messenger sector which acts to communicate SUSY breaking to the visible sector. Another intriguing alternative is anomaly-mediated SUSY breaking, an extra dimensional model wherein SUSY breaking on one brane is communicated to the visible sector brane via the superconformal anomaly [4]. The form of the scalar masses again allows a solution to the SUSY flavor (and $CP$) problems. Alas, the minimal version of this model leads to tachyonic slepton masses, although the tachyons can be exorcized in a variety of proposals [5].

An interesting alternative, also based on extra dimensions, is known as gaugino-mediated SUSY breaking (inoMSB) [6]. Like AMSB models, one postulates the existence of both hidden and visible sector branes, spatially separated in an extra dimensional world. However, gauge superfields (and perhaps also Higgs superfields) are allowed to propagate in the bulk. Upon compactification of the extra dimensions, a tree level SSB gaugino mass is generated, but all scalar masses and $A$ (and perhaps $B$) terms are only generated at the loop level, and so are suppressed, and can be justifiably set to zero at the compactification scale. The gravitino can be made heavier than the gauginos; it then decouples and plays no role in our considerations.

Compactification is assumed to occur at or beyond the GUT scale, thus preserving the successful unification of gauge coupling constants [7]. Thus, at the compactification scale, we expect

$$m_{1/2} \neq 0; \quad m_0 \sim A_0 \simeq 0,$$

which are the same boundary conditions that arise in no-scale models [8]. If $M_c$ is taken equal to the GUT scale, then evolution of soft SUSY breaking parameters leads in general to the tau slepton being the lightest SUSY particle (LSP), a result in conflict with cosmological considerations, since then the present day universe would be filled with charged relics, for which there exist stringent limits. A way out, proposed by Schmaltz and Skiba [9], is that $M_c > M_{GUT}$, and that above $M_{GUT}$ some four-dimensional GUT gauge symmetry is valid, such as $SU(5)$ or $SO(10)$. In this case, the additional beyond-the-GUT-scale RGE running leads to large enough slepton masses at $M_{GUT}$ that regions of parameter space exist [10,11] with a neutralino LSP, in accord with cosmological constraints.

1We assume that there are no Higgs fields in the bulk.
In the minimal gaugino mediation model, the bilinear SSB term $B \sim 0$. By minimizing
the scalar potential of the MSSM at the weak scale, the weak scale value of $B$ is related to
the parameter $\tan \beta$. Thus, in minimal gaugino mediation, the value of $\tan \beta$ is predicted,
and found for instance in Ref. [4] to be $\tan \beta \sim 9 - 22$. On a different track, the assumption
of a GUT theory above $M_{GUT}$ frequently implies relations amongst the Yukawa couplings
of the theory, especially for the third generation. Thus, in minimal $SU(5)$ we expect $f_b = f_\tau$
for scales $Q > M_{GUT}$ and in minimal $SO(10)$ we expect $f_b = f_i = f_\tau$, where the $f_i$ are
Yukawa couplings. We adopt the computer program ISAJET v7.58 [10] for calculating RG
evolution. Starting with $\overline{DR}$ fermion masses and gauge couplings at the weak scale, ISAJET
calculates an iterative solution to the relevant set of RGEs of the MSSM by running between
the weak and $GUT$ scales. To test Yukawa coupling evolution, it is imperative to include
SUSY loop corrections to fermion masses at the weak scale [11,12]. It has been found that
a high degree of $f_b - f_\tau$ Yukawa coupling unification at $Q = M_{GUT} \sim 2 \times 10^{16}$ can occur
only for values of $\tan \beta \sim 30 - 50$, and $\mu < 0$. Similarly, a high degree of $f_b - f_\tau - f_i$
Yukawa unification only occurs for $\tan \beta \sim 50$ and $\mu < 0$ [12,13]. We adopt the criteria of
Yukawa coupling unification as being more fundamental than the generation of tiny GUT
scale values of $B$, so that $\tan \beta$ (and the sign of $\mu$) are free parameters, although they are
highly constrained by the requirement of $b - \tau$ unification.

In this paper, we adopt as an example choice a model of gaugino mediation which reduces
to a SUSY $SU(5)$ GUT at the compactification scale. Our goal is to calculate the spectrum
of superpartners at the weak scale, so that collider scattering events may be generated. We
then evaluate the reach of both the Tevatron $p\bar{p}$ and CERN LHC $pp$ colliders for inoMSB
models. In Sec. II we discuss our results for the spectrum of SUSY particles expected in
inoMSB including $SU(5)$ gauge symmetry below $M_{GUT}$. In Sec. III, we present our results
for the reach of the Fermilab Tevatron for inoMSB models. In Sec. IV we present similar results
for the CERN LHC. Finally, we present our conclusions in Sec. V.

