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Probing minimal supergravity at the CERN LHC for large tan β

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For large values of the minimal supergravity model parameter tan β, the tau lepton and the bottom quark Yukawa couplings become large, leading to reduced masses of τ sleptons and b squarks relative to their first and second generation counterparts, and to enhanced decays of charginos and neutralinos to τ leptons and b quarks. We evaluate the reach of the CERN Large Hadron Collider (LHC) pp collider for supersymmetry in the MSUGRA model parameter space. We find that values of $m_{\tilde{g}} \sim 1500-2000$ GeV can be probed with just 10 fb^{-1} of integrated luminosity for tan β values as high as 45, so that MSUGRA cannot escape the scrutiny of LHC experiments by virtue of having a large value of tan β. We also perform a case study of an MSUGRA model at $\tan\beta = 45$ where $\widetilde{Z}_2 \to \tau\tilde{\tau}_1$ and $\widetilde{W}_1 \to \tilde{\tau}_1 \nu_\tau$ with $\sim 100\%$ branching fraction. In this case, at least within our simplistic study, we show that a di-tau mass edge, which determines the value of $m_{\widetilde{Z}_2} - m_{\widetilde{Z}_1}$, can still be reconstructed. This information can be used as a starting point for reconstructing SUSY cascade decays on an event-by-event basis, and can provide a strong constraint in determining the underlying model parameters. Finally, we show that for large tan β, there can be an observable excess of τ leptons, and argue that τ signals might serve to provide new information about the underlying model framework. [S0556-2821(99)04205-8]

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I. INTRODUCTION

The minimal supergravity model (MSUGRA) [1] provides a well-motivated and economical realization of the minimal supersymmetric standard model [2] (MSSM). In MSUGRA, supersymmetry is broken in the ''hidden sector'' which consists of fields which couple to the fields of the MSSM only gravitationally. Thus, supersymmetry (SUSY) breaking is communicated to the visible sector MSSM fields via interactions of gravitational strength. The technical assumption of minimality implies that kinetic terms for matter fields take the canonical form; this assumption, which is equivalent to assuming an approximate global $U(n)$ symmetry between n chiral multiplets, leads to a common mass squared m_0^2 (defined at a high scale $M_X \sim M_{GUT} - M_{Planck}$) for all scalar fields, and a common trilinear scalar coupling A_0 for all A parameters. These parameters, which determine the sparticle-particle mass splitting in the observable sector, are taken to be of similar magnitude as the weak scale, M_{weak}. In addition, motivated by the apparently successful gauge coupling unification in the MSSM, one usually adopts a common value $m_{1/2}$ for all gaugino masses at the scale $M_{GUT} \simeq 2 \times 10^{16}$ GeV. For simplicity, it is commonly assumed that in fact, the scalar masses and trilinear terms unify at M_{GUT} as well. The resulting effective theory, valid at energy scales $E < M_{GUT}$, is then just the MSSM with the usual soft SUSY breaking terms unified at M_{GUT}. The soft SUSY breaking scalar and gaugino mases, the trilinear A terms and, in addition, a bilinear soft term B, the gauge and Yukawa couplings and the supersymmetric μ term are all then evolved from M_{GUT} to some scale $M \simeq M_{weak}$ using renormalization group equations (RGE's). The large top quark Yukawa coupling causes the squared mass parameter of one of the Higgs fields H_u to be reduced. For phenomenologically viable choices of parameters, $m_{H_u}^2$ becomes negative so that electroweak symmetry is spontaneously broken, and μ^2 can be determined in terms of M_Z^2. It is customary to trade the parameter B for tan β, the ratio of Higgs field vacuum expectation values. Finally, it is assumed that superpotential interactions conserve R-parity. The resulting weak scale spectrum of superpartners and their couplings can thus be derived in terms of four continuous plus one discrete parameters

$$m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ \text{and}\ \mathrm{sgn}(\mu), \tag{1.1}$$

in addition to the usual parameters of the standard model (SM).

The implications of the MSUGRA model for supersymmetry searches at the CERN Large Hadron Collider (LHC) have been examined by several groups in Refs. [3–7]. In Refs. [4] the reach of the LHC for SUSY via a variety of search channels has been obtained. In channels with jets plus missing transverse momentum $\not{E}_T$ plus 0–3 isolated leptons, values of $m_{\tilde{g}} \sim 1500-2000$ GeV could be probed with just 10 fb^{-1} of integrated luminosity. This compares well with the reach obtained CMS and ATLAS studies [3] using somewhat different strategies to isolate the signal. In addition, for part of this parameter space, a characteristic edge [8] in the dilepton mass spectrum gave precision information on the mass difference $m_{\widetilde{Z}_2} - m_{\widetilde{Z}_1}$. This measurement could be used as a starting point in various ''case studies'' to reconstruct ultimately many of the sparticle masses in cascade decay chains [5,6]. These studies, using the event generator ISAJET [9], were at the time limited to low values of the parameter $\tan\beta \lesssim 10$.

For higher values of the parameter $\tan\beta$, the b quark and τ lepton Yukawa couplings can become large. This can affect SUSY phenomenology in several ways.

Large b and τ Yukawa couplings cause the $m^2_{\tilde{\tau}_{L/R}}$ and $m^2_{\tilde{b}_{L/R}}$ soft SUSY breaking masses to run to weak scale values that are lower than the corresponding mass terms for first and second generation squarks and sleptons. Also, for large values of $\tan\beta$, there can be large off-diagonal mixing in sbottom and stau mass matrices. Together, these effects can make the physical stau and sbottom mass eigenvalues significantly lower than their first and second generation squark and slepton counterparts [10].

Contributions to the renormalization group equation (RGE) proportional to the squared b and τ Yukawa couplings reduce the mass of the CP-odd Higgs boson m_A, which in turn reduces the masses of the CP-even Higgs boson H and of the charged Higgs boson [10]. The upper bound on $\tan\beta$ is often determined by the experimental lower bound on m_A.

The relatively lower stau and sbottom masses result in larger production cross sections for third generation SUSY particles compared to first and second generation SUSY particles.

The large τ and b Yukawa couplings, along with relatively light values of $\tilde{b}_i$ and $\tilde{\tau}_i$ masses can yield enhanced decays of gluinos to b quarks [10,11] and of charginos and neutralinos to τ leptons and b quarks [12,13].

