

The importance of tau leptons for supersymmetry searches at the Tevatron

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Abstract

Supersymmetry is perhaps most effectively probed at the Tevatron through production and decay of weak gauginos. Most of the analyses of weak gaugino observables require electrons or muons in the final state. However, it is possible that the gauginos will decay primarily to τ leptons, thus complicating the search for supersymmetry. The motivating reasons for high τ multiplicity final states are discussed in three approaches to supersymmetry model building: minimal supergravity, minimal gauge mediated supersymmetry, and more minimal supersymmetry. The concept of “ $e/\mu/\tau$ candidate” is introduced, and an observable with three $e/\mu/\tau$ candidates is defined in analog to the trilepton observable. The maximum mass reach for supersymmetry is then estimated when gaugino decays to τ leptons have full branching fraction.

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1 Introduction

The effects of minimal supersymmetry on hadron collider observables are not expected to be spectacular. It would be easier if supersymmetry strongly implied additional resonances in $p\bar{p}$ scattering, or narrow invariant mass peaks of two leptons, etc. Perhaps we will find high multiplicity lepton, photon or jet signals from R-parity violation or prompt decays to gravitinos in low energy supersymmetry breaking theories. This is not the most likely scenario. Simplicity, proton stability arguments, and dark matter considerations constitute a mild preference for R-parity conservation. Furthermore, it appears most natural in gauge mediated models to have the superpartners feel only a small fraction of the full supersymmetry breaking in nature [1]. Thus, prompt decays of the NLSP (next lightest supersymmetric partner) on the time scales of detector sizes are not favored [2].

The classic signatures of supersymmetry are not quite as spectacular as those created by promptly decaying NLSPs or R-parity violation. Perhaps the most probing signal [3, 4] of supersymmetry at the Tevatron is

$$p\bar{p} \rightarrow \chi_1^\pm \chi_2^0 \rightarrow 3l + \cancel{E}_T \quad (1)$$

where $l = e$ or μ . Cutting on the p_T values of these leptons and requiring that $m_{l+l^-} \neq m_Z$, leaves a small background from $W^\pm Z$ production followed by $W \rightarrow l\nu$ and $Z \rightarrow \tau\tau$, where the τ 's decay leptonically to $e\nu\nu$ or $\mu\nu\nu$. The maximum mass reach of degenerate gaugino-like χ_1^\pm and χ_2^0 states is about 200 GeV with 2 fb^{-1} of integrated luminosity [5].

One of the main purposes here is to demonstrate that it is quite natural to expect that the $3l$ signal is not present at any reasonable rate at the Tevatron. Instead, one expects over a large region of supersymmetry parameter space to be dominated by multiple τ events from $\chi_1^\pm \chi_2^0$ production. The reasons for this are explained in the subsequent section for three different approaches to supersymmetry model building (standard supergravity scenarios, gauge mediated models, and “more minimal” supersymmetry). Because τ 's are more difficult to tag and identify than leptons, and because quark and gluon jets sometimes look like τ 's, the searches in this mode are difficult. Some estimates are made for the search capabilities.

2 Reasons for 3τ events

There are several reasons why χ_1^\pm may decay preferentially into $\tau^\pm\nu\chi_1^0$ over $l^\pm\nu\chi_1^0$, and why χ_2^0 may decay to $\tau^+\tau^-\chi_1^0$ over $l^+l^-\chi_1^0$. Firstly, $\tilde{\tau}_1$ is lighter than \tilde{l}_R . If the τ Yukawa coupling is large then renormalization group effects will drive $\tilde{\tau}_R$ below \tilde{l}_R . More importantly the $\tilde{\tau}$ mass matrix can have a large mixing from $\lambda_\tau v\mu$, where $v = 174$ GeV. This mixing angle will drive the lightest eigenvalue down, thus potentially making $m_{\tilde{\tau}_1} \ll m_{\tilde{l}_R}$. This is especially true for large $\tan\beta$ which enhances the τ Yukawa coupling,

$$\lambda_\tau \simeq \frac{m_\tau \tan\beta}{v}. \quad (2)$$

The large $\tan\beta$ correlation with high τ multiplicity has been recently emphasized in ref. [6]. Large mixing also results in models with large A_τ triscalar soft mass Yukawa.