II. SPARTICLE MASS SPECTRUM

If the scale at which SSB terms are generated is substantially higher than $M_{GUT}$ (but
smaller than $M_P$) then renormalization group (RG) evolution induces a non-universality at
the GUT scale. The effect can be significant if large representations are present. Here, we
assume that supersymmetric $SU(5)$ grand unification is valid at mass scales $Q > M_{GUT} \simeq
2 \times 10^{16}$ GeV, extending at most to the reduced Planck scale $M_P \simeq 2.4 \times 10^{18}$ GeV. Below $Q =
M_{GUT}$, the $SU(5)$ model breaks down to the MSSM with the usual $SU(3)_C \times SU(2)_L \times U(1)_Y$
gauge symmetry. This model is well described in the work of Polonsky and Pomarol [14].

In the $SU(5)$ model, the $\hat{D}^c$ and $\hat{L}$ superfields are elements of a $\hat{5}$ superfield $\phi$, while the
$\hat{Q}, \hat{U}^c$ and $\hat{E}^c$ superfields occur in the $10$ representation $\hat{\psi}$. The Higgs sector is comprised
of three super-multiplets: $\hat{\Sigma}(24)$ which is responsible for breaking $SU(5)$, plus $\hat{H}_1(\hat{5})$
and $\hat{H}_2(\hat{5})$ which contain the usual Higgs doublet superfields $H_d$ and $H_u$ respectively, which
occur in the MSSM. The superpotential is given by

\[ \hat{f} = \mu_2 tr \hat{\Sigma}^2 + \frac{1}{6} \lambda tr \hat{\Sigma}^3 + \mu H_1 \hat{H}_2 + \lambda \hat{H}_1 \hat{\Sigma} \hat{H}_2 
+ \frac{1}{4} f_t \epsilon_{ijklm} \hat{\psi}^{ij} \hat{\psi}^{kl} \hat{\psi}^m + \sqrt{2} f_v \hat{\psi}^{ij} \phi_i \hat{\psi}_{1j}, \]

(2)
where a sum over families is understood. \( f_t \) and \( f_b \) are the top and bottom quark Yukawa couplings, \( \lambda \) and \( \lambda' \) are GUT Higgs sector self couplings, and \( \mu_\Sigma \) and \( \mu_R \) are superpotential Higgs mass terms.

Supersymmetry breaking is parametrized by the SSB terms:

\[
\mathcal{L}_{\text{soft}} = -m_{H_1}^2 |H_1|^2 - m_{H_2}^2 |H_2|^2 - m_\Sigma^2 tr\{\Sigma \Sigma\} - m_\phi^2 |\phi|^2 - m_{10}^2 tr\{\psi^\dagger \psi\} - \frac{1}{2} M_5 \tilde{\lambda}_\alpha \lambda_\alpha \\
+ \left[ B_{\Sigma \mu \Sigma} tr\Sigma^2 + \frac{1}{6} A_{\lambda} \lambda' tr\Sigma^3 + B_{H \mu H} H_1 H_2 + A_{\lambda} \lambda H_1 \Sigma H_2 \\
+ \frac{1}{4} f_t \epsilon_{ijklm} \psi^i j \psi^{kl} H_2^m + \sqrt{2} A_b f_b \psi^i j \phi_i H_{1j} + \text{h.c.} \right],
\]

where the fields without the carets denote the appropriate scalar components. The various soft masses and gauge and Yukawa couplings evolve with energy according to the renormalization group equations given in Ref. [16,9].

Varying the parameters \( \lambda \) and \( \lambda' \) typically induces small changes only in third generation scalar masses, so that other sparticle masses should not be very sensitive to variations in these parameters.

