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A clean slepton mixing signal at the LHC

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Abstract: In supersymmetric scenarios where the scalar tau lepton is stable or long-lived, a search for a decay mode $\chi^0 \to \tilde{\tau}\mu$ at the LHC has a good sensitivity to the flavor mixing in the scalar lepton sector. We demonstrate that the sensitivities to the mixing angle at the level of $\sin\theta_{23} = 0.15$ are possible with an integrated luminosity of $100\,\mathrm{fb}^{-1}$ if the total production cross section of supersymmetric particles is of the order of 1 pb. The sensitivity to the mixing parameter can be better than the experimental bound from the $\tau \to \mu\gamma$ decay depending on model parameters.

Keywords: Global Symmetries, Supersymmetry Phenomenology, Supersymmetric Standard Model, Rare Decays.

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If new physics contains a charged stable particle, such as the scalar tau lepton ($\tilde{\tau}$) in supersymmetric (SUSY) models, it provides a very clean signal at the LHC experiments. Once they are produced, most of them penetrate detectors and leave charged tracks just like muons. By measuring the velocity at the muon system, we can easily distinguish from the muon background. A very precise mass measurement is possible by combining with the momentum measurements [1].

Scenarios with such a charged stable or long-lived particle have sounded exotic and regarded as alternative possibilities. However, recent serious considerations of SUSY phenomenology have shown that it is indeed theoretically motivated [2]. The presence of such particles does not immediately contradict with cosmological history. There are interesting cosmological scenarios and even motivations for such a long-lived particle [3 – 6]. If it is the case, we will have new kinds of signals in new physics search experiments.

In this paper, we propose a search strategy for flavor mixing in the scalar lepton sector in the stable (or long-lived) $\tilde{\tau}$ scenario at the LHC. In the presence of the flavor mixing, we will have a decay mode of the neutralinos $\chi^0 \to \tilde{\tau}\mu$. By looking for sharp peaks in the $\tilde{\tau}$-μ invariant mass, we show that we will be able to discover lepton flavor violation for $\Gamma(\chi_1^0 \to \tilde{\tau}\mu)/\Gamma(\chi_1^0 \to \tilde{\tau}\tau) \simeq \tan^2\theta_{23} \gtrsim 10^{-2}$, where θ_{23} is the slepton mixing angle.

There have been many studies on lepton flavor violation at the LHC and e^+e^- colliders assuming the neutralino to be the lightest SUSY particle. The possibility of observing $e^\pm\mu^\mp$ + missing E_T final states at e^+e^- colliders has been pointed out in ref. [7]. The correct treatment of the process including quantum interference (slepton oscillation) has been studied in ref. [8] and discussion has been expanded to the LHC experiments and CP violation in ref. [9]. Following those papers, LHC studies on searches for decay processes $\chi_2^0 \to l_i^\pm l_j^\mp \chi_1^0$ with $i \neq j$ have been done in refs. [10]. The sensitivities of $O(0.1)$ for mixing angles have been derived in various SUSY models.

Lepton flavor violation in the long-lived $\tilde{\tau}$ scenario has also been studied. In ref. [11], the decay of $\tilde{\tau}$ into e or μ and a gravitino is studied under an assumption that a significant number of $\tilde{\tau}$'s will be collected at the LHC or future linear collider experiments by placing a massive stopper material close to the detectors [12]. A linear collider study with long-lived $\tilde{\tau}$ has also been done in ref. [13] where it is proposed to search for lepton flavor violating final states such as $(e^+\tau^\pm\tilde{\tau}^\mp)\tilde{\tau}^-$ through slepton pair production processes. Very good sensitivities as well as $\sin\theta \sim$ (a few)$\times 10^{-2}$ are reported in both of the works. We study in the following the LHC signals of slepton flavor mixing without new detectors or future colliders. Therefore it serves as the first search strategy that can be done immediately after the LHC starts if $\tilde{\tau}$ is stable or long-lived.

In order to estimate the sensitivity, we performed the following Monte Carlo simulation. We used a model of ref. [2] where the spectrum of the SUSY particles are parametrized by four quantities:

$$\mu, \quad M_{\text{gaugino}} \left(\equiv M_{\tilde{g}}/g_3^2\right), \quad M_{\text{mess}}, \quad N_{\text{mess}}. \tag{1}$$

The μ parameter and M_{gaugino} control the Higgsino mass and the gaugino masses, respectively. The messenger scale M_{mess} and the number of messenger particle N_{mess} determines