If the slepton masses are lighter than χ_1^\pm and χ_2^0 masses, then on-shell decays into $\tilde{\tau}_1$ will be more likely than \tilde{l}_R . Not only is the phase space larger for $\tilde{\tau}_1$, but also the substantially mixing introduces a large $\tilde{\tau}_L$ component to $\tilde{\tau}_1$ thus coupling much more effectively to χ_1^\pm and χ_2^0 which can be shown to be mostly $SU(2)_L$ gauginos after radiative electroweak symmetry breaking conditions are imposed in minimal supergravity [7] and minimal gauge mediated models [8, 9, 10]. (The result is more robust than these minimal models.) Furthermore, the large τ Yukawa coupling enables interactions with Higgsinos, which is negligible in the case of \tilde{e} or $\tilde{\mu}$.

Another reason why the τ final states might dominate can be extracted from the ideas of “more minimal” supersymmetry [11]. According to this approach, all the first two generations squarks and sleptons must be very heavy (greater than a few TeV) to suppress large unwanted CP violation and flavor changing neutral current effects in the electric dipole moment of the neutron, $K - \bar{K}$ mixing, $\mu \rightarrow e\gamma$, etc. The \tilde{t}_i, \tilde{b}_L , Higgsinos and $SU(2)_L \times U(1)_Y$ must be light in order to have natural electroweak symmetry breaking. The remaining fields (\tilde{g}, b_R and $\tilde{\tau}_i$) can be either light or heavy without causing problems. It is natural to assume that they are light since \tilde{g} is probably tied up with the other gauginos in some unification relation, and it is reasonable to put all scalars of the same generation at the same scale. Since \tilde{t}_i and \tilde{b}_L must be light, then by this argument so should the other third generation scalars \tilde{b}_R and $\tilde{\tau}_i$. In this case, decays of χ_1^\pm and χ_2^0 may only be allowed to decay into τ 's via $\tilde{\tau}_1$ since no other slepton is close in mass. Although this approach may lead to new problems [12], it

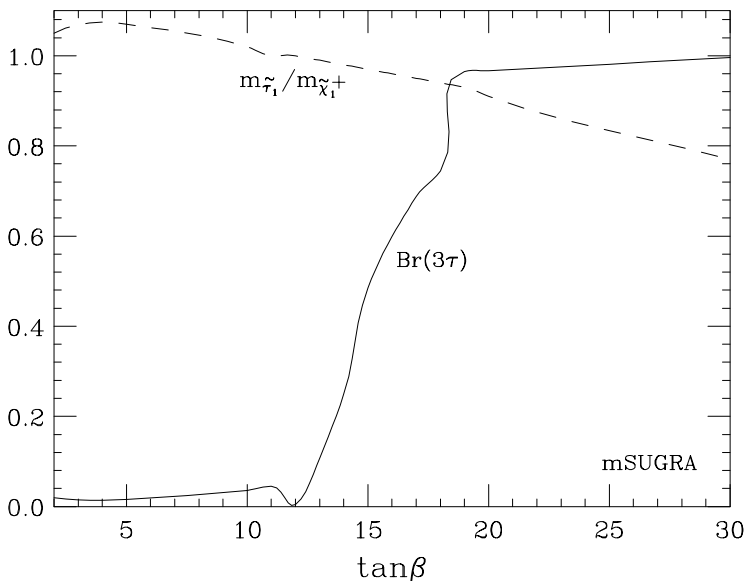


Figure 1: Branching ratio of $\chi_1^\pm \chi_2^0$ into three τ -leptons for the minimal supergravity model described in the text.

is an attractive contributing solution to FCNC and CP violation suppression.

