Tau Polarization in the Analysis of $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell^+ \ell^-$ *

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ABSTRACT

The decay $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell^+ \ell^-$ would provide much information about the supersymmetric sector. The endpoint of the dilepton spectrum would provide the difference of the masses of the two lightest neutralinos. The observation of this decay in the tau channel would provide complementary information about the mixing of the neutralinos and about the masses and mixing of sleptons.

The decay of the second lightest (neutral) supersymmetric particle to the lightest and a lepton pair is potentially an important source of information, accessible at the LHC.[1] In particular, the endpoint of the $\ell^+\ell^-$ invariant mass spectrum is $m(\tilde{\chi}_2^0) - m(\tilde{\chi}_1^0)$, the difference of the two neutralino masses. The decay $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell^+ \ell^-$ is important and competes with $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 q\overline{q}$, provided channels like $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h^0$ are not open.

The decay $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell^+ \ell^-$ proceeds via slepton exchange. Because the neutralinos are Majorana particles, either lepton can come from the $\tilde{\chi}_1^0$ or $\tilde{\chi}_2^0$ vertex. The couplings of the neutralinos depend on the mixing of the gauginos and higgsinos. For our purposes we consider only the gaugino portions. In addition to gaugino mixing, there is mixing of the left and right sleptons.

The decay to e^+e^- or $\mu^+\mu^-$ allows measurement of the invariant mass distribution, $d\Gamma/dm_{+-}^2$. The decay to $\tau^+\tau^-$ allows observation of the τ polarization and thus complementary information. This is quite analogous to the process $Z' \to \ell^+\ell^-$. [2]. The polarization information in the neutralino decay will constrain a combination of the gaugino mixing angle, the slepton mixing angle, and the slepton masses. To demonstrate the principles involved we consider a particularly simple limit:

1. We take the sleptons to be unmixed. As a result, left-handed leptons and right-handed antileptons will come only from left slepton exchange and right slepton exchange will lead only to the opposite handedness.

2. We take the neutralinos to be linear combinations of the $\tilde{B}$ and $\tilde{W}^3$

3. We take the sleptons to be much heavier than the gauginos.

4. We consider only $\tau \to \nu\pi$ as an analyzing decay.

Following Wess and Bagger [3] and the guidance of Haber and Kane [4], we write the pertinent interaction Lagrangian as

$$\begin{aligned}\mathcal{L} &= i\sqrt{2}g_{Lj}[\tilde{\psi}_L\overline{\psi}_L\Lambda_j - \overline{\tilde{\psi}}_L\overline{\Lambda}_j\psi_L] \\ &\quad -i\sqrt{2}g_{Rj}[\tilde{\psi}_R\overline{\psi}_R\Lambda_j - \overline{\tilde{\psi}}_R\overline{\Lambda}_j\psi_R] \end{aligned} \tag{1}$$

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where ψ_L and ψ_R are the left- and right-handed parts of the lepton field, $\Lambda_j,\ j = 1,2$ are the Majorana fields for $\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0$, and $\tilde{\psi}_L$ and $\tilde{\psi}_R$ are the left- and right-handed sleptons (which have opposite electric charges). The couplings g_L and g_R reflect the $\tilde{B} - \tilde{W}^3$ mixing and the SU(2) x U(1) quantum numbers of the leptons and sleptons. For example, if $\tilde{\chi}_2^0$ is pure $\tilde{W}^3$, then $g_{R2} = 0$.

