$\tilde{\tau}$ at the future linear e^+e^- colliders *

Toshifumi TSUKAMOTO
KEK, National Laboratory for High Energy Physics,
1-1 Oho, Tsukuba, 305 Japan

Abstract

Study on $\tilde{\tau}$ has been started following the previous study of SUSY at e^+e^- linear colliders, where LSP (Lightest SUSY particle) and NLSP (Next LSP) such as $\tilde{e}_R$,$\tilde{\mu}_R$ and $\tilde{\chi}_1^\pm$ are focused.

τ arising from $\tilde{\tau}$ decay is polarized and its polarization depends on the left-right mixing of the $\tilde{\tau}$ and the gaugino-higgsino mixing of the neutralino. The polarization could be measured from the energy distribution of decay products from τ. Monte Calro study was done to estimate detection efficiency and effect of detectors and selection cuts on the energy distribution of decay products. Polarized electron beam plays same role as in the previous study.

1 Introduction

We have studied $\tilde{e}_R$ and $\tilde{\mu}_R$ in the light slepton case, and $\tilde{\chi}_1^\pm$ in the light chargino case[6]. In these cases, SUSY particles decay to ordinary particles and LSP and ordinary particles are detected. Event signature is acoplanar and energy distribution of detected particles is used to determine masses of SUSY particles.

It is natural to study $\tilde{\tau}$ as a next SUSY target: 1) $\tilde{\tau}$ is expected to be light as $\tilde{e}$ and $\tilde{\mu}$, 2) $\tilde{\tau}$ cascade decay, $\tilde{\tau} \to \tau\tilde{\chi}_1^0$ and $\tau \to X\nu_\tau$, might be the simplest case of cascade decay of SUSY particles and be suitable as the first step for cascade decay study, 3) $\tilde{\tau}_R$ and $\tilde{\tau}_L$ can be mixed up to be mass eigenstates $\tilde{\tau}_1$ and $\tilde{\tau}_2$, and it is important to study whether we can measure the mixing.

2 $\tilde{\tau}$

The mass matrix of $\tilde{\tau}$ is written as follows[1],

$$M_{\tilde{\tau}}^2 = \begin{pmatrix} m_{LL}^2 & m_{LR}^2 \\ m_{RL}^2 & m_{RR}^2 \end{pmatrix} = \begin{pmatrix} m_L^2 + m_\tau^2 + 0.27D & -m_\tau(A_\tau + \mu\tan\beta) \\ -m_\tau(A_\tau + \mu\tan\beta) & m_R^2 + m_\tau^2 + 0.23D \end{pmatrix}$$

*Talk presented by T.Tsukamoto at INS workshop "Physics of e^+e^-, $e^-\gamma$, and $\gamma\gamma$ collisions at linear accelerators", INS, Tokyo, December 20-22, 1994.

which is same as for $\tilde{e}$ and $\tilde{\mu}$. As $m_\tau \gg m_e, m_\mu$, there might be a case where $\tilde{\tau}_R$ and $\tilde{\tau}_L$ are mixed and mass eigenstates $\tilde{\tau}_{1/2}$ are not $\tilde{\tau}_{R/L}$ as follows,

$$\begin{pmatrix} \tilde{\tau}_1 \\ \tilde{\tau}_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_\tau & \sin\theta_\tau \\ -\sin\theta_\tau & \cos\theta_\tau \end{pmatrix} \begin{pmatrix} \tilde{\tau}_L \\ \tilde{\tau}_R \end{pmatrix}$$

Fig.1 shows total cross section for $e^+e^- \longrightarrow \tilde{\tau}_1\bar{\tilde{\tau}}_1$[3]. θ_τ=0°(90°) corresponds to $\tilde{\tau}_1$=$\tilde{\tau}_L$($\tilde{\tau}_1$=$\tilde{\tau}_R$). In study of $\tilde{\mu}_R$, polarized e^- beam helps us to reduce background from W pair and enhance the signal of $\tilde{\mu}_R$ pair. In the $\tilde{\tau}$ case, polarized e^- beam also helps to reduce background and enhance the dependence of cross section on mixing angle θ_τ.