As a result, for large values of $\tan\beta$, we expect SUSY events to contain many more b quarks and τ leptons than anticipated in earlier studies that were mostly carried out for relatively low values of $\tan\beta$. Recently, a number of improvements [12] have been made[1] to the event generator ISAJET [9] to allow realistic event generation in supersymmetric models even if $\tan\beta$ is large.

The consequences of the MSUGRA model at large $\tan\beta$ for the Fermilab Tevatron collider have been examined in Ref. [13]. In this study, it was found that for large $\tan\beta$, significantly fewer hard isolated e's and μ's are produced in SUSY events, so that the reach for SUSY in various isolated lepton channels is greatly *reduced* compared to the corresponding reach at low $\tan\beta$. For instance, much of the reach of the Fermilab Main Injector (and possible luminosity upgrades thereof) comes from $\widetilde{W}_1\widetilde{Z}_2 \to 3l$ production [15], where $l=e$ or μ, if $\tan\beta$ is small. However, for high $\tan\beta$ values, decays such as $\widetilde{W}_1 \to \tau\nu\widetilde{Z}_1$ and $\widetilde{Z}_2 \to \tau\bar{\tau}\widetilde{Z}_1$ can become dominant so that far fewer hard isolated leptons are produced, and the reach for SUSY is considerably diminished. In fact, in Ref. [13], it was found that for $\tan\beta=45$, there would be *no reach* of the Fermilab Tevatron Main Injector ($\int \mathcal{L}dt = 2\ \mathrm{fb}^{-1}$) for MSUGRA beyond the current existing bounds from LEP2 experiments. More recently, the authors of Ref. [16] found that some reach might be recovered in the three lepton channel if one can use leptons with p_T as small as 5 GeV. Potentially worrisome physics backgrounds from heavy flavor production (which are very effectively reduced with harder lepton cuts), as well as instrumental backgrounds from lepton mis-identification are thought to be under control [17]. Nevertheless, it is then natural to ask if the CERN LHC reach for MSUGRA at large $\tan\beta$ is also diminished, and if in fact, SUSY could hide from LHC searches if the parameter $\tan\beta$ happens to be large.

We have several goals for this paper.

(1) We wish to establish the range of parameter space of the MSUGRA model that can be probed by CERN LHC experiments. In particular, is the reach of the LHC sufficient to discover or rule our MSUGRA at large $\tan\beta$, or could MSUGRA effectively hide from SUSY searches? This issue is addressed in Sec. II.

(2) If a SUSY signal can be established at large $\tan\beta$, is it still possible for LHC experiments to make precision measurements of (differences of) sparticle masses and model parameters? In Sec. III, we perform a case study for the parameter space point $(m_0, m_{1/2}, A_0, \tan\beta) = (200\ \mathrm{GeV}, 200\ \mathrm{GeV}, 0, 45)$, where $\widetilde{W}_1$ and $\widetilde{Z}_2$ decay almost exclusively to τ leptons, to answer this question. For this case, we find that an edge is reconstructable in the $\tau^+\tau^-$ invariant mass distribution which gives information on $m_{\widetilde{Z}_2} - m_{\widetilde{Z}_1}$. Combining the τ's with jets to form an invariant mass can also give an estimate of the mass of any squarks produced in SUSY events.

(3) In Sec. IV, we examine the extent to which the τ lepton multiplicity exceeds the electron multiplicity in SUSY events if $\tan\beta$ is large. We discuss various complications for such a measurement, and point out that τ signals could provide a novel diagnostic for SUSY analysis, and that these signals could provide an alternative handle on the magnitude of $\tan\beta$.

We end with a summary of our results and some general remarks in Sec. V.

II. THE REACH OF THE CERN LHC FOR MSUGRA AT LARGE tan β

We evaluate the MSUGRA signal using the ISAJET 7.37 event generator program, which is described in more detail in Ref. [9]. We use the same toy detector simulation as in Ref. [4].

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[1] Potentially large finite one loop corrections [14] that alter the relationship between the fermion mass and the corresponding Yukawa coupling have not been included in ISAJET and so are not included in this analysis. These corrections, which can be very significant when $\tan\beta$ is large, would mainly alter how the experimentally observable quantities such as masses, cross sections, and decay widths would be mapped onto the underlying model parameters. Since determination of underlying parameters from experimental observables is not the thrust of our paper, we expect that the main conclusions that we obtain will remain unaltered despite our neglect of this effect. If these radiative corrections are included in the expressions for SM fermion masses and Higgs-fermion-antifermion couplings, they should also be explicitly included in the computation of sparticle decay rates.

For $m_{\tilde{g}}$, $m_{\tilde{q}} \lesssim 1$ TeV, $\tilde{g}\tilde{g}$, $\tilde{g}\tilde{q}$ and $\tilde{q}\tilde{q}$ production are the dominant sources of SUSY events at the LHC. These production mechanisms, together with $\tilde{g}$ and $\tilde{q}$ cascade decays, naturally lead to events with n-leptons + m-jets + $\not{E}_T$, where typically $n=0-4$ and $m \geq 2$. In our simulation, we generate all SUSY processes using ISAJET. However, our cuts are designed to pick out selectively gluino and squark events, whose characteristics are high transverse momentum jets and large missing transverse energy. Furthermore, the p_T of the primary jets from gluinos as well as the $\not{E}_T$ are expected to scale with $m_{\tilde{g}}$. In contrast, the momenta of leptons, produced far down in the cascade decay chain from chargino and neutralino daughters, will, in general, be much softer than the jets and $\not{E}_T$, which can be produced in the first step of the cascade decay. Thus, following Ref. [4] for the multilepton plus multijet signals for SUSY, we vary the missing-energy and jet E_T cuts using a parameter E_T^c, but fix the lepton cuts:

jet multiplicity, $n_{\rm jet} \geq 2$ [with $E_T({\rm jet}) > 100$ GeV],

transverse sphericity $S_T > 0.2$,

$E_T(j_1),\ E_T(j_2)\ > E_T^c$ and $\not{E}_T > E_T^c$.

We classify the events by the multiplicity of *isolated* leptons, and in the case of dilepton events, we also distinguish between the opposite sign (OS) and same sign (SS) samples as these could have substantially different origins. For the leptons we require

$p_T(l) > 20$ GeV ($l=e$ or μ) and $M_T(l,\not{E}_T) > 100$ GeV for the $1l$ signal, and

$p_T(l_1,l_2) > 20$ GeV for $n=2,3,\ldots$ lepton signals.