Let the momenta of the $\tilde{\chi}_2^0$, $\tilde{\chi}_1^0$, ℓ^- and ℓ^+ be p_2, p_1, k^+, and k^-, respectively. Consider first the case in which ℓ^- is produced left-handed (and ℓ^+ is right-handed). The two diagrams give

$$\begin{aligned}-i\mathcal{M} &= -\sqrt{2}g_{L2}\overline{u}_L(k^-)u(p_2)\sqrt{2}g_{L1}\overline{u}(p_1)v_R(k^+)\frac{i}{-\tilde{m}_L^2} \\ &\quad -[-\sqrt{2}g_{L2}\overline{v}(p_2)v_R(k^+)\sqrt{2}g_{L1}\overline{u}_L(k^-)v(p_1)]\frac{i}{-\tilde{m}_L^2}\end{aligned} \tag{2}$$

where the minus sign between the two terms reflects the Dirac statistics of the charged leptons. Here

$$\begin{aligned}u_L(k^-) &= \tfrac{1}{2}(1-\gamma_5)u(k^-) \\ v_R(k^+) &= \tfrac{1}{2}(1-\gamma_5)v(k^+)\end{aligned} \tag{3}$$

The peculiar mixture of spinors in the amplitude is the consequence of the presence of Majorana particles and is resolved by the relations

$$\begin{aligned}v(k,s) &= C\overline{u}^T(k,s) \\ u(k,s) &= C\overline{v}^T(k,s)\end{aligned} \tag{4}$$

where C is the charge-conjugation matrix.
The spin sums

$$\begin{aligned}\sum_s u(k,s)\overline{u}(k,s) &= \not{k} + m \\ \sum_s v(k,s)\overline{v}(k,s) &= \not{k} - m\end{aligned} \tag{5}$$

are, using Eq.(4), supplemented by

$$\begin{aligned}\sum_s u(k,s)v(k,s)^T &= (\not{k} + m)C^T \\ \sum_s \overline{u}(k,s)^T\overline{v}(k,s) &= C^{-1}(\not{k} - m)\end{aligned} \tag{6}$$

Combining these relations, we have

$$
\begin{aligned}
|\mathcal{M}|^2 &= \left(\frac{2g_{L1}g_{L2}}{\tilde{m}_L^2}\right)^2 (4p_2\cdot k^- p_1\cdot k^+ \\
&\quad +4p_1\cdot k^- p_2\cdot k^+ + 4m_1m_2k^+\cdot k^-)
\end{aligned} \tag{7}
$$

This result is similar to that for the process $e^+e^- \to \tilde{\gamma}\tilde{\gamma}$ discussed by Haber and Kane [4].

The pertinent distribution is with respect to the invariant mass, m_{+-}, of the observed lepton pair. The decay distribution is given by

$$
d\Gamma \propto |\mathcal{M}|^2 p_1 dm_{+-}^2\, d\cos\theta \tag{8}
$$

where θ is the polar angle in the lepton-pair center of mass of one lepton relative to the line of flight of $\tilde{\chi}_1^0$. If

$$
\begin{aligned}
E_{+-} &= \gamma m_{+-} \\
&= \frac{m_2^2 + m_{+-}^2 - m_1^2}{2m_2}
\end{aligned} \tag{9}
$$

is the energy of the lepton pair in the $\tilde{\chi}_2^0$ restframe and $p_{+-} = \beta\gamma m_{+-}$ is its momentum, we find using Eq. (7)

$$
\begin{aligned}
\frac{d\Gamma}{dm_{+-}^2} &\propto \left(\frac{2g_{L1}g_{L2}}{\tilde{m}_L^2}\right)^2 p_1 \left[(m_2^2 - m_1^2)E_{+-}\right. \\
&\quad \left. -m_2(E_{+-}^2 + \tfrac{1}{3}p_{+-}^2) + m_1 m_{+-}^2\right]
\end{aligned} \tag{10}
$$

where E_{+-} and p_{+-} are the energy and momentum of the lepton pair. The result for right-slepton exchange, with the production of a right-handed lepton and left-handed anti-lepton, is identical except for the replacement $g_{L1}g_{L2}/\tilde{m}_L^2 \to g_{R1}g_{R2}/\tilde{m}_R^2$. Of course in the limit considered here, it is only these two combination of couplings and masses that are accessible.

