Using Tau Polarization as a Distinctive SUGRA Signature at LHC

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Abstract

In the minimal SUGRA model the lighter tau slepton is expected to be the second lightest superparticle over a large parameter range at large $\tan \beta$. Consequently one expects a viable SUGRA signal at LHC in the tau lepton channel coming from the decay of these tau sleptons. The model predicts the polarization of this tau lepton to be $+1$ to a very good accuracy. We show how this prediction can be tested by looking at the momentum fraction of the tau-jet, carried by the charged prong, in its 1-prong hadronic decay channel.
The minimal supergravity (SUGRA) model provides a well-motivated and economical parametrisation of the minimal supersymmetric standard model (MSSM) in terms of the four continuous and one discrete parameters \[1\]

\[m_{1/2}, m_0, A_0, \tan \beta \text{ and } \text{sgn}(\mu).\]  

The mass parameter $\mu$ represents the mixing between the two Higgs doublets, while $\tan \beta$ denotes the ratio of their vacuum expectation values. The magnitude of $\mu$ is determined by the electroweak symmetry breaking condition. The other mass parameters $m_{1/2}, m_0$ and $A_0$ denote the common gaugino and scalar masses and the common trilinear coupling term at the unification scale. In fact $m_{1/2}$ continues to represent the rough magnitude of the $SU(2)$ gaugino mass $M_2$ down to the weak scale, i.e.

\[m_{\tilde{W}_1}, m_{\tilde{Z}_2} \simeq M_2 \simeq 0.8m_{1/2},\] (2)

where $\tilde{W}_1$ denotes the lighter chargino and $\tilde{Z}_2$ the second lightest neutralino. Similarly $m_0$ continues to represent the rough magnitude of the right-handed slepton masses down to the weak scale, i.e.

\[m_{\tilde{\ell}_R}^2 \simeq m_0^2 + 0.15m_{1/2}^2,\] (3)

neglecting the Yukawa coupling contribution to the RGE. However at large $\tan \beta$ the Yukawa coupling contribution drives the $\tilde{\tau}_R$ mass significantly below (3). Moreover there is a significant mixing between the $\tilde{\tau}_{L,R}$ states, as represented by the off-diagonal term

\[m_{LR}^2 = -m_\tau(A_\tau + \mu \tan \beta),\] (4)

which drives the lighter mass eigen value further down. Thus the lighter stau mass eigen state

\[\tilde{\tau}_1 = \tilde{\tau}_R \sin \theta_\tau + \tilde{\tau}_L \cos \theta_\tau\] (5)

is predicted to be significantly lighter than the other sleptons at large $\tan \beta$. Moreover one sees from eqs. (2,3) that for $m_0 \leq m_{1/2}$ it is expected to be lighter than $\tilde{W}_1$ and $\tilde{Z}_2$ as well, which makes it the second lightest superparticle after $\tilde{Z}_1$ [2]. The cascade decay of superparticles via $\tilde{\tau}_1$ leads to

\[\tilde{\tau}_1 \rightarrow \tau \tilde{Z}_1.\] (6)
Thus the channels containing $\tau$ lepton(s) plus missing $E_T$ ($E_T^\tau$) have attracted a great deal of attention as promising channels for SUGRA signal, particularly for large values of $\tan \beta$ [2-6].

We consider here a distinctive SUGRA prediction for the polarization of the $\tau$ resulting from $\tilde{\tau}_1$ decay (6), i.e.

$$P_\tau = +1,$$

(7)

which has not received much attention so far [7]. As we shall see below, this is a robust prediction of the minimal SUGRA model, which holds to a very good precision over the canonical ranges of the model parameters (1). Of course its practical utility as a distinctive SUSY signal is restricted to those parameter ranges where the superparticle decays have a large branching fraction into the $\tau$ channel (6), i.e. large $\tan \beta$ and $m_0 \leq m_{1/2}$. In this case the identification of $\tau$ in its hadronic decay channel at LHC will enable us to measure its polarization and test the above prediction rather unambiguously. Note that in contrast to the SUGRA prediction of $P_\tau = +1$, the SM background from $W \rightarrow \tau \nu$ and $Z(H^0) \rightarrow \tau^+\tau^-$ decays predict $P_\tau = -1$ and 0 respectively. Of course there is an alternative source of $P_\tau = +1$ in the MSSM, i.e. the charged Higgs decay $H^\pm \rightarrow \tau^\pm \nu$ [8,9]. However it will not pose a serious problem for the SUGRA signal at least in the $\tau\tau$ channel considered below, since the pair production of charged Higgs boson has a negligible cross-section at LHC. Thus the experimental confirmation of the predicted $\tau$ polarization will provide a distinctive test for the minimal SUGRA model.