For minimal supergravity (mSUGRA) and minimal gauge mediated supersymmetry breaking (mGMSB) models, we can quantify the prevalence of 3τ events in the data with a small number of parameters. For mSUGRA, I have chosen $m_0 = 150$ GeV, $m_{1/2} = 225$ GeV, $A_0 = 0$, and $\text{sign}(\mu) = +$ to be fixed for illustration purposes [13]. Both $m_{\chi_1^\pm}$ and $m_{\chi_2^0}$ are close to 170 GeV for all $\tan\beta$ and are mostly the superpartners of W^\pm and W^3 gauge bosons respectively. In Fig. 1 the value of $\tan\beta$ is varied from 2 to 30 and the branching fraction of 3τ events expected from $\chi_1^\pm \chi_2^0$ production and subsequent decays is plotted [14]. Furthermore, the ratio of $m_{\tilde{\tau}_1}/m_{\tilde{\chi}_1^\pm}$ is shown. As expected, the 3τ rate becomes dramatic for larger $\tan\beta$ and near almost 100% probability for $\tan\beta > 20$, when the $\tilde{\tau}_1$ mass dips sufficiently below χ_1^+ .

In minimal gauge mediated supersymmetry (mGMSB) I have chosen $\Lambda = M = 72$ TeV, one $5+\bar{5}$ messenger multiplet, and $\text{sign}(\mu) = +$ [15]. Again, $m_{\chi_1^\pm}$ and $m_{\chi_2^0}$ are close to 170 GeV for all $\tan\beta$ and are mostly the superpartners of W^\pm and W^3 gauge bosons respectively. We see in Fig. 2 that the $\text{Br}(3\tau)$ branching rate turns on much more smoothly. Here, the spectrum allows very light $\tilde{\tau}_1$ and \tilde{l}_R . The dominance of the 3τ final state is mostly due to the increasing $\tilde{\tau}_L$ component of $\tilde{\tau}_1$ as $\tan\beta$ increases. When $\tan\beta > 25$ the 3τ branching

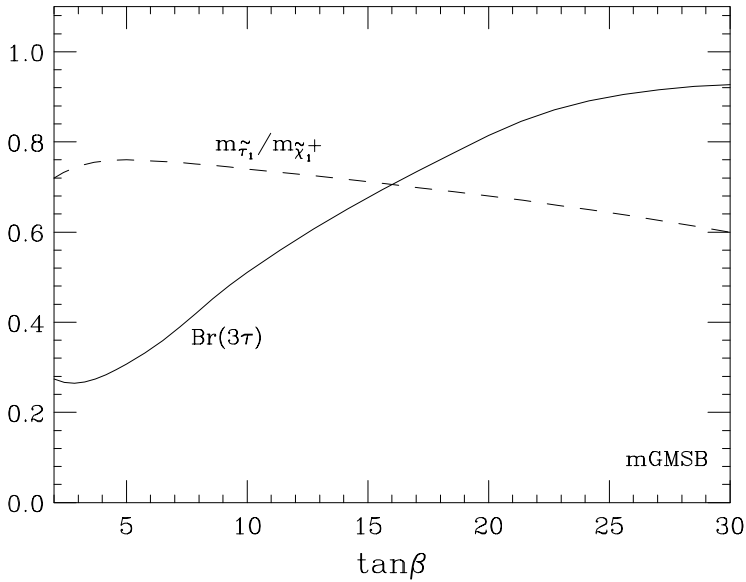


Figure 2: Branching ratio of $\chi_1^\pm \chi_2^0$ into three τ -leptons in the gauge mediated model described in the text.

fraction climbs above 90%. Even if the decays of $\chi_1^\pm \rightarrow W^\pm \chi_1^0$ and $\chi_2^0 \rightarrow Z \chi_1^0$ are on-shell, they do not compete with on-shell $\tilde{\tau}_1$ decay modes in large $\tan \beta$.