To generate the weak scale MSSM mass spectrum, one begins with the input parameters

\[
\alpha_{\text{GUT}}, f_t, f_b, \lambda, \lambda'
\]

stipulated at \( Q = M_{\text{GUT}} \), where \( f_b = f_\tau \) is obtained from the corresponding mSUGRA model. The first three of these can be extracted, for instance, from ISASUGRA by finding points in mSUGRA parameter space with \( f_0 = f_\tau \). The couplings \( \lambda(M_{\text{GUT}}) \) and \( \lambda'(M_{\text{GUT}}) \) are additional inputs, where \( \lambda(M_{\text{GUT}}) \gtrsim 0.7 \) \([17]\) to make the triplet Higgsinos heavy enough to satisfy experimental bounds on the proton lifetime. The gauge and Yukawa couplings can be evolved via the RGEs to determine their values at \( Q = M_c \). Assuming universality at \( M_c \), we impose

\[
m_{10} = m_5 = m_{H_1} = m_{H_2} = m_\Sigma \equiv m_0 = 0 \\
A_t = A_b = A_\lambda = A'_\lambda \equiv A_0 = 0,
\]

as boundary conditions that define our \( SU(5) \) inoMSB framework. We then evolve all the \( SU(5) \) soft masses from \( M_c \) to \( M_{\text{GUT}} \). The MSSM soft breaking masses at \( M_{\text{GUT}} \) are specified via

\[
m_Q^2 = m_U^2 = m_E^2 \equiv m_{10}^2, \\
m_D^2 = m_L^2 \equiv m^2, \\
m_{H_u}^2 = m_{H_1}^2, \quad m_{H_d}^2 = m_{H_2}^2,
\]

which can serve as input to ISAJET \([10]\) via the \( NUSUGi \) keywords. Yukawa couplings induce an inter-generation splitting amongst the scalars. Since there is no splitting amongst the gaugino masses, the gaugino masses may be taken to be \( M_1 = M_2 = M_3 \equiv m_{1/2} \) where \( m_{1/2} \) is stipulated most conveniently at the GUT scale.

In Fig. [1], we show the evolution of the various SSB parameters of the MSSM, starting with the inoMSB boundary conditions. Here, the unified gaugino mass is taken to be 400 GeV at \( Q = M_{\text{GUT}} \). The compactification scale is taken to be \( M_c = 10^{18} \) GeV, with \( \tan \beta = 35 \), \( \mu < 0 \), \( \lambda = 1.0 \) and \( \lambda' = 0.1 \). We see that RG evolution results in GUT scale
scalar masses and $A$-parameters that are substantial fractions of $m_{1/2}$; i.e. although we have inoMSB boundary conditions at the scale $M_c$, there are substantial deviations from these at $M_{GUT}$. While the inter-generation splitting is small, the splittings between the 5 and the 10 dimensional matter multiplets, as well as between these and the Higgs multiplets is substantial.

In Fig. 2, we show values of various sparticle and Higgs masses, plus the $\mu$ parameter, as a function of $m_{1/2}$ for $\tan \beta = 35$ and $\mu < 0$. In this plot, we adopt the values of $f_t = 0.489$, $f_b = f_\tau = 0.246$, $g = 0.703$ at the scale $M_{GUT} = 1.52 \times 10^{16}$ GeV. The output values of $m_{10}$ and $m_5$ for first and third generations, and $m_{H_u}$ and $m_{H_d}$ serve as GUT scale inputs for ISAJET to generate the weak scale sparticle masses shown in the figure. We cut off the curves at $m_{1/2} = 285$ GeV below which $m_{\tilde{\tau}_1}$ becomes less than $m_{\tilde{Z}_1}$. Note that the lower limit on $m_{1/2}$ implies that $m_{\tilde{W}_1} > \sim 200$ GeV. The following pattern of sparticle masses occurs:

$$m_{\tilde{Z}_1} < m_{\tilde{\ell}_R} < m_{\tilde{W}_1} < m_{\tilde{\ell}_L} < m_A < m_{\tilde{t}_1} < m_{\tilde{b}_1} < m_{\tilde{q}} < m_{\tilde{g}}.$$  

The large value of $|\mu|$ that occurs means that the $\tilde{Z}_1$ is mainly bino-like, and a good candidate for cold dark matter [7].

Specific sparticle masses for an $m_{1/2} = 400$ GeV case study are shown in Table I, along with an mSUGRA model with a universal GUT scale mass squared that is a weighted average of the corresponding inoMSB values. Many aspects of the spectra shown are similar. However, it is noteworthy that the splitting of the 10 and 5 dimensional representations in inoMSB lead to increased right slepton and decreased left-slepton masses relative to the mSUGRA case. Such a splitting may be measurable at linear $e^+e^-$ colliders; we discuss this further in Sec. V.