The SM background to the various multilepton plus multijet plus $\not{E}_T$ signal events was calculated in Ref. [4] for the processes $t\bar{t}$ production, W or Z plus jets production, WW, ZZ and WZ production and QCD jet production (where leptons can arise from decays of heavy flavors produced directly or via gluon splitting). We use these numerical results for our background estimates. For each point in MSUGRA parameter space, we require that, for 10 fb^{-1} of integrated luminosity, the number of signal events S exceed $5\sqrt{B}$, where B is the number of background events, for *some* value of the cut parameter E_T^c. We also require $S \geq 0.2B$, and further, that $S \geq 5$ as the minimum number of events in 10 fb^{-1}.

Our results for the reach of the LHC are presented in Fig. 1 in the m_0 vs $m_{1/2}$ plane, for $A_0=0$, $\mu>0$ and (a) $\tan\beta=2$, (b) $\tan\beta=20$, (c) $\tan\beta=35$ and (d) $\tan\beta=45$. We take $m_t=170$ GeV. The bricked regions are excluded by lack of appropriate radiative electroweak symmmetry breaking, or (for $m_0^2 \ll m_{1/2}^2$) if the lightest neutralino $\tilde{Z}_1$ is not the lightest SUSY particle (the LSP). The shaded region is excluded by experimental searches for supersymmetry, and mainly corresponds to the LEP2 bound $m_{\tilde{W}_1} > 85$ GeV, or the SUSY translation of the LEP2 bound that $m_H > 88$ GeV for a SM Higgs boson. Mass contours for a 1000 GeV gluino and 1000 GeV first generation squark are shown to orient the reader.

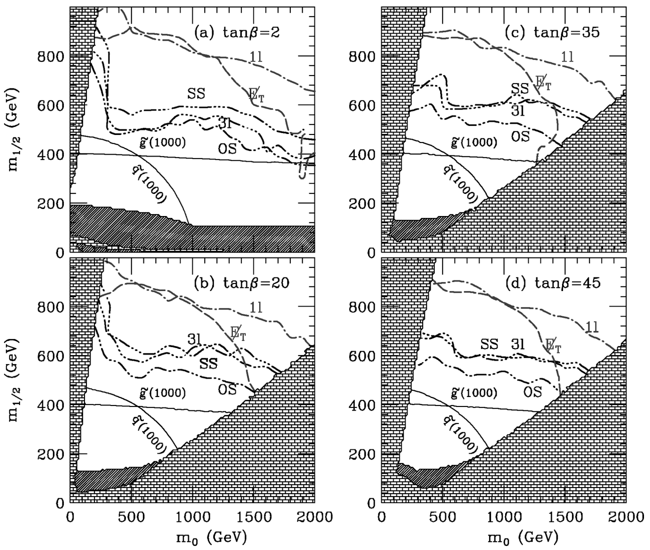

FIG. 1. A plot of the reach of the CERN LHC for various n-lepton plus multijet plus missing E_T events from MSUGRA in the m_0 vs $m_{1/2}$ plane for $A_0=0$, $\mu>0$ and (a) $\tan\beta=2$, (b) $\tan\beta=20$, (c) $\tan\beta=35$ and (d) $\tan\beta=45$. We take $m_t=170$ GeV.

The results shown in Fig. 1(a) for $\tan\beta=2$ are updated versions of similar results presented in Ref. [4], and are useful for comparison with the higher $\tan\beta$ cases shown in frames (b), (c), and (d). The largest reach is generally obtained in the single isolated lepton plus jets plus $\not{E}_T$ channel (labelled $1l$) or in the jets plus $\not{E}_T$ channel with no isolated leptons (labelled $\not{E}_T$). For 10 fb^{-1} of integrated luminosity, values of $m_{\tilde{g}}=2300$ GeV (1600 GeV) can be probed for small (large) values of m_0. Contours for jets plus $\not{E}_T$ plus two opposite sign isolated leptons (labelled OS), or two same sign leptons (labelled SS) or three isolated leptons (labelled $3l$) are also shown. Each of these multilepton channels also gives a significant reach for MSUGRA, so that for much of the parameter space shown, a SUSY signal ought to be visible in several different channels.

In the case of reach projections for the Fermilab Tevatron, as $\tan\beta$ increased, it became more difficult to obtain high p_T isolated leptons, since chargino and neutralino branchings to τ's and b's increased at the expense of e's and μ's. Consequently, as $\tan\beta$ increased, the Fermilab Tevatron reach for MSUGRA decreased, and in fact for $\tan\beta=45$, there was *no reach* for Tevatron Run 2 (2 fb^{-1}) beyond the region already excluded by the CERN e^+e^- collider LEP2 [13]. As mentioned, if it is possible to use softer cuts on the leptons, the situation might be somewhat ameliorated [16].

The corresponding situation for the CERN LHC is shown in frames (b), (c) and (d) of Fig. 1. For large $\tan\beta$, we see first of all that the theoretically excluded region increases substantially at large m_0. This region actually depends somewhat sensitively on the assumed value of the top mass (and on which higher order corrections are included in the program used). This excluded region also increases at low m_0 and large $m_{1/2}$ when $m_{\tilde{\tau}_1}$ becomes lighter than $m_{\tilde{Z}_1}$.

Next, as $\tan\beta$ increases from 2 to 20, 35 and 45, we see that the ultimate reach for MSUGRA only decreases slightly in the $1l$ and $\not{E}_T$ channels, and only for low values of m_0. If m_0 is large, for $m_{1/2}$ close to the LHC reach in frame (a), charginos and neutralinos mainly decay to real W, Z and Higgs bosons, and leptonic signals from these decays, and, hence, the LHC reach, are only weakly dependent on $\tan\beta$. For low values of m_0, however, the decays $\tilde{Z}_2\to\tilde{\tau}_1\tau$ and $\tilde{W}_1\to\tilde{\tau}_1\nu$ (bars are omitted), and possibly, those to other sleptons are also kinematically accessible. The decays to stau dominate for high values of $\tan\beta$, while for low $\tan\beta$ and low m_0, $\tilde{Z}_2\to\tilde{Z}_1 h$ or $\tilde{l}l$ and $\tilde{W}_1\to W\tilde{Z}_1$ or $\tilde{l}\nu$ or $l\tilde{\nu}$. It is easier to get hard isolated leptons from the subsequent W or $\tilde{l}$ decays than from a $\tilde{\tau}_1\to\tau\tilde{Z}_1\to l\nu\nu\tilde{Z}_1$ decay, which accounts for the somewhat higher reach in the $1l$ channel at low $\tan\beta$. Similarly, the reach for MSUGRA in the multilepton channels decreases as $\tan\beta$ increases, but again only for low m_0.