The handedness of the final state leptons, when they are τs, is reflected in the decay distributions. In particular, for $\tau^- \to \pi^-\nu$, the fraction x, of the τ^-'s energy given to the π^-, has the distribution

$$
\frac{dN}{dx} = 2(1-x) \tag{11}
$$

for left-handed τ^- and

$$
\frac{dN}{dx} = 2x \tag{12}
$$

for right-handed τ^-. If both τs decay in this fashion, the invariant mass of the observed pion pair is $m_{obs} = x_+x_-m_{+-}$, where $x_\pm$ is the fraction of the $\tau^\pm$ energy carried by the $\pi^\pm$. Thus the distribution for left-handed τ^- and right-handed τ^+ is

$$
\begin{aligned}
\frac{d\Gamma(\tau_L^-\tau_R^+)}{dm_{\rm obs}^2} &= 4\int_{m_{\rm obs}^2}^{m_{\rm max}^2} \frac{d\mu^2}{\mu^2}\frac{d\Gamma}{dm_{+-}^2}(\mu^2) \\
&\quad \times\left[(1+\frac{m_{\rm obs}^2}{\mu^2})\ln\frac{\mu^2}{m_{\rm obs}^2} + \frac{2m_{\rm obs}^2}{\mu^2} - 2\right]
\end{aligned} \tag{13}
$$

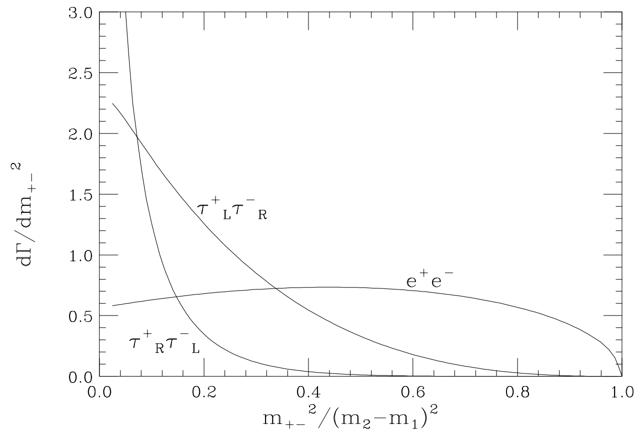

Figure 1: The distribution $d\Gamma/dm_{+-}^2$ in the decay $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\ell^+\ell^-$. In this example, $m_2 = 2m_1$. The distribution for e^+e^- is for the observed lepton pair, while for $\tau^+\tau^-$ it is for the observed charged pion pair, assuming both τs decay as $\tau \to \pi\nu$. The distribution for e^+e^- has some arbitrary normalization. The distributions for the two τ cases are each normalized to have the same area as the e^+e^- distribution. If the left and right sleptons are unmixed, then only the combinations $\tau_L^+\tau_R^-$ and $\tau_R^+\tau_L^-$ are possible.

where $m_{\rm max} = m_2 - m_1$. Similarly for right-handed slepton exchange, and thus right-handed τ^- with left-handed τ^+, we have

$$
\frac{d\Gamma(\tau_R^-\tau_L^+)}{dm_{\rm obs}^2} = 4\int_{m_{\rm obs}^2}^{m_{\rm max}^2} \frac{d\mu^2}{\mu^2}\frac{d\Gamma}{dm_{+-}^2}(\mu^2)\left(\frac{m_{\rm obs}^2}{\mu^2}\ln\frac{\mu^2}{m_{\rm obs}^2}\right) \tag{14}
$$

The observed invariant mass distributions for the underlying lepton pair and for the observed charged pion pairs are shown in Fig. 1.

The strikingly different distributions for the two alternative handednesses provide some hope that this approach might actually be effective. Some additional analyzing power is available in the other τ decay modes, though the presence of neutral pions in $\tau \to \rho\nu$ and in some $\tau \to a_1\nu$ decays is a serious complication. The leptonic decay modes are not very effective is separating the polarizations [2]. In addition, the questions of rates, triggering, and backgrounds need investigation. Should these issues be resolved satisfactorily, a more thorough study including the effects of slepton mixing and slepton masses would be warranted.

I. REFERENCES

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