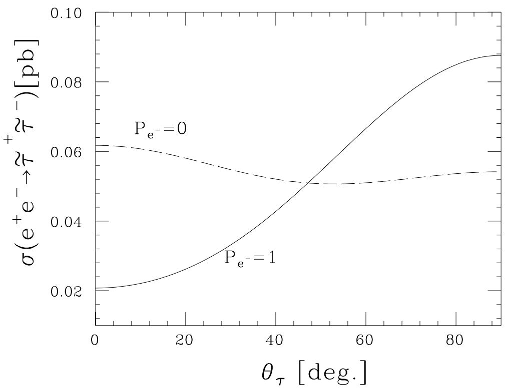

Figure 1: The total cross section for $e^+e^- \longrightarrow \tilde{\tau}_1\bar{\tilde{\tau}}_1$ as a function of mixing angle θ_τ for $\tilde{\tau}$. We take $m_{\tilde{\tau}_1}$=150GeV, $\sqrt{s}$=500GeV.

The lighter stau, $\tilde{\tau}_1$, decays into $\tau\tilde{\chi}_i^0$(neutralino) and $\nu_\tau\tilde{\chi}_i^\pm$(chargino). $\tilde{\chi}_i^0$ is a mixture of $\tilde{B}$, $\tilde{W}_3$, $\tilde{H}_1$ and $\tilde{H}_2$, $\tilde{\chi}_i^\pm$ is a mixture of $\tilde{W}^\pm$ and $\tilde{H}^\pm$ through the mass matrices as follows[2];

$$M_N(\tilde{B}, \tilde{W}_3, \tilde{H}_1, \tilde{H}_2) =$$

$$\begin{pmatrix} M_1 & 0 & -m_Z\sin\theta_W\cos\beta & m_Z\sin\theta_W\sin\beta \\ 0 & M_2 & m_Z\cos\theta_W\cos\beta & -m_Z\cos\theta_W\sin\beta \\ -m_Z\sin\theta_W\cos\beta & m_Z\cos\theta_W\cos\beta & 0 & -\mu \\ m_Z\sin\theta_W\sin\beta & -m_Z\cos\theta_W\sin\beta & -\mu & 0 \end{pmatrix},$$

$$M_C(\tilde{W}, \tilde{H}) = \begin{pmatrix} M_2 & m_W\sqrt{2}\sin\beta \\ m_W\sqrt{2}\cos\beta & \mu \end{pmatrix}$$

These are diagonalized by a real orthogonal matrix N for M_N and unitary matrices U and V for M_C as follows:

$$U^* M_C V^{-1} = M_D^C, \quad N M_N N^{-1} = M_D^N.$$

If both of $\tilde{\tau}_1$ decay to $\tau\tilde{\chi}_1^0$, event signature for $\tilde{\tau}_1\bar{\tilde{\tau}}_1$ is the simplest one; acoplanar $\tau\bar{\tau}$. This happens if $\tilde{\tau}_1$ is the NLSP as $\tilde{\mu}_R$ and $\tilde{e}_R$ in our previous study[6].

If other $\tilde{\chi}_i^0$ or $\tilde{\chi}_i^\pm$ channels are kinematically opened, event signatures are more complicated[3] than the simplest case as the branching ratio of $\tilde{\tau}_1$ depends on mixing angle θ_τ and $\tilde{\chi}_i^{0,\pm}$

cause cascade decays like $\tilde{\chi}_i^{0,\pm} \to \tilde{\chi}_j^{0,\pm} f_1 \bar{f}_2$. In these complicated cases, if both of $\tilde{\tau}_1$ decay to $\tau\tilde{\chi}_i^0$, event signature is $\tau\bar{\tau}$ + jets or leptons + missing, while if both decay to $\nu_\tau\tilde{\chi}_i^{\pm}$, there are no τ's in the final state and so this is not a good channel to identify $\tilde{\tau}$ pair production.