Although the LHC reach for MSUGRA is somewhat reduced at large $\tan\beta$, the contours still lie far beyond parameter space preference curves due to ''naturalness'' considerations [18], which tend to lie below the $m_{\tilde{g}},m_{\tilde{q}}=1000$ GeV contours. It is worth noting that the selection criteria designed to extract the SUSY signal for the low $\tan\beta$ regime suffice even if $\tan\beta$ is large; i.e., no new analysis is necessary. The large reach for MSUGRA at large $\tan\beta$ is due in part to the large squark and gluino production cross sections, and the fact that for very large sparticle masses, leptons occuring very far down the cascade decay chain can still have substantial p_T. From these reach contours, we conclude that it would be difficult for MSUGRA to hide from detection at the LHC by virtue of having a large value of $\tan\beta$. This is in sharp contrast to the corresponding situation for the Fermilab Tevatron $p\bar{p}$ collider [13].

III. A LARGE $\tan\beta$ MSUGRA MODEL CASE STUDY

In Refs. [5,6], five MSUGRA parameter space points were adopted for detailed case studies. It was found that in fact precision measurements of (differences of) SUSY particle masses and model parameters could in many instances be made at LHC experiments. We briefly summarize the results of Refs. [5,6] as follows.

A global variable

$$M_{eff}=p_T(j1)+p_T(j2)+p_T(j3)+p_T(j4)+\not{E}_T \quad (3.1)$$

(scalar sum) for events with $\geq 4-$jets$+\not{E}_T$ was defined. Distributions in M_{eff} were shown to be dominated at low values by SM backgrounds, but were dominated by the MSUGRA signal at high values of M_{eff}. The peak in the M_{eff} distribution scaled with $min(m_{\tilde{g}},m_{\tilde{q}})$ and provided a good first estimate of the strongly interacting SUSY particle masses involved in the signal events.

Gluino and squark cascade decay events involving $\tilde{Z}_2$ were found to be very useful for reconstructing the cascade decay chain whenever the branching fraction for the decay $\tilde{Z}_2\to h\tilde{Z}_1$ or the decay $\tilde{Z}_2\to l\bar{l}\tilde{Z}_1$ is substantial. In the case that $\tilde{Z}_2\to h\tilde{Z}_1$ followed by $h\to b\bar{b}$, the $b\bar{b}$ mass could be reconstructed to yield m_h; then by combining with other hard jets present in the events, mass estimates could be made of other SUSY particles occurring earlier in the cascade decay sequence. In the $\tilde{Z}_2\to l\bar{l}\tilde{Z}_1$ case, the endpoint of the $m(l\bar{l})$ distribution leads to a precise determination of $m_{\tilde{Z}_2}-m_{\tilde{Z}_1}$ (or if the decay is mediated by an on-shell slepton, yields information about $m_{\tilde{l}}$); again, by combining dilepton masses with various jets, other sparticle mass estimates could be obtained. These reconstructed decay chains thus yield information of several sparticle masses which can then be used to constrain the underlying model parameters.

Finally, a global fit of event characteristics and/or mass measurements to various SUSY model parameters could be made. An overconstrained fit allowed rejection of many possible SUSY models, while honing in on possible choices for underlying model parameters.

The MSUGRA parameter space choices made in Ref. [5,6] were necessarily restricted to values of $\tan\beta\leq 10$, since ISAJET was at the time only valid for that parameter space regime.

We expect that the M_{eff} distribution will continue to yield a measure of the SUSY mass scale regardless of the magnitude of $\tan\beta$. However, any sparticle mass reconstruction strategies involving $\tilde{Z}_2$ decays are in need of re-analysis since at large $\tan\beta$, $\tilde{Z}_2\to\tau\bar{\tau}\tilde{Z}_1$ can be the dominant decay mode of $\tilde{Z}_2$. For this reason, we select an additional case study point, ''LHC point 6,'' with MSUGRA parameter values $[m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ \mathrm{sgn}(\mu)]=(200,\ 200,\ 0,\ 45,\ -1)$, as suggested in [19], where mass parameters are in units of GeV. In this case, $m_{\tilde{g}}=540$ GeV, $m_{\tilde{q}}=498-517$ GeV, $m_{\tilde{b}_1}=390$ GeV, $m_{\tilde{Z}_2}\simeq m_{\tilde{W}_1}=152$ GeV, $m_{\tilde{Z}_1}=81$ GeV, $m_{\tilde{\tau}_1}=131$ GeV and $m_{\tilde{l}_R}=219$ GeV. In this case, $\tilde{Z}_2\to\tilde{\tau}_1\tau$ at 99.8% and $\tilde{W}_1\to\tilde{\tau}_1\nu_\tau$ at 99.6%. In addition, $\tilde{g}\to\tilde{b}_1 b$ occurs at 55%. The SUSY signal events in this case are expected to be rich in b jets and τ leptons.

A signal sample of 500 k events (corresponding to an integrated luminosity of about 5 fb^{-1}) was generated, along with 250 k event background samples each for $W+$jets, $Z+$jets, $t\bar{t}$ production as in Ref. [6]. QCD backgrounds are expected to be small after basic selection cuts discussed below. Hadronic τ's were found using generator information rather than selecting narrow jets. In addition, hadronic τ's were required to have visible $p_T>20$ GeV and $|\eta|<2.5$. We used the Collider Detector at Fermilab (CDF) rate[2] for jets to fake τ's, namely, 0.5% at $p_T(jet)=20$ GeV and 0.1% for $p_T(jet)>50$ GeV, with a linear interpolation in between [20]. The following standard cuts were made:

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[2] The CDF analysis also involves other cuts that we have not applied to the data.