### III. REACH OF THE TEVATRON COLLIDER

From the spectra shown in Fig. 2, we see that first and second generation squarks and gluinos have masses of at least 600 GeV, and hence are inaccessible [15] to Tevatron searches due to low production cross sections. Sleptons [19] and third generation squarks [20] are also too heavy to be searched for at the Tevatron. However, charginos and neutralinos may be light enough that $\tilde{W}_1\tilde{W}_1$ and $\tilde{W}_1\tilde{Z}_2$ production serve as the main SUSY production mechanisms at the Tevatron.

Since $m_{\tilde{W}_1} > m_{\tilde{\tau}_1}$, while $m_{\tilde{W}_1} < m_{\tilde{\ell}_L}$, the chargino dominantly decays via $\tilde{W}_1 \rightarrow \tilde{\tau}_1 \nu_\tau$. The neutralino $\tilde{Z}_2$ is mainly wino-like, and so has only a small coupling to $\tilde{\ell}_R$. Thus, even though the decay mode $\tilde{Z}_2 \rightarrow \tilde{\ell}_R \ell$ is open, the decay mode $\tilde{Z}_2 \rightarrow \tilde{\tau}_1 \tau$ is dominant. Thus, we expect signals rich in tau leptons.

The two most promising avenues to explore for Tevatron reach consist of a clean trilepton search [21], where the focus is on soft trileptons originating from tau decays, or for trilepton events where in fact one or more of the identified leptons is a hadronic tau [22].

To estimate the Tevatron reach for inoMSB models with soft trileptons, we adopt the cuts SC2 advocated in the last of Refs. [23–25]. These cuts have been optimized to maintain signal while rejecting backgrounds coming from $WZ$ production, $t\bar{t}$ production and $W^*\gamma^*$ and $W^*Z^*$ production, where the starred entries correspond to off-shell processes. The cuts
include requiring three isolated\textsuperscript{3} leptons (either $e$s or $\mu$s) with $p_T(\ell_1, \ell_2, \ell_3) > 11, 7, 5$ GeV respectively, and with $|\eta(\ell)| < 2$, but including at least one lepton with $p_T > 11$ GeV within $|\eta| < 1$. In addition, a missing energy cut $E_T > 25$ GeV is required. Furthermore, a $Z$ veto $m(\ell\bar{\ell}) < 81$ GeV and a virtual photon veto $m(\ell\bar{\ell}) > 20$ GeV is required for opposite sign/same flavor dilepton pairs. A transverse mass veto $M_T(\ell, \bar{E}_T) < 85$ GeV is also required to reject on and off shell backgrounds including $W$ bosons. The background estimate is then 1.05 fb.

In Fig. 3, we show the isolated trilepton cross section after cuts SC2, along with the signal levels needed to achieve a $5\sigma$ signal at 2 fb$^{-1}$ of integrated luminosity, and a $5\sigma$ or $3\sigma$ signal at 25 fb$^{-1}$. We see that the trilepton signal level corresponds to $< 1$ trilepton event even with an integrated luminosity of 25 fb$^{-1}$ and so appears to be undetectable for the entire range of $m_{1/2}$.

The other possible signal channel is to look for trilepton events where one or more of the leptons is, in fact, a tau identified via its hadronic decay. These can be separated into $\ell\ell\tau$ (opposite-sign), $\ell\ell\tau$ (same-sign), $\ell\tau\tau$ and $\tau\tau\tau$ channels. Signals including tau leptons were first examined in the context of large $\tan\beta$ in Ref. [22], and refined background estimates were presented in Ref. [26]. We adopt the cuts and backgrounds presented in Ref. [26] for our analysis. Following Ref. [26], we define tau jets to be hadronic jets with $|\eta| < 1.5$, net charge $\pm 1$, one or three tracks in a $10^\circ$ cone with no additional tracks in a $30^\circ$ cone, $E_T > 5$ GeV, $p_T > 5$ GeV, plus an electron rejection cut. The cuts that we implement depend on the event topology, and include: two isolated ($E_T(cone) < 2$ GeV) leptons with $p_T > 8$ GeV and $p_T > 5$ GeV, and one identified tau jet with $p_T(\tau) > 15$ GeV for $\ell\ell\tau$ and $\ell\ell\tau$ signatures; two tau jets with $p_T > 15$ GeV and $p_T > 10$ GeV and one isolated lepton with $p_T > 7$ GeV for $\ell\tau\tau$ signature; three tau jets with $p_T > 15, 10$ and $8$ GeV, respectively for $\tau\tau\tau$ signature. For the $\ell\ell\tau$ topology, following Ref. [26], we impose additional cuts for same flavor, opposite sign leptons: $|m(\ell\bar{\ell}) - M_Z| > 10$ GeV and $m(\ell\bar{\ell}) > 11$. To maximize the signal statistics we chose set “A)” from the paper [26]: $E_T > 20$ GeV and no jet veto requirement.