The polarization formalism for $\tau$ leptons in SUSY cascade decay has been discussed in ref. [10]. The polarization of the $\tau$ for $\tilde{\tau}_1$ decay (6) is given in the collinear approximation ($m_\tau \ll m_{\tilde{\tau}_1}$) by

$$P_\tau = \frac{(a_{11}^R)^2 - (a_{11}^L)^2}{(a_{11}^R)^2 + (a_{11}^L)^2},$$

$$a_{11}^R = -\frac{2g}{\sqrt{2}} N_{11} \tan \theta_W \sin \theta_{\tau} - \frac{g m_\tau}{\sqrt{2} m_W \cos \beta} N_{13} \cos \theta_{\tau},$$

$$a_{11}^L = \frac{g}{\sqrt{2}} [N_{12} + N_{11} \tan \theta_W] \cos \theta_{\tau} - \frac{g m_\tau}{\sqrt{2} m_W \cos \beta} N_{13} \sin \theta_{\tau},$$

(8)

where

$$\hat{Z}_1 = N_{11} \hat{B} + N_{12} \hat{W} + N_{13} \hat{H}_1 + N_{14} \hat{H}_2.$$  

(9)
At low $\tan \beta$ the stau mixing angle $\cos \theta_\tau$ is small, so that the first term of $a_{11}^R$ dominates over the others. Consequently $P_\tau = +1$ holds to very good precision. But the SUSY cascade decay into the $\tau$ channel (6) becomes large only for a small part of the parameter space ($m_0 \sim \frac{1}{2} m_{1/2}$) at low $\tan \beta$. In the high $\tan \beta$ region of our interest both the stau mixing angle $\cos \theta_\tau$ and the higgsino coupling factor in eq. (8) become significant. However, there is an effective cancellation between the two terms in $a_{11}^L$, which ensures $a_{11}^L \ll a_{11}^R$. Consequently $P_\tau = +1$ holds to a very good approximation in the high $\tan \beta$ region as well.

In Figs. 1 and 2 we have shown the regions of large $P_\tau$ and large $\tilde{W}_1 \rightarrow \tilde{\tau}_1 \nu$ branching fraction for different sets of SUGRA parameters using the ISASUGRA code-version 7.48 [11]. Fig. 1 shows that at $\tan \beta = 30$ we have $P_\tau > 0.9$ over almost the entire $m_0 - m_{1/2}$ plane for both signs of $\mu$. Fig. 2 shows that this remains true when we change the trilinear coupling parameter from 0 to 500 GeV or the $\tan \beta$ value from 30 to 40. Thus the $\tau$ polarization prediction (7) for the decay channel (6) is seen to be a very robust prediction of the minimal SUGRA model.

Figs. 1 and 2 show the contours for large branching fractions of

$$\tilde{W}_1 \rightarrow \tilde{\tau}_1 \nu,$$

which is the most important source of $\tau$ production in the SUGRA model. They also show the threshold contour for this two-body decay channel along with that of the competing channel, $\tilde{W}_1 \rightarrow \tilde{W} \tilde{Z}_1$. The region, $m_0 \lesssim m_{1/2}$, corresponds to large branching fractions for the decay process (10) and hence to a large SUGRA signal in the $\tau$ channel. We have checked that the $\tau$ polarization remains $> 0.95$ over this region.

For a detailed investigation of the SUGRA signal in the $\tau\tau$ channel and the effect of $\tau$ polarization we have selected a representative point from Fig. 2b, i.e.

$$m_0 = 250 \text{ GeV}, m_{1/2} = 300 \text{ GeV}, A_0 = 0, \tan \beta = 40, \text{Sgn}(\mu) = +ve.$$  \hspace{1cm} (11)

The resulting superparticle masses (in GeV) and mixing angle are

$$m_{\tilde{g}} = 736, m_{\tilde{q}} = 680, m_{\tilde{W}} = 232, m_{\tilde{Z}_2} = 233, m_{\tilde{\tau}_1} = 197, m_{\tilde{Z}_1} = 124, \cos \theta_\tau = 0.41.$$  \hspace{1cm} (12)
The relevant decay branching fractions are

\[ B(\tilde{q} \to q\tilde{W}_1, q\tilde{Z}_2, q\tilde{Z}_1) = 0.62, 0.30, 0.08 \]
\[ B(\tilde{W}_1 \to \tilde{\tau}_1 \nu \to \tau \nu \tilde{Z}_1) = 0.76, B(\tilde{Z}_2 \to \tau' \tilde{\tau}_1 \to \tau' \tau \tilde{Z}_1) = 0.97. \] (13)