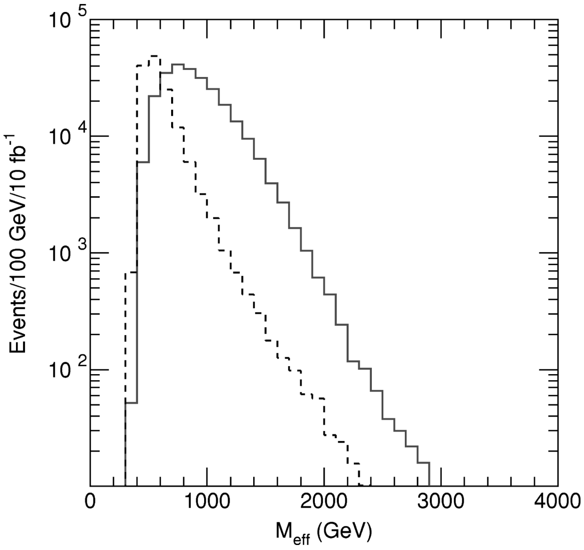

FIG. 2. Distribution in M_{eff} for the case study of Sec. III. The signal is the solid histogram, while the dashed histogram represents background.

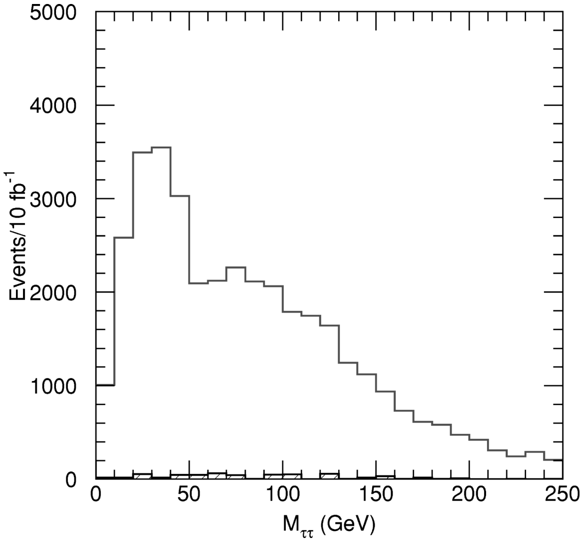

FIG. 3. Visible $\tau\tau$ mass for all hadronic decays.

at least four jets were required (using the ISAJET GETJET routine) with $p_T(j_1)>100$ GeV and $p_T(j_{2,3,4})>50$ GeV (leptons and taus are counted as jets),

$\not\!\!E_T>100$ GeV,

transverse sphericity $S_T>0.2$,

$M_{eff}>500$ GeV.

Efficiencies of 60% for b-tagging and 90% for lepton and (hadronically decaying) τ identification were assumed. (The τ efficiency is too optimistic, but studying it requires more than a toy detector simulation.) With these cuts, the event sample was already dominated by signal so that errors in the mis-identification rate of b's and τ's are not expected to be a problem.

The distribution in M_{eff} is shown in Fig. 2. The signal is shown by the solid histogram, while background is shown by the dashed histogram. The signal easily dominates background as expected for large values of $M_{eff}\geqslant 650$ GeV. At low $\tan\beta$ the ratio of M_{eff} where signal just exceeds background to M_{SUSY} is noted [6] to be $\sim$1.5–1.6, and provides an estimate of M_{SUSY}. In this case, the ratio is $\sim$1.3, which is due mainly to the larger mass splittings of squarks $(m_{\tilde{b}_1},\ m_{\tilde{t}_1}\leqslant m_{\tilde{u}_{L,R}})$ at large $\tan\beta$.

For events with at least two hadronic taus, we plot in Fig. 3 the visible $\tau\tau$ mass for the two highest p_T tau leptons. The distribution shown exhibits an edge near the endpoint for $\tilde{Z}_2\to\tau\bar{\tau}\tilde{Z}_1$, but the signal to SUSY background ratio is poor, since a large fraction of the mass is lost to neutrinos; i.e., a substantial number of SUSY events with the "real mass" beyond the end point appear below the end point because of the mass carried off in neutrinos. The rate is very much larger than the SM background shown as the hatched histogram, so observing a signal in this distribution would be trivial. The end point of the neutralino decay appears as a kink in the $m_{\tau\tau}$ distribution. The visible $\tau\tau$ mass is calculated using generator information and so does not include the effects of calorimeter and/or tracker resolution.

A more faithful $\tau\tau$ mass distribution can be obtained by selecting multiparticle hadronic τ decays with a visible mass close to the τ mass to reduce the mass carried off by neutrinos. The $\tau^+\tau^-$ mass distribution for 3-prong τ decays from the signal and SM background is shown in Fig. 4 for events with exactly two opposite sign hadronic τ's and no additional isolated leptons. The requirement of exactly two τ's was imposed to remove combinatorial background. There is very little real SM τ background after cuts, but there still is a substantial contamination from other SUSY sources. Since most of the SUSY events contain at least one gluino, which is a Majorana fermion and has equal branching ratios to τ^+ and τ^-, the background from two independent chargino de-

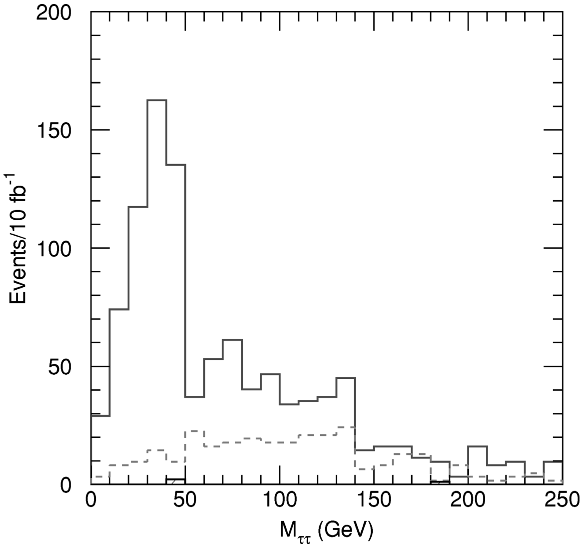

FIG. 4. Visible $\tau\tau$ mass with 3-prong decays (solid), SUSY background estimate from $\tau^\pm\tau^\pm$ (dashed), and SM background (shaded).