We consider a signal to be observable if (i) the signal to background ratio, $S/B \geq 0.2$, (ii) the signal has a minimum of five events, and (iii) the signal satisfies a statistical criterion $S \geq 5\sqrt{B}$. Our results for signals including tau leptons are shown in Fig. 4. We use the background estimates from Ref. [26] to determine the minimum signal level for observability. These background cross sections for $\ell\ell\tau$, $\ell\ell\tau$, $\ell\tau\tau$ and $\tau\tau\tau$ topologies are 10.7 fb, 0.85 fb, 60.4 fb and 24.7 fb, respectively. We clearly see that signal is, once again, too low to be detectable at luminosity upgrades of the Tevatron. We conclude that in this framework direct detection of sparticles will not be possible at the Tevatron.

\textbf{IV. REACH OF THE CERN LHC}

At the CERN LHC, gluino and squark pair production reactions will be the dominant SUSY production reactions. Gluino and squark production will be followed by cascade

\textsuperscript{3}Leptons with $p_T \geq 5$ GeV are defined to be isolated if the hadronic $E_T$ in a $\Delta R = 0.4$ cone about the lepton is smaller than 2 GeV.
decays \cite{27}, in which a variety of jets, isolated leptons and missing energy will be produced. A variety of signals emerge, and can be classified by the number of isolated leptons present. The signal channels include \( i. \) no isolated leptons plus jets plus \( E_T \) (\( \ell \)), \( ii. \) single isolated lepton plus jets plus \( E_T \) (1\( \ell \)), \( iii. \) two opposite sign isolated leptons plus jets plus \( E_T \) (OS), \( iv. \) two same sign isolated leptons plus jets plus \( E_T \) (SS) and \( v. \) three isolated leptons plus jets plus \( E_T \) (3\( \ell \)).

The reach of the CERN LHC for SUSY has been estimated for the mSUGRA model in Ref. \cite{28,29} at low \( \tan \beta \) and in Ref. \cite{30} at large \( \tan \beta \). We adopt the cuts and background levels presented in Ref. \cite{28}, for our analysis of the signal channels listed above. Hadronic clusters with \( E_T > 100 \) GeV and \( |\eta(\text{jet})| < 3 \) within a cone of size \( R = \sqrt{\Delta \eta^2 + \Delta \phi^2} = 0.7 \) are classified as jets. Muons and electrons are classified as isolated if they have leptons plus jets plus \( \not{T}_\nu \).

The reach of the CERN LHC for SUSY has been estimated for the mSUGRA model in Ref. \cite{28} for our analysis of the signal channels listed above. Hadronic jet: \( 30^\circ \) \( E_T \) less than 100 GeV and \( |\eta(\text{jet})| < 3 \) are chosen to roughly optimize the signal from gluino and squark production. For the leptons \( S \) \( \phi \) also applied the cut on the transverse plane angle \( \Delta \phi(\vec E_T, j_c) \) between \( \vec E_T \) and closest jet: \( 30^\circ < \Delta \phi < 90^\circ \), in the case of the \( E_T \) channel, \( i \).

Following Ref. \cite{28}, we required that the jet multiplicity, \( n_{\text{jet}} \geq 2 \), transverse sphericity \( S_T > 0.2 \), \( E_T(j_1) \), and further, that \( E_T(j_2) > E_T^c \) and \( E_T > E_T^c \), where the cut parameter \( E_T^c \) is chosen to roughly optimize the signal from gluino and squark production. For the leptons we require \( p_T(\ell) > 20 \) GeV \( (\ell = e \) or \( \mu \) \) and \( M_T(\ell, E_T) > 100 \) GeV for the 1\( \ell \) signal. For the OS, SS and 3\( \ell \) channels, we require that the two hardest leptons have \( p_T \geq 20 \) GeV. We have also applied the cut on the transverse plane angle \( \Delta \phi(\vec E_T, j_c) \) between \( \vec E_T \) and closest jet: \( 30^\circ < \Delta \phi < 90^\circ \), in the case of the \( E_T \) channel, \( i \).