As the τ from $\tilde{\tau}_1$ decays to $X\nu_\tau$, we can get polarization of τ by measuring momentum(or energy) distribution of X[4], which is not able in case of $\tilde{e}$ and $\tilde{\mu}$. Fig.2 shows dependence of energy distribution of X=π on τ polarization (P_τ). The polarization of τ carries information of mixing angle of θ_τ in $\tilde{\tau}$ and $\tilde{\chi}_i^0$ mixture of $\tilde{B}$, $\tilde{W}_3$, $\tilde{H}_1$ and $\tilde{H}_2$ as shown by the Lagrangian for $\tilde{\tau}$-$\tilde{\chi}_i^{0,\pm}$-fermion[5],

$$\mathcal{L} = \sum_{i=1,2 \quad j=1,\dots,4} \tilde{\tau}_i \bar{\tau}(P_L a_{ij}^R + P_R a_{ij}^L)\tilde{\chi}_j^0 + \sum_{i=1,2 \quad j=1,2} \tilde{\tau}_i \bar{\nu}_\tau P_R b_{ij} \tilde{\chi}_j^{\pm} + h.c.,$$

where

$$\begin{pmatrix} a_{1j}^{R(L)} \\ a_{2j}^{R(L)} \end{pmatrix} = \begin{pmatrix} \cos\theta_\tau & \sin\theta_\tau \\ -\sin\theta_\tau & \cos\theta_\tau \end{pmatrix} \begin{pmatrix} a_{Lj}^{R(L)} \\ a_{Rj}^{R(L)} \end{pmatrix},$$

$$\begin{pmatrix} b_{1j} \\ b_{2j} \end{pmatrix} = \begin{pmatrix} \cos\theta_\tau & \sin\theta_\tau \\ -\sin\theta_\tau & \cos\theta_\tau \end{pmatrix} \begin{pmatrix} b_{Lj} \\ b_{Rj} \end{pmatrix},$$

$$a_{Lj}^R = -\frac{g m_\tau}{\sqrt{2} m_W \cos\beta} N_{j3}, \quad a_{Lj}^L = \frac{g}{\sqrt{2}}(N_{j2} + N_{j1}\tan\theta_W),$$

$$a_{Rj}^R = -\frac{2g}{\sqrt{2}} N_{j1}\tan\theta_W, \quad a_{Rj}^L = -\frac{g m_\tau}{\sqrt{2} m_W \cos\beta} N_{j3},$$

$$b_{Lj} = -g U_{j1}, \quad b_{Rj} = \frac{g m_\tau}{\sqrt{2} m_W \cos\beta} U_{j2}.$$

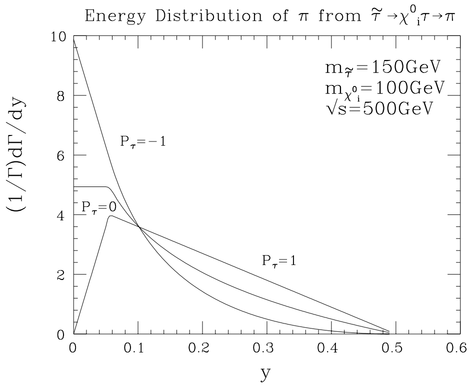

Figure 2: Energy distribution of π from the cascade $\tilde{\tau}$ decay: $\tilde{\tau} \to \tau\tilde{\chi}_1^0$, and $\tau \to \pi\nu_\tau$ at $e^+e^- \to \tilde{\tau}\bar{\tilde{\tau}}$. We take $m_{\tilde{\tau}_1}$=150GeV, $m_{\tilde{\chi}_1^0}$=100GeV and $\sqrt{s}$=500GeV.

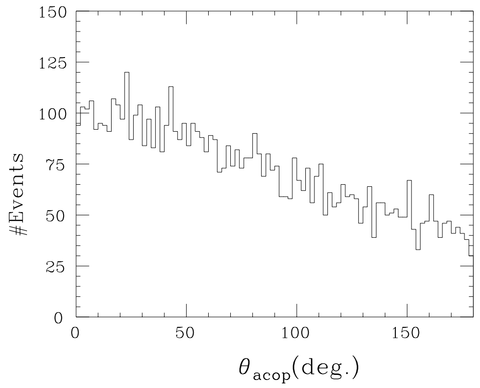

Figure 3: Acoplanarity angle distribution for selected acoplanar $\tau\bar{\tau}$ pair of 1-1 or 1-3 topology. The cut applied on the acoplanarity angle is 30°. We take $m_{\tilde{\tau}_1}$=150GeV, μ=150GeV, M_2=400GeV, $\tan\beta$=2 and $\sqrt{s}$=350GeV. 10000 events are simulated.