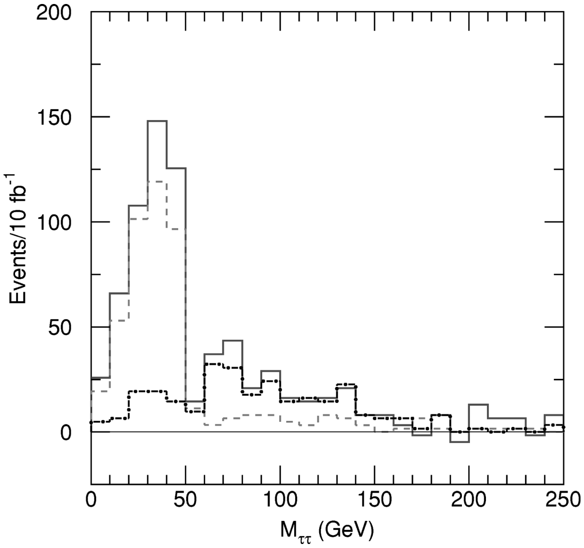

FIG. 5. Visible mass distribution for the difference of $\tau^+\tau^-$ and $\tau^\pm\tau^\pm$ (solid). The contribution of $\tilde{Z}_2$ events (dashed), and $\tilde{Z}_3+\tilde{Z}_4$ events (dashed-dotted) are also shown.

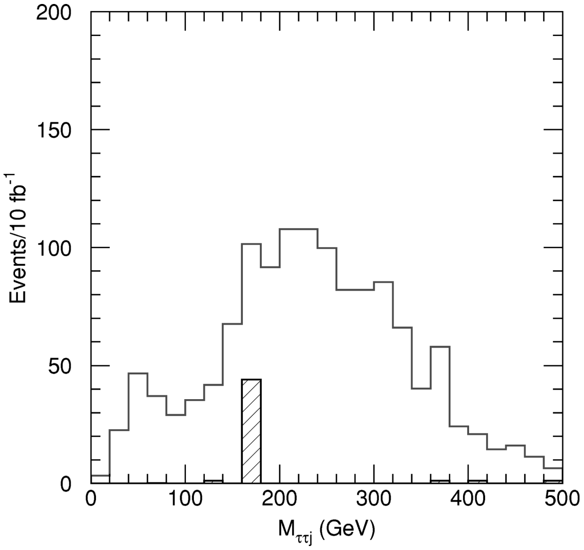

FIG. 6. Visible $\tau\tau-jet$ mass distribution for the smaller of two combinations. The shaded histogram is the SM background.

cays can be estimated from the $\tau^\pm\tau^\pm$ distribution, which is also shown as the dashed histogram in Fig. 4.

The subtracted distribution, shown in Fig. 5, has a clear low mass enhancement with an endpoint near, but slightly below the limit for two body decays neglecting the τ mass:

$$M_{max}=m_{\tilde{Z}_2}\sqrt{1-\frac{m^2_{\tilde{\tau}_1}}{m^2_{\tilde{Z}_2}}}\sqrt{1-\frac{m^2_{\tilde{Z}_1}}{m^2_{\tilde{\tau}_1}}}=60.6\ \text{GeV}. \tag{3.2}$$

The contribution to this distribution of events with exactly one $\tilde{Z}_2$ and no $\tilde{W}_1$ is shown as the dashed curve in the figure and clearly accounts for most of the low mass enhancement. There is also a contribution from events containing at least one $\tilde{Z}_3$ or $\tilde{Z}_4$, the dash-dot curve in Fig. 5, which accounts for the excess of $\tau^+\tau^-$ pairs at higher mass. Many channels contribute to these decays; the branching ratio for $\tilde{Z}_4\to\tilde{\tau}_1\tau$ is only 8.8%, so the distribution appears to end before the kinematic limit,

$$M_{max}=m_{\tilde{Z}_4}\sqrt{1-\frac{m^2_{\tilde{\tau}_1}}{m^2_{\tilde{Z}_4}}}\sqrt{1-\frac{m^2_{\tilde{Z}_1}}{m^2_{\tilde{\tau}_1}}}=216.0\ \text{GeV}. \tag{3.3}$$

Thus, from these distributions, it should be possible to extract information not only on $m_{\tilde{Z}_2}-m_{\tilde{Z}_1}$, but perhaps also information on heavier neutralino masses as well, although this will probably be very difficult.

We should point out that while focussing on taus with three charged prong decays indeed gives us a truer di-tau mass distribution, it also leads to a reduction in event rate by more than an order of magnitude. We have not attempted to examine whether the end point is better determined from this ‘‘truer’’ distribution or from the kink in the distribution in Fig. 3 which includes an order of magnitude larger data sample. Our study here should be regarded as a first look at the sort of measurements that might be possible when charginos and neutralinos dominantly decay to taus.

Most of the $\tilde{Z}_2$’s originate from squark cascade decays in this case study. It is then interesting to see if an estimate can be made of the squark masses as well as the neutralino masses. In Fig. 6, we have required events with exactly two τ’s, each decaying into three prongs, and then have constructed the invariant mass of the τ pair with each of the two fastest jets; finally, we plot the minimum of these two masses. Since the hardest jets typically come from $\tilde{q}\to q\tilde{Z}_i$ decay, this distribution should be approximately bounded by the squark mass. This is verified in Fig. 6, where the bulk of the $m_{\tau\tau j}$ distribution is in fact bounded by $m_{\tilde{q}}\simeq 500$ GeV.

A similar calculation can be performed using only identified b-jets, to try to extract the $\tilde{b}_1$ mass from $\tilde{b}_1\to b\tilde{Z}_2$ decays. In Fig. 7, we plot the distribution for $M_{\tau\tau b}$ using again the smaller of the two mass combinations. The bulk of the distribution is bounded by $m_{\tilde{b}_1}=390$ GeV, although a tail extends to higher mass values. This is due in part to contributions from $\tilde{b}_2$ decays, where $m_{\tilde{b}_2}=480$ GeV. It might also be interesting to see whether it is similarly possible to isolate the decay chain $\tilde{g}\to b\tilde{b}_1\to bb\tilde{Z}_2\to bb\tau\tau\tilde{Z}_1$ by looking at the $M_{bb\tau\tau}$ which should be bounded by $m_{\tilde{g}}$.