Our results for the \( E_T \) signal channel are shown in Fig. \ref{fig:reach} for choices of the cut parameter \( E_T^c = 100, 300 \) and, for the \( E_T \) and 1\( \ell \) channels, also 500 GeV. The error bars denote the statistical uncertainty in our Monte Carlo calculation. The solid (dashed) horizontal mark on each curve denotes the minimum cross section needed for discovery, incorporating the three criteria listed in the last section, for an integrated luminosity of 10 (100) fb\(^{-1} \). For those values of \( E_T^c \) where the reach is limited by the \( S/B \geq 0.2 \) requirement, increasing the integrated luminosity does not improve the reach, and we have no dashed horizontal line. Although the signal is largest for the softer cuts, larger \( E_T^c \) values (corresponding to harder cuts) are more effective in selecting signal events over background for very heavy squarks and gluinos. This is why the reach is maximized for the largest \( E_T^c \) value for which the signal still leaves an observable number of events. Thus, in the \( E_T \) channel, the 5\( \sigma \) reach is found to be 925 (1100) GeV in the parameter \( m_{1/2} \) for 10 (100) fb\(^{-1} \). This corresponds to a reach in \( m_\tilde{g} \) of 2000 (2400) GeV, respectively.

The corresponding situation for the 1\( \ell \) channel is shown in Fig. \ref{fig:reach}. Once again, the largest reach is obtained for \( E_T^c = 500 \) GeV. We see that \( m_{1/2} = 1000 \) (1160) GeV should be accessible for 10 (100) fb\(^{-1} \) of integrated luminosity, corresponding to a reach in \( m_\tilde{g} \) of 2150 (2500) GeV.

For channels with \( \geq 2 \) leptons, we have conservatively restricted our analysis to \( E_T^c \) smaller than 300 GeV, because for larger values of this cut parameter, the estimates of the SM backgrounds may have considerable statistical fluctuations. The results for the opposite sign (OS) dilepton channel is shown in Fig. \ref{fig:reach}, where the reach with \( E_T^c = 300 \) GeV is found to be \( m_{1/2} = 750 \) (900) GeV for 10 (100) fb\(^{-1} \) of integrated luminosity, corresponding to a reach in \( m_\tilde{g} \) of \( \sim 1650 \) (1950) GeV. The expectation for the same sign (SS) dilepton channel is shown in Fig. \ref{fig:reach}, where the reach with \( E_T^c = 300 \) GeV is found to be \( m_{1/2} = 800 \) (925) GeV for 10 (100) fb\(^{-1} \) of integrated luminosity, corresponding to a reach in \( m_\tilde{g} \) of 1700 (2000)
GeV. Finally, for the $3\ell$ channel shown in Fig. 9, the reach with $E_T = 300$ GeV is found to be essentially the same as that for the $SS$ channel.

Thus, for inoMSB, we expect a robust signal for SUSY in a variety of channels, with the $1\ell$ channel offering the best ultimate reach for SUSY, corresponding to $m_{\tilde{g}}$ up to 2.1-2.5 TeV, for an integrated luminosity of 10-100 fb$^{-1}$.

V. CONCLUSIONS

In this paper we have addressed the question of discovery reach for SUSY breaking models with gaugino mediated SUSY breaking. These models give rise to “no-scale” boundary conditions for SSB parameters. The boundary conditions are assumed valid at a scale $M_c$ beyond the GUT scale, but somewhat below the Planck scale. A four dimensional SUSY GUT model is assumed valid at these high scales, and for definiteness, we chose a model based on $SU(5)$ gauge symmetry. Simple models based on $SO(10)$ gauge symmetry are more difficult to accommodate, since they must obey the more stringent condition of $t - b - \tau$ Yukawa coupling. Such Yukawa unified solutions are difficult to reconcile with the constraint of radiative EWSBW and no-scale type boundary conditions.

We found that the Fermilab Tevatron has no reach for sparticles in the inoMSB model. This occurs for several reasons. First, gluinos and squarks are beyond the reach of the Tevatron. Second, charginos and neutralinos dominantly decay to third generation leptons and sleptons, and taus are more difficult to detect than $e$s and $\mu$s. Moreover, the lower limit on parameter space implies $m_{\tilde{W}_1} \gtrsim 200$ GeV, so there is not a lot of sparticle production cross section to begin with. Finally, since $m_{\tilde{\tau}_1} \simeq m_{\tilde{Z}_1}$ at the lower values of allowed $m_{1/2}$, the stau decays give rise to very soft visible decay products, reducing greatly the efficiency to detect signals including hadronic taus.