The two main sources of \( \tau \tau \) signal are

\[ \tilde{q} \bar{q} \to q\tilde{W}_1^+ \tilde{W}_1^- \to q\tilde{\nu}\bar{\nu} \tilde{Z}_1 \tau \tau, \] (14)
\[ \tilde{q} \bar{q} \to q\tilde{W}_1^\pm \tilde{Z}_2 \to q\tilde{\nu}\bar{\nu} \tilde{Z}_1 \tau' \tau \tau, \] (15)

which have branching fractions of 22 and 27% respectively. It may be noted here that \( P_\tau = 0.985 \), but \( P_{\tau'} = -0.996 \). The dominant contribution to the \( \tau' \) polarization comes from \( a_{12}^L \simeq g \sqrt{2} N_{22} \cos \theta_* \) [10]. However we shall see below that the presence of \( \tau' \) shall not seriously compromise the experimental test of \( P_\tau \).

We have done a parton level Monte Carlo study of the SUGRA signal from \( \tilde{g} \tilde{g} \) and \( \tilde{g} \tilde{q} \) production in the channels (14) and (15). In addition to the taus and the \( E_T \) there are at least three hadronic jets. To simulate detector resolution we have applied Gaussian smearing on each jet \( p_T \) (including the \( \tau \)-jets) with

\[ (\sigma(p_T)/p_T)^2 = (0.6/\sqrt{p_T})^2 + (0.04)^2 \] (16)
in GeV units. The \( E_T \) is evaluated from the vector sum of the jet \( p_T \)'s after resolution smearing. To suppress the SM background we require the identified \( \tau \)-jet pair to be accompanied by at least three hard jets and a large \( E_T \) with

\[ E_T, p_{T_1} > 100 \text{ GeV}, p_{T_2}, p_{T_3} > 50 \text{ GeV}, M_{\text{eff}} > 500 \text{ GeV}, \] (17)

where \( M_{\text{eff}} \) is the scalar sum of all the jet \( p_T \)'s and \( E_T \) [6].

The hadronic decay channel of \( \tau \) is known to be sensitive to \( \tau \) polarization [8,9]. We shall concentrate on the 1-prong hadronic decay of \( \tau \), which is best suited for \( \tau \) identification. It accounts for 80% of hadronic \( \tau \) decay and 50% of its total decay width. The main contributors to the 1-prong hadronic decay are

\[ \tau^\pm \to \pi^\pm \nu(12.5\%), \rho^\pm \nu(26\%), a_1^\pm \nu(7.5\%), \] (18)

where the branching fractions for \( \pi \) and \( \rho \) include the small \( K \) and \( K^* \) contributions respectively, which have identical polarization effects [12]. Together
they account for 90% of the 1-prong hadronic decay. The CM angular distribution of \( \tau \) decay into \( \pi \) or a vector meson \( v(= \rho, a_1) \) is simply given in terms of its polarization as

\[
\frac{1}{\Gamma_{\pi}} \frac{d\Gamma_{\pi}}{d\cos \theta} = \frac{1}{2} (1 + P_{\tau} \cos \theta),
\]

(19)

\[
\frac{1}{\Gamma_v} \frac{d\Gamma_v}{d\cos \theta} = \frac{1}{2} \frac{m_{\pi,v}^2}{m_{\tau}^2 + 2m_{\nu}^2} (1 \pm P_{\tau} \cos \theta),
\]

(20)

where \( L, T \) denote the longitudinal and transverse polarization states of the vector meson. The fraction \( x \) of the \( \tau \) lab. momentum carried by its decay meson is related to the angle \( \theta \) via

\[
x = \frac{1}{2} (1 + \cos \theta) + \frac{m_{\pi,v}^2}{2m_{\tau}^2} (1 - \cos \theta)
\]

(21)

in the collinear approximation. The only measurable \( \tau \) momentum is the visible momentum of the \( \tau \)-jet,

\[
p_{\tau-\text{jet}} = xp_{\tau}.
\]

(22)

We see from eqs. (19-22) that \( P_{\tau} = +1 \) gives a harder \( \tau \)-jet than \( P_{\tau} = -1 \).