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masses of scalar particles relative to the gaugino masses. We have chosen two parameter points where $\tilde{\tau}$ is the lightest SUSY particle (except for the gravitino):

$$\text{Model I}: \quad \mu = 300 \text{ GeV}, \quad M_{\text{gaugino}} = 900 \text{ GeV}, \quad M_{\text{mess}} = 10^{10} \text{ GeV}, \quad N_{\text{mess}} = 1\,, \tag{2}$$

$$\text{Model II}: \quad \mu = 500 \text{ GeV}, \quad M_{\text{gaugino}} = 900 \text{ GeV}, \quad M_{\text{mess}} = 10^{8} \text{ GeV}, \quad N_{\text{mess}} = 1\,. \tag{3}$$

The $\tilde{\tau}$ and neutralino masses in Model I are $m_{\tilde{\tau}} = 116$ GeV and ($m_{\chi_1^0}$, $m_{\chi_2^0}$, $m_{\chi_3^0}$, $m_{\chi_4^0}$) = (187 GeV, 276 GeV, 306 GeV, 404 GeV). In Model II, $m_{\tilde{\tau}} = 157$ GeV and ($m_{\chi_1^0}$, $m_{\chi_2^0}$, $m_{\chi_3^0}$, $m_{\chi_4^0}$) = (194 GeV, 346 GeV, 505 GeV, 525 GeV). We chose a parameter with heavier Higgsinos in Model II.

With the SUSY spectra, we have generated 40,000 SUSY events for each model by using the Herwig 6.50 event generator [14] with the CTEQ5L parton distribution function [15]. This corresponds to an integrated luminosity of 33 fb^{-1} (46 fb^{-1}) at the LHC for Model I (Model II). We set the mixing angle of the right-handed sleptons to be $\sin\theta_{23} = 0.33$ with which the branching ratio of the lightest neutralino is $\Gamma(\chi_1^0 \to \tilde{\tau}\mu)/\Gamma(\chi_1^0 \to \tilde{\tau}\tau) \simeq 0.1$. Heavier neutralinos do not have significant branching ratios for the $\chi^0 \to \tilde{\tau}\mu$ decays because the amplitudes are suppressed by the Yukawa coupling constant of the muon. With SUSY spectra with the lightest neutralino being almost the Bino and the lighter $\tilde{\tau}$ to be almost right-handed (which is the case in the above two models), the following method is not sensitive to mixings in left-handed sleptons. The events are passed through a detector simulator AcerDET 1.0 [16] where muon momenta are smeared according to the resolutions of the ATLAS detector. We have also smeared the momenta and velocities of $\tilde{\tau}$'s according to the resolution obtained in ref. [17];

$$\frac{\sigma(p)}{p} = k_1 p \oplus k_2 \sqrt{1 + \frac{m^2}{p^2}} \oplus \frac{k_3}{p}\,, \tag{4}$$

where $k_1 = 0.0118\%$, $k_2 = 2\%$ and $k_3 = 89\%$. The momentum p is in GeV. The resolution of the velocity is

$$\frac{\sigma(\beta)}{\beta} = 2.8\% \times \beta\,. \tag{5}$$

We have ignored the η dependence of the resolutions. Also, in the following analysis, we assume that the $\tilde{\tau}$ mass is known with a good accuracy by the method of ref. [1].

We have followed the strategy of ref. [1] for the identification of $\tilde{\tau}$. We require the candidate tracks to be within $|\eta| < 2.4$, $P_T > 20$ GeV and $\beta\gamma_{\text{meas}} > 0.4$. The cut on the measured velocity ensures $\tilde{\tau}$ to reach the muon system. A consistency condition: $|\beta' - \beta_{\text{meas}}| < 0.05$ is imposed, where β' is a velocity calculated from the momentum $\left(\beta' = \sqrt{p^2/(p^2 + m_{\tilde{\tau}}^2)}\right)$. By also requiring the measured velocities of at least one candidate $\tilde{\tau}$ to be within $0.4 < \beta\gamma_{\text{meas}} < 2.2$ for each event, this selection strategy reduces background from mis-identified muons to a negligible level [1]. We therefore ignore in the following analysis the background from the standard model processes as well as from muons in SUSY events.

In order to look for lepton flavor violating neutralino decays, we selected events with only one isolated muon with $P_T > 20$ GeV and at least one opposite-sign $\tilde{\tau}$ candidate. If