IV. LEPTON NON-UNIVERSALITY AT LARGE tan β

Over a significant portion of MSUGRA parameter space it is expected that the multiplicity of τ leptons should be enhanced relative to es or μs at large tan β. This suggests that if it is possible to establish conclusively tau lepton non-universality in SUSY events, we may be able to interpret it as an indicator of a sizeable tau Yukawa interaction, at least within the MSUGRA framework. It should, of course, be kept in mind that within the more general MSSM frame-

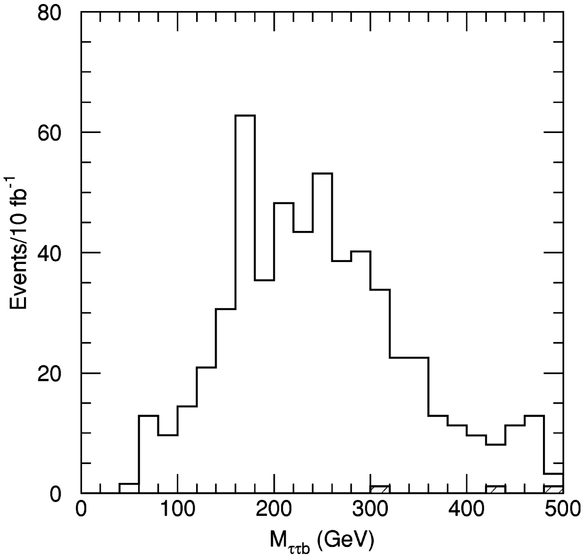

FIG. 7. Visible $\tau\tau b$ mass distribution for the smaller of two possible combinations. The shaded histogram is the SM background.

work, SUSY events may exhibit lepton non-universality even if Yukawa couplings are negligible, as long as $m_{\tilde{\tau}_1}$ differs from selectron and smuon masses. The observation of universality between e and μ in a SUSY event sample would strongly tempt us to suggest [21,22] that an observed tau non-universality indeed originates in a sizeable tau Yukawa coupling.

While the principle is simple, its implementation poses a challenge. Even in a sample of purely SM events, there should be a superficial non-universality of $e:\mu:\tau$ simply due to the different acceptance cuts and efficiencies for identifying each species of lepton. It should be possible to determine these directly from a data sample rich in SM events. However, these efficiencies will also change somewhat with the cuts used to select out SUSY events, but this can presumably be taken into account, again using the data; e.g., by using selection cuts that smoothly interpolate between SM and signal samples. Hadronically decaying taus pose yet another challenge, since the visible energy spectrum in their decays, and hence, the tau detection efficency, is sensitive to their polarization [23].[3] Moreover, for a data sample enriched in New Physics (in our case SUSY) events, the tau polarization is not known *a priori*, but may be possible to determine from the data.

A complete quantitative analysis of lepton non-universality is beyond the scope of this study. For one, it would entail a correct simulation of tau decays (including effects of tau polarization) both for SM backgrounds and the SUSY sample. These effects are not yet completely included in ISAJET. Our study should, therefore, be regarded as exploratory, and simply indicative of the magnitude of asymmetries that we will have at our disposal for future studies.

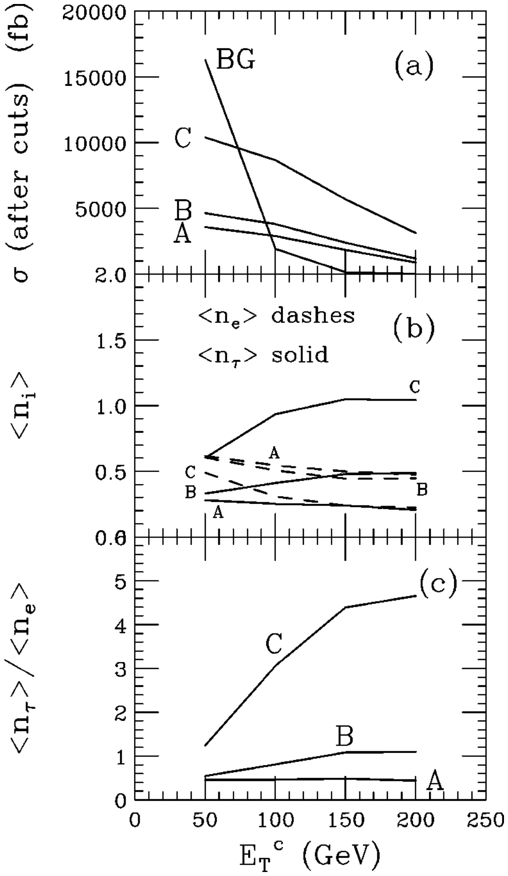

FIG. 8. A plot of (a) background (BG) and 3 signal cases A, B and C given in the text after modest cuts. In (b), we plot the average e and τ multiplicities in the signal plus background sample of events that survive cuts. In (c), the ratio of τ to e multiplicities is plotted versus E_T^c for the three cases of signal plus background.

To illustrate this with a direct computation, we examine three different MSUGRA parameter space points with $m_0=225$ GeV, $m_{1/2}=250$ GeV, $A_0=0$, $\mu>0$ and (A) $\tan\beta=2$, (B) $\tan\beta=35$ and (C) $\tan\beta=45$, along with the SM background. We impose a simple set of cuts:

we require 2 jets each with $E_T>E_T^c$ and $\not{E}_T>E_T^c$,

we require transverse sphericity $S_T>0.2$,

for events with a single isolated lepton, we require $M_T(l,\not{E}_T)>100$ GeV ($l=e$, μ or τ), where in the case of τ we use the visible τ energy to construct M_T.