We shall require two identified \( \tau \)-jets with

\[
p_{\tau-\text{jet}}^T > 40 \text{ GeV, } |\eta_{\tau-\text{jet}}| < 2.5, \ R > 0.2,
\]

(23)

where

\[
R = p_{\tau \pm}/p_{\tau-\text{jet}},
\]

(24)

i.e. the fraction of the visible \( \tau \)-jet momentum carried by the charged prong. This can be obtained by combining the charged prong momentum measurement in the tracker with the calorimetric energy deposit of the \( \tau \)-jet. This quantity \( R \) is a good discriminator of \( \tau \) polarization [9].

Before proceeding to the test of \( \tau \)-polarization, however, let us discuss the size of the \( \tau \tau \) signal and also the contamination of \( P_{\tau} \) by the presence of \( \tau' \). With the kinematic cuts of (23) the CDF collaboration has estimated a \( \tau \) detection efficiency of 50% and a fake tau rejection factor of 0.1% at Tevatron [13]; and one expects similar numbers for the CMS experiment at LHC [14]. With the SM background already suppressed by the \( E_T \) and \( M_{\text{eff}} \)
cuts of (17) it should be possible to get a better efficiency for \( \tau \) detection at the cost of a lesser rejection factor for fakes. However we shall conservatively assume a 50% detection efficiency for each \( \tau \)-jet. Combining this with the 50% branching fraction for 1-prong hadronic \( \tau \) decay and the 22 and 27% branching fractions for the decay chains (14) and (15) gives a net probability factor of about 1.5% for catching the SUGRA signal in the two identified \( \tau \)-jets channel via each of these decay chains. The effect of the kinematic cuts (17) and (23) are taken into account through the Monte Carlo program. We get a net signal cross-section of \( \sim 15 \text{ fb} \) in this channel from \( \tilde{g}\tilde{g} \) and \( \tilde{q}\tilde{g} \) production, which includes an average \( K \) factor of 1.4 from NLO correction [15]. It corresponds to 150 events for the low luminosity (10 \( \text{fb}^{-1}/\text{yr} \)) run of LHC, going up to 1500 events at high luminosity (100 \( \text{fb}^{-1}/\text{yr} \)).

We have tried to minimise the contamination of the \( \tau \) polarization by the presence of the \( \tau' \) in the decay chain (13) via the following requirements. Firstly the two identified \( \tau \)-jets are required to have an invariant mass > 100 GeV, which ensures that they come from different gauginos. Secondly they are required to have opposite charge. This ensures that the detection probability for the \( \tau\tau \) and \( \tau\tau' \) pair in (13) is 1/2 each, while it is 1 for the \( \tau\tau \) pair in (14). Moreover the probability of the \( \tau \)-jet passing the visible \( p_T > 40 \text{ GeV} \) cut (23) is only 25% for the \( \tau' \) against 60% for \( \tau \). The difference comes partly due to their opposite polarization and partly due to the different kinematics. The end result is that the relative probability factors of detecting the \( \tau\tau \) and \( \tau\tau' \) pairs from (14,15) are \(.60 \times (.22 + .27/2) \) and \(.25 \times (.27/2) \) respectively. One can easily check that it has the effect of reducing the predicted polarization (6) by 13-14% for each \( \tau \). We shall neglect this effect as a first approximation. Note that the requirement of opposite charge for the pair of \( \tau \)-jets also cuts the fake \( \tau \) background by half.

To test \( \tau \)-polarization we observe from eqs. (19-22) that the hard \( \tau \)-jet is dominated by the \( \pi \) and longitudinal vector meson (\( \rho_L, a_1L \)) contributions for \( P_\tau = +1 \), while it is dominated by the transverse \( \rho \) and \( a_1 \) contributions for \( P_\tau = -1 \). The two sets can be distinguished by exploiting the fact that the transverse \( \rho \) and \( a_1 \) decays favour even sharing of momentum among the decay pions, while the longitudinal \( \rho \) and \( a_1 \) decays favour uneven sharing, where the charged pion carries either very little or most of the momentum. It is easy to derive this quantitatively for \( \rho \) decay; but one has to assume a dynamical model for \( a_1 \) decay for a quantitative result. We shall assume the model of ref. [16], based on conserved axial-vector current approximation,
which provides an accurate description of the $a_1 \to 3\pi$ decay data. A detailed account of the $\rho$ and $a_1$ decay formalisms including finite width effects can be found in [8,9]. A simple FORTRAN code for 1-prong hadronic decay of polarized $\tau$ based on these formalisms can be obtained from one of the authors (D.P. Roy).