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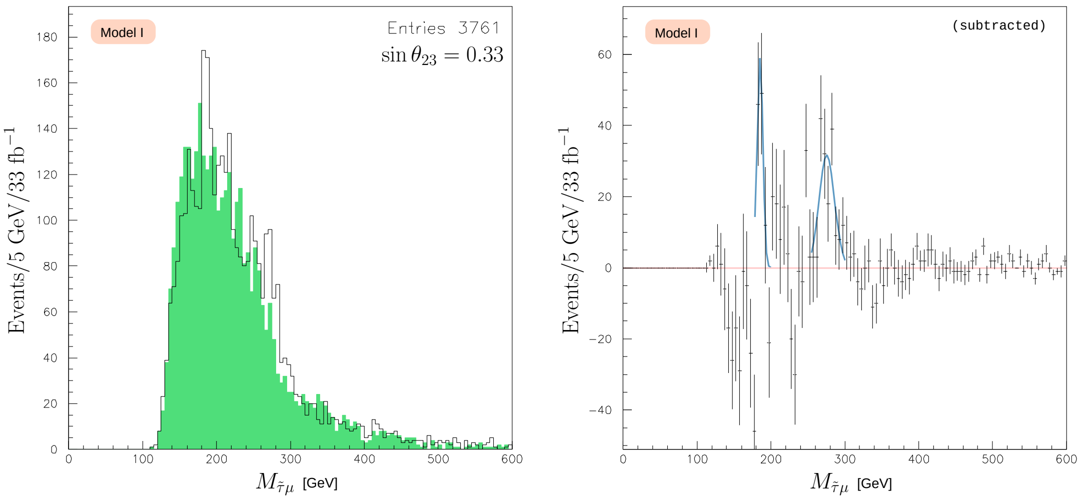

Figure 1: The $\tilde{\tau}$-μ invariant mass distribution in Model I. The shaded histogram in the left panel is the estimated background, i.e., the $\tilde{\tau}$-e invariant mass distribution. By subtracting the estimated background, we obtain the histogram in the right panel.

there are two opposite-sign $\tilde{\tau}$-μ pairs, we use both of them for the analysis. The invariant mass $M_{\tilde{\tau}\mu}$ is calculated for each candidate event.

The invariant mass distribution is shown in the left panel of figure 1, where we can clearly see a peak at the lightest neutralino mass (187 GeV). The shape and normalization of the background distribution can be obtained from the $M_{\tilde{\tau}e}$ distribution directly from the data (shaded histogram). By subtracting those estimated background, we obtain the histogram in the right panel where we see that the background is successfully subtracted. Therefore we can reliably use the $M_{\tilde{\tau}e}$ distribution as an expected background. We can also find an excess around masses of the lighter Higgsino-like neutralino (~ 276 GeV). Most of the background originates from the $\chi^0 \to \tilde{\tau}\tau$ decay followed by $\tau \to \mu\nu\bar{\nu}$. Although the signal region is the kinematic endpoint of this background for each neutralino, the background $\tilde{\tau}\mu$ pairs from heavier neutralinos fall into the signal region. There are also backgrounds from leptonic decays of W bosons. Numbers of such background events depend on cascading pattern of heavy SUSY particles.

We fitted two peaks in the right panel of figure 1 with the gaussian function and defined the signal region to be the 1σ region around the peaks; $|M_{\tilde{\tau}\mu} - 185.2\text{ GeV}| < 3.8$ GeV and $|M_{\tilde{\tau}\mu} - 276\text{ GeV}| < 10$ GeV. In the case where there are not enough events to find the neutralino masses by the $M_{\tilde{\tau}\mu}$ distribution, one should look for edges in the invariant mass of $\tilde{\tau}$ and τ-jet, $M_{\tilde{\tau}j_\tau}$, for the neutralino mass measurements as is done in ref. [2]. There are $S + B = 584$ events in the signal region whereas the number of the expected background in the signal region is $B = 374$. Therefore we obtain 9σ excess with 33 fb^{-1} of data.[1]

[1]This level of excess is somewhat optimistic given that we know the correct location of the peaks. In the actual experimental situation, the peak locations (the neutralino masses) will be measured by looking for the endpoint locations of the invariant mass $M_{\tilde{\tau}j_\tau}$. The uncertainty of this measurement is estimated to be at most of order 5% [2] by taking into account the effects of fake τ-jets and the uncertainties in calibration