On the other hand, the CERN LHC has a substantial reach for inoMSB models. In this case, we expect gluino and squark pair production to dominate, so that a variety of cascade decay signals will be present if $m_{1/2}$ is not too large. We find the greatest reach via the $E_T$ and $1\ell$ channels, where there should be observable signals for gluinos as heavy as 2150 (2500) GeV for 10 (100) fb$^{-1}$ of integrated luminosity. If gluinos are lighter than $\sim 1700$ (2000) GeV, there should be confirmatory signals also in the OS, SS and $3\ell$ channels. These reach values are comparable to expectations within the mSUGRA framework, which is not surprising in that the sparticle mass spectra for the two models are not that different. Although we have performed our analysis assuming that there are no Higgs fields in the bulk, we expect that our conclusions about the LHC reach will be qualitatively unchanged even if this is not the case. The reason is that gaugino and scalar masses for the first two generations are insensitive to our boundary condition $m_{H_u} = m_{H_d} = 0$. We also expect that our estimates of the SUSY reach of the LHC are insensitive to the couplings in the GUT Higgs sector.

The question then arises whether the inoMSB and mSUGRA models can be differentiated by collider experiments. The main spectral difference between the two models arises due to the non-universal GUT scale scalar masses arising in the inoMSB model. Most noticeably, the splitting between the $10$ and $5$ of $SU(5)$ gives rise to heavier right-sleptons and lighter left-sleptons in the inoMSB model compared to mSUGRA with a similar overall spectrum.
(see Table I). Differentiation of the two models is a very difficult task to accomplish at the CERN LHC.

However, a method has recently been proposed to differentiate models with GUT scale scalar mass non-universality from the mSUGRA framework at $e^+e^-$ linear colliders [31]. These authors have proposed that the measurable quantity

$$
\Delta = m_{\tilde{e}_R}^2 - m_{\tilde{e}_L}^2 + \frac{m_{W_1}^2}{2\alpha_2(m_{W_1})} \left[ \frac{3}{11} (\alpha_1^2(m_\tilde{e}) - \alpha_1^2(M_{GUT})) - 3(\alpha_2^2(m_\tilde{e}) - \alpha_2^2(M_{GUT})) \right],
$$

(8)
could be used to differentiate the two classes of models. This quantity $\Delta$ is expected to be small, within the range $-4000 \text{ GeV}^2 < \Delta < 2000 \text{ GeV}^2$ for mSUGRA, while it is expected to be much larger in the inoMSB framework. For instance, for the case study in Table I, $\Delta \sim 15,000 \text{ GeV}^2$. The difference is sufficiently large so that the two models should be distinguishable via precision measurements at a linear $e^+e^-$ collider where chargino and selectron masses can be determined to about 1-2%.

In conclusion, if nature has chosen to be described by inoMSB model with an $SU(5)$ gauge symmetry above the GUT scale, then we may expect a SUSY Higgs boson discovery at the luminosity upgrade of the Tevatron, but no sign of sparticles. Conversely, we would expect a SUSY discovery at the CERN LHC (unless sparticle masses are so heavy they are in the fine-tuned region of SUSY parameter space, with $m_\tilde{g} > 2500$ GeV). However, the underlying model will not be revealed until a sufficient data set has been accumulated at a linear $e^+e^-$ collider, where precision measurements of sparticle masses would point to an inoMSB model with a $SU(5)$ GUT symmetry.

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4Note that the theoretical expectation for $\Delta$ is slightly different than shown in Ref. [31] because the quantity $S_{GUT}$ (defined therein) is now just $m_{\tilde{H}_2}^2 - m_{\tilde{H}_1}^2$. 