3 Monte Carlo study

Although $\tilde{\tau}$ may cause more complicated event signature than $\tilde{e}$ and $\tilde{\mu}$ as we discussed in the previous section, at first we did Monte Carlo study for the simplest case, ie. $\tilde{\tau} \rightarrow \tau\tilde{\chi}_1^0$ resulting acoplanar $\tau\bar{\tau}$, to know the detection efficiency and momentum distribution of decay products from τ including detector resolution and event selection cuts.

The event generator is made from the one for $\tilde{\mu}$[6] by changing $\tilde{\mu}$ to $\tilde{\tau}$ and the decay $\tilde{\mu} \rightarrow \mu\tilde{\chi}_1^0$ to the decay $\tilde{\tau} \rightarrow \tau\tilde{\chi}_1^0$. The detector simulation is same in the previous work[6]. We should note that we treated $\tilde{\tau}_R$ and did not include polarization of τ from $\tilde{\tau}$, ie. polarization of τ is zero.

For the signature of acoplanar $\tau\bar{\tau}$, we applied the following selection cuts; (1) 2 $\leq$ the number of tracks ≤ 4, (2) 20GeV $< E_{vis} < \sqrt{s}$ $-$ 100GeV, (3) there are two or more jets with $y_{cut} = 0.5 \times 10^{-3}$, (4) 1-1 or 1-3 topology after clustering into two jets with $y_{cut} \geq 0.5 \times 10^{-3}$, where 1 and 3 means the number of tracks in the jet, (5) $|\cos\theta_j| < 0.95$ for each jet, (6) $\theta_{acop} > 30°$.

Fig.3 shows acoplanarity angle distribution with cuts (1)$\sim$(5) for $m_{\tilde{\tau}}$=150GeV, μ=150GeV, M_2=400GeV, $\tan\beta$=2 at $\sqrt{s}$=350GeV. The detection efficiency was estimated to be about 50%, which is same level for $\tilde{e}$ and $\tilde{\mu}$[6].

To test the effect of detector and selection cuts on energy distribution from τ decay, we did simulation with one decay mode of $\tau \rightarrow \pi\nu_\tau$. Fig.4 shows energy distribution of a hadron which is identified as "1" in 1-1 or 1-3 topology and there are nothing in the "1"-side other than it. Fig.4(a) is for standard τ decay, (b) is for $\tau \rightarrow \pi\nu_\tau$ and (c) is same as (b) but cut-(2) (E_{vis} cut) is not applied. Although we would like to have the distribution (c), which shows the same distribution as the one for P_τ=0, but the distribution is distorted in the low energy region due to cut-(2) which cannot be dropped to suppress background from two photon events and mini-jets events.

It is desirable to get the more correct distribution not to introduce systematic errors due to acceptance correction. The decay channel of $\tau \rightarrow \rho\nu_\tau$ is one candidate as $m_\tau - m_\rho$ is small resulting in $\beta_\tau \sim \beta_\rho$, and ρ in $\tau \rightarrow \rho\nu_\tau$ is more energetic than π in $\tau \rightarrow \pi\nu_\tau$. Fig.5 shows energy distribution of ρ from $\tau \rightarrow \rho\nu_\tau$ for (a) generator level (ie. original) and (b)

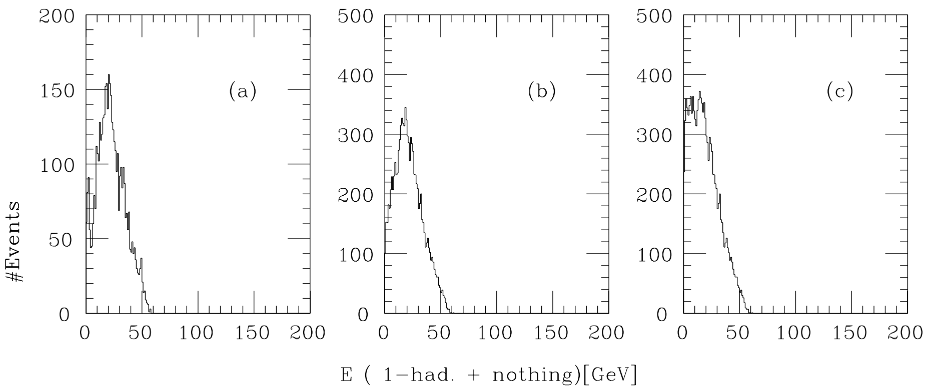

Figure 4: Energy distribution of visible decay products from τ, which arises from $\tilde{\tau}$ decay. (a) τ decays to all modes, (b) τ decays to $\pi\nu_\tau$ only, and (c) same as (b) without visible energy cut. We take $m_{\tilde{\tau}_1}$=150GeV, μ=150GeV, M_2=400GeV, $\tan\beta$=2 and $\sqrt{s}$=350GeV. 10000 events are simulated for each case.