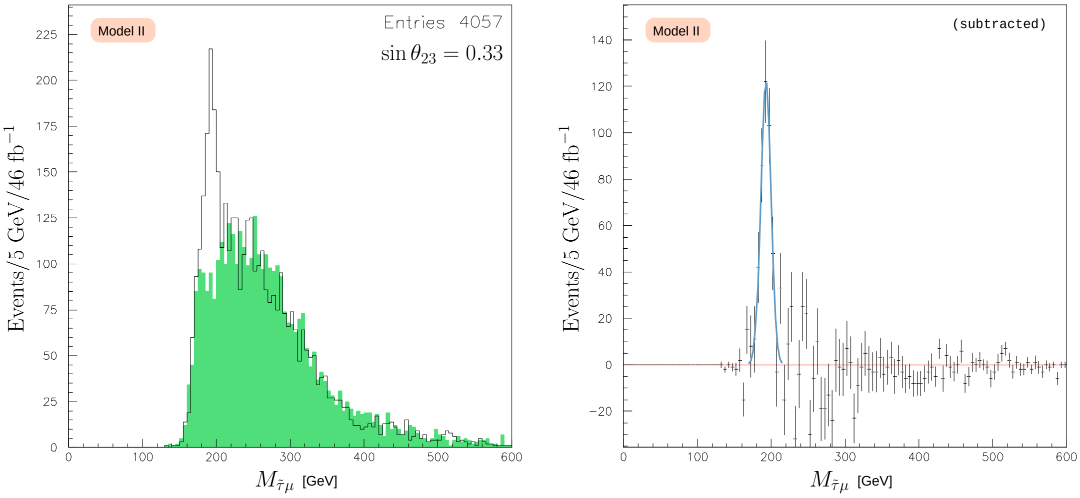

Figure 2: The $\tilde{\tau}$-μ invariant mass distribution in Model II. The shaded histogram in the left panel is the estimated background, i.e., the $\tilde{\tau}$-e invariant mass distribution. By subtracting the estimated background, we obtain the histogram in the right panel.

Normalizing to the integrated luminosity of $100\,\text{fb}^{-1}$, the number of needed signal events for 5σ discovery to be 181, corresponding to $\sin\theta_{23} > 0.18$.

We repeat the same analysis for the Model II and the result is shown in figure 2. There is only one peak associated with the Bino-like neutralino because the number of Higgsinos in cascade decays is reduced and the branching ratios of $B(\chi^0_{3,4} \to \tilde{\tau}\tau)$ are suppressed with the relatively heavy Higgsinos. A slightly better sensitivity than Model I is obtained. In the signal region, $|M_{\tilde{\tau}\mu} - 193.0\text{ GeV}| < 6.9$ GeV, we find $S + B = 539$ and $B = 238$ for $46\,\text{fb}^{-1}$. Normalizing to $100\,\text{fb}^{-1}$ of data, we obtain the 5σ sensitivity to be $\sin\theta_{23} > 0.15$.

If no peak is found due to small mixing angles, one can put a bound on the branching fraction (or equivalently the mixing angle). This requires a counting of the $\chi^0 \to \tilde{\tau}\tau$ events that involves the efficiency measurement of the τ identification. That will be the dominant uncertainty in putting the experimental bound. As far as order of magnitude is concerned, the sensitivity will be at the level of $\sin\theta_{23} \sim 0.1 - 0.2$.

The search for the $\tau \to \mu\gamma$ decay has already put a stringent bound on a combination of various SUSY parameters involving the slepton mixings. Although a model independent comparison is not possible, we can get a sense of sensitivities to the mixing parameter by calculating the $\tau \to \mu\gamma$ branching ratio with a particular parameter set. We have done that in Model I and II with $\sin\theta_{23} = 0.15$. The branching ratios are $B(\tau \to \mu\gamma) = 1 \times 10^{-6}$ and 4×10^{-9} for Model I and II, respectively. Compared with the current experimental bound, 4.5×10^{-8} [18], the LHC sensitivities can be much better (or worse) depending on model parameters. One should also note that the measurement of $\Gamma(\chi^0 \to \tilde{\tau}\mu)/\Gamma(\chi^0 \to \tilde{\tau}\tau)$ at the LHC will directly probe the slepton mixing parameter. Therefore, measuring/constraining

of the τ-jet energies. If we use the central values given in table 2 of ref. [2] and the 5% errors for the definition of the signal region, i.e., 194 ± 10 GeV and 279 ± 14 GeV, we obtain about a 7σ excess, where most of the significance is a contribution from the second peak.

	$\sigma_{\rm SUSY}$ $(\mathcal{L})$	$S+B$	B	$S/\sqrt{S+B}$	$\sin\theta_{23}^{\rm min}$ $(100\,{\rm fb}^{-1})$	$B(\tau\to\mu\gamma)$
Model I	1.2 pb $(33\,{\rm fb}^{-1})$	584	374	9	0.18	1×10^{-6}
Model II	0.88 pb $(46\,{\rm fb}^{-1})$	539	238	13	0.15	4×10^{-9}

Table 1: LHC sensitivities and comparison to the $\tau\to\mu\gamma$ decay. The number of signal (S) and background (B) events are shown for 40,000 SUSY events and $\sin\theta_{23}=0.33$. For this level of the large mixing angle, the statistical significances can be as large as 10σ. The 5σ-level discovery with an integrated luminosity of $100\,{\rm fb}^{-1}$ requires the angle to be $\sin\theta_{23}>0.15$. The $\tau\to\mu\gamma$ branching ratios are shown for $\sin\theta_{23}=0.15$.

the branching fractions of both processes will be important to understand the flavor structure of SUSY models. We summarize the results in table 1.

A similar analysis will go through for a $\chi^0\to\tilde{\tau}e$ search at the LHC. Also, if a linear collider is built in future, searches for a decay mode $\chi^0\to\tilde{\tau}\mu$ through a neutralino pair production process may give a better sensitivity to the mixing angle as background from heavier neutralinos and W bosons will be under better control.

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