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TABLE I. GUT scale SSB parameters and weak scale sparticle masses and parameters (GeV) for mSUGRA and inoMSB case studies with $m_{1/2} = 400$ GeV, $\tan \beta = 35$ and $\mu < 0$.

| parameter | mSUGRA | inoMSB |
|-----------|--------|--------|
| $m_{10}(1)$ | 205.2 | 233.3 |
| $m_{10}(3)$ | 205.2 | 226.8 |
| $m_{5}(1)$ | 205.2 | 190.5 |
| $m_{5}(3)$ | 205.2 | 188.5 |
| $m_{H_d}$ | 205.2 | 134.9 |
| $m_{H_u}$ | 205.2 | 128.0 |
| $A_t$ | -148.4 | -157.9 |
| $A_b$ | -148.4 | -139.0 |
| $f_t(M_{GUT})$ | 0.497 | 0.489 |
| $f_b(M_{GUT})$ | 0.287 | 0.246 |
| $m_{\tilde{g}}$ | 916.6 | 919.5 |
| $m_{\tilde{u}_L}$ | 836.5 | 843.8 |
| $m_{\tilde{d}_R}$ | 805.5 | 801.8 |
| $m_{\tilde{t}_1}$ | 622.0 | 629.4 |
| $m_{\tilde{b}_1}$ | 691.2 | 689.6 |
| $m_{\tilde{\ell}_L}$ | 340.6 | 331.8 |
| $m_{\tilde{\ell}_R}$ | 256.3 | 279.8 |
| $m_{\tilde{\nu}_e}$ | 331.1 | 322.1 |
| $m_{\tilde{\nu}_1}$ | 193.0 | 210.5 |
| $m_{\tilde{\nu}_\tau}$ | 318.9 | 310.0 |
| $m_{\tilde{W}_1}$ | 303.5 | 304.9 |
| $m_{Z_2}$ | 303.3 | 304.8 |
| $m_{Z_1}$ | 162.4 | 162.5 |
| $m_h$ | 117.7 | 117.7 |
| $m_A$ | 376.1 | 379.8 |
| $m_{H^+}$ | 386.8 | 390.3 |
| $\mu$ | -515.1 | -539.3 |
FIG. 1. Evolution of SSB masses in the $SU(5)$ model from $M_c$ to $M_{GUT}$, for $\tan \beta = 35$, $\mu < 0$, $\lambda = 1.0$ and $\lambda' = 0.1$, for $m_{1/2} = 400$ GeV.

FIG. 2. Mass values of various SUSY particles and $\mu$ parameter in the $SU(5)$ inoMSB model with $\tan \beta = 35$ and $\mu < 0$ versus the GUT scale common gaugino mass $m_{1/2}$. The lighter chargino and $\tilde{Z}_2$ are essentially degenerate, and $\tilde{e}_L$ is slightly heavier.
FIG. 3. Cross section after cuts SC2 of Ref. [25] for trilepton events at the Fermilab Tevatron. The horizontal lines denote the minimum cross section for the signal to be observable.

FIG. 4. Cross section after cuts of Ref. [26] for trilepton events including identified hadronically decaying tau leptons at the Fermilab Tevatron. The horizontal lines denote the minimum cross section for the signal to be observable.
FIG. 5. Cross section after cuts of Ref. [28] for $E_T + jets$ events at the CERN LHC for $E_T$ values of 100, 300 and 500 GeV. For each $E_T$ value, the reach is given by the horizontal solid (dashed) line for 10 (100) fb$^{-1}$ of integrated luminosity.

FIG. 6. Cross section after cuts of Ref. [28] for $1\ell + \not{E}_T + jets$ events at the CERN LHC for $E_T$ values of 100, 300 and 500 GeV. For each $E_T$ value, the reach is given by the horizontal solid (dashed) line for 10 (100) fb$^{-1}$ of integrated luminosity.
FIG. 7. Cross section after cuts of Ref. [28] for OS dilepton+$\not{E}_T$+jets events at the CERN LHC for $E_T^c$ values of 100 and 300 GeV. For each $E_T^c$ value, the reach is given by the horizontal solid (dashed) line for 10 (100) fb$^{-1}$ of integrated luminosity.

FIG. 8. Cross section after cuts of Ref. [28] for SS dilepton+$\not{E}_T$+jets events at the CERN LHC for $E_T^c$ values of 100 and 300 GeV. For each $E_T^c$ value, the reach is given by the horizontal solid (dashed) line, for 10 (100) fb$^{-1}$ of integrated luminosity.
FIG. 9. Cross section after cuts of Ref. [28] for 3ℓ + ET + jets events at the CERN LHC for ET values of 100 and 300 GeV. For each ET value, the reach is given by the horizontal solid (dashed) line for 10 (100) fb⁻¹ of integrated luminosity.