Figs. 3 shows the $P_\tau = +1$ signal as a function of the $\tau$-jet momentum fraction $R$, carried by the charged-prong. For comparison it also shows the corresponding distribution assuming the signal to have $P_\tau = -1$. This could be the case e.g. in some nonuniversal SUSY models with a higgsino LSP or the anomaly mediated SUSY model with a wino LSP. In particular the decay of a stau into tau and a wino LSP will always proceed via its left component giving $P_\tau = -1$. The $P_\tau = +1$ signal shows the peaks at the two ends from the $\rho_L, a_{1L}$ along with the pion contribution (added to the last bin). Of course the peak at the low $R$ end is partly cut out by the $\tau$-identification requirement [23]. In contrast the $P_\tau = -1$ distribution shows a central peak due to the $\rho_T, a_{1T}$ along with a reduced pion contribution. The complimentary shape of the two distributions reflects the uneven sharing of momentum between the charged and the neutral pions for $\rho_L, a_{1L}$ decays and its even sharing for $\rho_T, a_{1T}$ decays. The distribution for $P_\tau = 0$, lying midway between the above two distributions, is also shown for comparison.

Let us look at the fractional cross-section lying above $R = 0.8$ as a measure of the $\tau$ polarization. This fraction is 0.60 for $P_\tau = +1$ but only .25 (.40) for $P_\tau = -1(0)$. Thus one can require both the identified $\tau$-jets to contain hard charged prongs carrying $> 80\%$ of the respective $\tau$-jet momenta, i.e. $R_{1,2} > 0.8$. Then 36\% of the $P_\tau = +1$ signal will pass this cut, while the corresponding fraction is only 6 (16)\% for $P_\tau = -1(0)$. Thus with the expected sample of $\sim 150$ signal events at the low luminosity run of LHC (10 fb/yr), one expects 54 events to pass this cut for $P_\tau = +1$ against only 9 (24) events for $P_\tau = -1(0)$. This will provide an unambiguous test for the $\tau$-polarization, predicted by the minimal SUGRA model. At the high luminosity run the test can be extended to a wider range of the parameter space of figs. 1 and 2, going down to $B(\tilde{W}_1 \to \tilde{\tau}_1 \nu \to \tau \nu \tilde{Z}_1) = 0.3$ and upto $m_{1/2} = 400 - 500$ GeV. One can extend this range further in the one identified $\tau$ channel. It may be added here that for the fake $\tau$ background from QCD jets the fractional cross-section surviving the $R > 0.8$ cut is even less than 0.2 [14]. Thus the $R > 0.8$ peak provides a distinctive test for the $P_\tau = +1$ signal not only against the $P_\tau = -1(0)$ background but against the fake $\tau$
background as well. Finally, it should be noted that while we have focussed the current analysis on the SUGRA model the same polarization strategy can be used to distinguish the SUSY signal from the SM backgrounds in the gauge mediated SUSY breaking model[17], where one expects $P_{\tau} = +1$ $\bar{\tau}_R \to \tau \bar{G}$ decay.

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Figure 1: $BR(\tilde{W}_1 \to \tilde{\tau}_1 \nu_{\tau})$ is shown as contour plots (dashed lines) in $m_0$ and $m_{1/2}$ plane for $A_0 = 0$, $\tan \beta = 30$ and (a) positive ($\mu$) (b) negative ($\mu$). The kinematic boundaries (dotted lines) are shown for $\tilde{W}_1 \to W\tilde{Z}_1$ and $\tilde{W}_1 \to \tilde{\tau}_1 \nu_{\tau}$ decay. The entire region to the right of the boundary (dot-dashed line) corresponds to $P_\tau > 0.9$. The excluded region on the right is due to the $\tilde{\tau}_1$ being the LSP while that on the left is due to the LEP constraint $m_{\tilde{W}_i^\pm} > 102$ GeV.
Figure 2: Same as Fig.1 for (a) $A_0 = 500$ GeV, $\tan \beta = 30$ and (b) $A_0 = 0$, $\tan \beta = 40$ with positive ($\mu$) in both cases.
Figure 3: The normalised SUSY signal cross sections for $P_{\tau}=1$ (solid line), 0 (dotted lines) and -1 (dashed lines) in the 1-prong hadronic $\tau$-jet channel shown as functions of the $\tau$ jet momentum fraction ($R$) carried by the charged prong.