We show the total signal and background as a function of E_T^c in Fig. 8(a). For low values of E_T^c, the resulting event sample is background dominated, while for high E_T^c, the sample is signal dominated. In Fig. 8(b), we plot the average

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[3] For every tau produced by decays of charginos, neutralinos, staus, stau neutrinos or Higgs boson bosons, ISAJET computes its polarization (average polarization for 3-body decays), which is then used for the computation of the hadronic decay of this tau. Thus the jet energies from tau decays are correct in the average sense. Spin correlations between the visible energies from for instance ditaus produced via neutral Higgs decays are not included. We do not make use of such correlations in this analysis.

lepton multiplicity in the surviving signal plus background event sample of e's and τ's, denoted by $\langle n_e \rangle$ (dashed) and $\langle n_\tau \rangle$ (solid). For case A, with low $\tan\beta=2$, the τ multiplicity is roughly constant versus E_T^c, and would correspond to a measured lepton universality after accounting for acceptances and efficiencies. For this case, the quantity $\langle n_e \rangle$ decreases somewhat with E_T^c, since jetty gluino and squark cascade decay events are more likely to pass our simple cuts listed above. For case B with $\tan\beta=35$, $\widetilde{W}_1 \to W\widetilde{Z}_1$ with a branching fraction of 98% while $\widetilde{Z}_2 \to \widetilde{Z}_1 \tau^+\tau^-$ 27% of the time, so that some violation of universality is expected. This is seen in Fig. 8(b) where the e and τ multiplicity is nearly that of case A for low E_T^c, while for high E_T^c, which is signal dominated, there is a distinct increase in τ multiplicity compared to e multiplicity. This can be seen more easily in Fig. 8(c) where we plot the ratio $\langle n_\tau \rangle / \langle n_e \rangle$ versus E_T^c. For case C, we have $B(\widetilde{W}_1 \to \tilde{\tau}_1 \nu_\tau)=93\%$ and $B(\widetilde{Z}_2 \to \tilde{\tau}\tau)=99\%$, so large deviations from universality should be expected at high E_T^c. For this case, we see in Fig. 8(b) that in fact $\langle n_\tau \rangle$ surpasses $\langle n_e \rangle$ for all $E_T^c > 50$ GeV, and Fig. 8(c) shows the huge deviations from universality that would be expected for very large $\tan\beta$ and small m_0.

While we recognize that our results should be regarded as qualitative, we are encouraged to see that the magnitudes of asymmetries in the three cases are quite different. As more complete simulations become available, it would be instructive to study the extent to which τ leptons may serve as a diagnostic of any new physics that might be discovered. Such analyses will have to be interpreted with care since, as we have said, the tau detection efficiency, and hence the expectation for tau multiplicity, depends on the unknown polarization (which may be possible to measure) in the new physics sample. Well-defined frameworks such as MSUGRA would, however, make unambiguous predictions for $\langle n_\tau \rangle$, so that this measurement could serve as an independent test, and possibly even provide a measure of $\tan\beta$ (especially if it happens to be large). Indeed in the future, it may prove worthwhile to examine the multiplicity of taus separately in various event toplogy samples ($1l, l^+l^-, l^\pm l^\pm, 3l$, etc.), since these generally have different SUSY origins.

V. SUMMARY AND CONCLUSIONS

In this paper we have studied SUSY signals at the CERN LHC collider as predicted by the minimal supergravity model for large values of the parameter $\tan\beta$. We found that increasing this parameter to values near its upper bound has little impact on the SUSY discovery reach of the LHC, in stark contrast to the Tevatron, whose reach is greatly diminished in this region of parameter space. The main reason for this difference is that increasing $\tan\beta$ can change the qualitative pattern of neutralino and chargino decays only for relatively small sparticle masses, where their decays into real W and Z bosons are kinematically disallowed. Even though in this region of parameter space, the efficiency for detecting SUSY through events containing hard leptons is low also at the LHC, the huge event rate guarantees that SUSY will still be seen in several different channels. Once decays into real gauge or Higgs bosons become possible, decay patterns become less sensitive to $\tan\beta$; in particular, except when m_0 is very small, many hard leptons now come from the decay of on-shell W and Z bosons, independent of the value of $\tan\beta$.

Apart from discovering SUSY, one would also like to determine its parameters, so as to pin down eventually the supersymmetric model that describes nature at a more fundamental level. Most previous studies that attempted to reconstruct some (differences of) SUSY masses at the LHC used events with hard isolated leptons. Unfortunately, for large values of $\tan\beta$ and not too heavy sparticles SUSY events are expected to contain τ leptons rather than electrons or muons. While leptonically decaying τ's still produce sufficiently many hard electrons and muons to ensure that SUSY will be discovered, the presence of many additional neutrinos would make mass reconstruction using electrons and muons all, but impossible in this part of parameter space. In Sec. III we instead used hadronic 3–prong decays of τ's to determine the difference between the masses of the lightest and next-to-lightest neutralino; we focussed on this decay mode since here the simultaneously produced ν_τs (which smear out the end point) are forced to be relatively soft, which minimizes their impact on kinematic event reconstruction. While the precision of this measurement will be worse than that of the analogous measurement based on e^+e^- pairs at smaller $\tan\beta$, it should still be sufficient to constrain greatly the SUSY model. We also showed how combining τ pairs with a hard jet might yield information about the overall scale of the squark masses or, if this jet contains a tagged b, the mass of bottom squarks.

Finally, the presence of many τ leptons also offers new opportunities to glean information about the underlying SUSY parameters. As a first attempt in that direction we studied in Sec. IV the violation of lepton universality that can be expected in SUSY events if $\tan\beta$ is large. In order to make this fully quantitative, a careful analysis of the different detection efficiencies for the three flavors of leptons is mandatory, which requires detailed understanding about the performance of LHC detectors as well as detailed simulation of τ decays. Here we instead simply showed corresponding results for event samples dominated by standard model contributions, where lepton universality is known to hold to very good approximation; this serves as a normalization for other event samples dominated by SUSY contributions. Some caution is advised when interpreting these results. For example, the average τ polarization is expected to change when going from the SM-dominated sample to the SUSY-dominated sample; this will change the E_T spectrum of the visible τ decay products, and hence, their detection efficiency. However, our results clearly show that at least for the extreme case where $\widetilde{W}_1$ and $\widetilde{Z}_2$ almost exclusively decay into real $\tilde{\tau}_1$ sleptons, a gross violation of lepton universality should be expected.

One can envision other, more ambitious studies of SUSY events containing hadronically decaying τ leptons. For example, a comparison of the visible spectra of events with 1-prong and 3-prong τ decays should allow one to determine the τ polarization, which in turn would yield information on the $\tilde{\tau}_L - \tilde{\tau}_R$ mixing angle, as well as the decomposition of the $\widetilde{W}_1$ and/or $\widetilde{Z}_2$ mass eigenstates in terms of gaugino and Higgsino current states. Copious production of τ leptons, possibly a bane for SUSY searches at the Tevatron, could therefore well turn out to be a boon for the LHC.

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