The 3τ final state is most expected when $\tan \beta$ is rather large. Many grand unified theories based on $b - \tau - t$ unification [16] prefer large $\tan \beta \simeq m_t/m_b$. In gauge mediated models, unwanted large CP violation effects are suppressed by requiring $B = 0$ at the messenger scale [1, 9, 8, 17]. This also implies large $\tan \beta$, hence high τ -multiplicity. Therefore, it is worthwhile to examine how effectively one can search for 3τ final states.

3 Searching in the 3τ mode

Analysis for τ lepton final states is possible for both CDF and D0 in the subsequent runs. The τ identification rate might be as high as 30% in the hadron decay modes when $p_T(\tau) > 15$ GeV [18]. This is encouraging for analysis of final state τ lepton signatures of new physics, such as the 3τ signature being considered here. The main background for 3τ events is $WZ \rightarrow 3\tau$ and Zg where $Z \rightarrow \tau\tau$ and the g fakes a τ with the right jet-charge and low hadron multiplicity. The fake rate for this is expected to be approximately 1% or less with $p_T > 15$ GeV.

One unifying approach to all trilepton signals, including $3l$ and 3τ , is to define an “ $e/\mu/\tau$ candidate.” An $e/\mu/\tau$ candidate is defined to be an isolated electron or muon or a fully tagged τ -jet in a hadronic decay mode of the τ . Therefore, the identification of a primary e or μ as an $e/\mu/\tau$ candidate is near 100%. The identification of a primary τ lepton is the sum of its branching ratios into $e\nu\nu$ (18%) and $\mu\nu\nu$ (18%) plus the τ identification rate (30%) that utilizes the hadronic decay modes of the τ . The combined $e/\mu/\tau$ candidate efficiency is then approximately 66% for a τ lepton. The estimate here is made assuming $p_T(\tau) > 15$ GeV, and $\eta(\tau) < 1$. For three τ 's in an event satisfying these p_T and η requirements, the identification rate is as high as $(0.66)^3 \simeq 30\%$.

The visible decay products of a τ can be significantly softer in p_T than the original τ itself. For this reason, it is best to insist that all three $p_T(\tau)$ in the signal events are greater than 15 GeV when analyzing search capabilities [19]. In the end, a detailed detector simulation with well-defined τ identification requirements for each decay mode of the τ will be required for complete understanding of the capabilities. Here, I will approximate this process by making sure that one τ satisfies $p_T > 20$ GeV, and the other two τ 's satisfy $p_T(\tau) > 15$. The trigger could occur by the substantial missing E_T in the events, and/or large enough p_T of an isolated lepton(s), and/or a dedicated τ trigger. The trigger issues at both collaborations have not been settled but the hope here is that requiring $p_T(\tau) = \{20, 15, 15\}$ GeV and $\eta(\tau) < \{1, 1, 1\}$ will yield a high overall trigger efficiency.

To reduce the WZ background all events with two opposite sign same-flavor leptons should satisfy $|m_{l+l-} - m_Z| > 10$ GeV. A small reduction in Zg can be obtained by cutting against back-to-back τ 's in the azimuthal plan; however, the high p_T requirements on the “ τ ” imposed above make this background reduction rather insignificant. Table 3 contains the estimated background to three $e/\mu/\tau$ candidate events after cuts. A veto on additional jet activity above $E_T > 15$ GeV has been applied to help reduce additional background. For example, the $gg \rightarrow b\bar{b}$ background rate is expected to be small with an effective veto in place.

To estimate the maximum supersymmetry mass reach for the 3τ mode, the following choices should be made: The 3τ branching ratio is 100% which is valid for high $\tan\beta$. The light charginos and neutralinos are mostly gaugino so that $m_{\chi_1^\pm} = m_{\chi_2^0} = 2m_{\chi_1^0}$, which is generally true in supersymmetric models with radiative electroweak symmetry breaking, and is certainly valid for mSUGRA and mGMSB. And lastly, for maximum kinematic efficiency we assume that $m_{\tilde{\tau}_1}$ is halfway between $m_{\chi_1^0}$ and $m_{\chi_2^0}$. With these choices, the total signal

	σ [pb]	Br("3 τ ")	ϵ_{kin}	ϵ_{id}	σ_{cuts} [fb]
$W^\pm Z$	2.6	0.01	0.11	0.40	1.1
Zg	8200	3.3×10^{-4}	0.005	0.45	6.1
total					7.2 fb

Table 1: Main backgrounds to 3τ events at 2 TeV center of mass energy. The Br("3 τ ") indicates the branching fraction into three $e/\mu/\tau$ candidates, but not allowing $Z \rightarrow ee, \mu\mu$. The ϵ_{kin} column is the efficiency of selecting all three $e/\mu/\tau$ candidates with $p_T = \{20, 15, 15\}$ GeV and $\eta < 1$. The ϵ_{id} column is the estimated probability of experimentally identifying all three leptons in the final state as $e/\mu/\tau$ candidates after the kinematic cuts have been applied. Note that the WZ background mainly sums over $e\tau\tau$, $\mu\tau\tau$, and $\tau\tau\tau$ final states, and the ϵ_{id} averages over these final states. Also, the fake rate for $g \rightarrow \tau$ is incorporated in Br("3 τ ") not ϵ_{id} .

$\int dt \mathcal{L}$	$m_{\chi_1^\pm}$ reach
1 fb $^{-1}$	135 GeV
2	145
10	170
25	185

Table 2: Estimated maximum mass reach for χ_1^\pm in the 3τ channel of $\chi_1^\pm \chi_2^0$ production and decay.

rate after cuts is

$$\sigma_{\text{cuts}}(3\tau \text{ signal}) \simeq 0.04\sigma(\chi_2^0 \chi_1^\pm). \quad (3)$$

Combing this equation with a background rate of 7.2 fb, it is required that

$$\sigma(\chi_1^\pm \chi_2^0) \gtrsim \frac{330 \text{ fb}}{\sqrt{\int dt \mathcal{L} \text{ in fb}^{-1}}} \quad (4)$$

to get a 5σ signal above background over the applicable range for $m_{\chi_1^\pm}$. Table 3 indicates what the corresponding mass reach is for these events for different integrated luminosity at 2 TeV center of mass energy.

The background and signal estimates require further consideration, especially after a detailed study has been completed on the possibility of triggering on τ leptons. The results above depend on having high efficiency triggers for central τ leptons with $p_T \gtrsim 20$ GeV. Because the leptonic decay products of the τ lepton are usually quite soft, mass reaches of the chargino depend very sensitively on the trigger capabilities of high τ -multiplicity events [6].

4 Conclusion

The use of τ leptons in supersymmetry goes well beyond the 3τ signal discussed here. High τ multiplicity events are present in some gauge mediated models when the $\tilde{\tau}_1$ is the NLSP [8, 20, 21]. In this case two prompt decays of $\tilde{\tau}_1 \rightarrow \tau + \tilde{G}$ may be present in all superpartner events. Without these τ leptons in the final state the supersymmetry events may be quite ordinary, and mimicked by large standard model backgrounds.

Tau leptons can also be used to gain significance in supersymmetry Higgs physics observables. For example, many studies of Higgs boson detection at the Tevatron require $Wh \rightarrow l\nu b\bar{b}$, where $l = e$ or μ . Identifying τ leptons in the decays of the W and/or h [22, 23] can only help in the search for the Higgs boson. Since supersymmetry generally requires a light Higgs boson with mass less than about 130 GeV, the Tevatron is well-poised to discover it. This requires high luminosity [24] and taking advantage of all possible production and decay modes of the Higgs.

Nevertheless, the search reach of the pure 3τ signal of supersymmetry is a good benchmark for τ studies. Not only is this final state ubiquitous in highly motivated large $\tan\beta$ models of supergravity and gauge mediated supersymmetry breaking frameworks, but it also may be the only way to see supersymmetry in the more minimal supersymmetry approaches where the $\tilde{\tau}$ is the only light slepton generation in the spectrum.

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