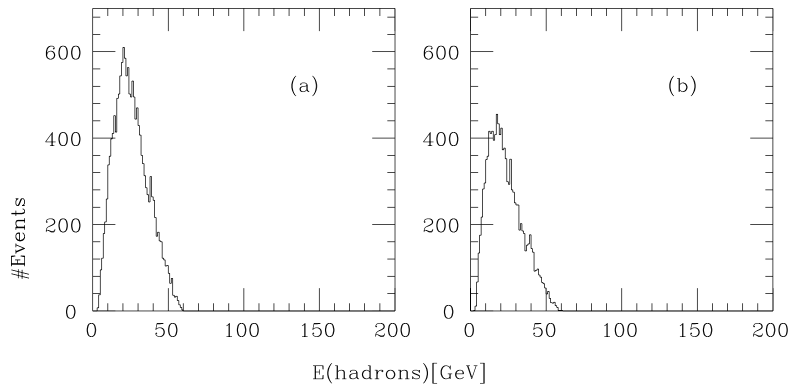

Figure 5: Energy distribution of hadrons from ρ, which arises from $\tilde{\tau}$ cascade decay, where τ decays to $\rho\nu_\tau$ only. (a) without detector simulation and selection cuts, (b) with detector simulation and selection cuts. We take $m_{\tilde{\tau}_1}$=150GeV, μ=150GeV, M_2=400GeV, $\tan\beta$=2 and $\sqrt{s}$=350GeV. 10000 events are simulated.

with detector and selection cuts and one can see that the distortion is small. Much better is a_1 decay mode as $m_{a_1} > m_\rho$ and decay of a_1 shows good signature $a_1 \to \pi\rho$ ($\rho \to \pi\pi$) , but we have not yet studied this mode.

$m_{\tilde{\tau}}$ can be determined by fitting the energy distribution of decay products as done in the previous study[6] or cross section dependence on $\sqrt{s}$. We have not yet done the first one but estimated the systematic error in the second one due to unknown polarization of τ. If polarization of τ is changed, the energy distribution of X from τ decay also changes resulting in change of detection efficiency. The systematic error of detection efficiency was estimated about 30% at most.

There are backgrounds such as $e^+e^- \to W\bar{W}, \tau\bar{\tau}, ZH, etc.$ Polarized e^- beam is required to suppress the background of W pair. The cross section of W pair at $\sqrt{s}$=350GeV is 11.4pb for unpolarized e^- beam and 0.072pb for polarized (P_{e^-}=+1) e^- beam. Efficiency of W pair with polarized e^- beam is estimated to be 4% and less than the signal of $\tilde{\tau}$ pair.

4 Summary

We have started to study $\tilde{\tau}$ as a next SUSY target following the previous study. $\tilde{\tau}$ is different from $\tilde{e}$ and $\tilde{\mu}$ as $\tilde{\tau}_{L/R}$ can be mixed up to be mass eigenstate $\tilde{\tau}_{1/2}$, τ from $\tilde{\tau}$ cause cascade decays, and polarization of τ carries information of $\tilde{\tau}$ mixing and neutralino mixing.

We did the Monte Carlo study for the simplest case, $\tilde{\tau}$ pair production and $\tilde{\tau} \to \tau\chi_1^0$, of which signature is acoplanar τ pair. Detection efficiency is same as for $\tilde{e}$ and $\tilde{\mu}$. To get more correct energy distribution of X from $\tau \to X\nu_\tau$ for m_τ and P_τ measurement, $X = \rho$ and a_1 are preferable as the effect of visible energy cut is less than $X = \pi$.

We should include τ polarization in the event generator for the Monte Carlo simulation, which is not included in the present generator, to know how correctly we can measure the P_τ.

Acknowledgments

The author would like to thank M.M.Nojiri, K.Fujii and Y.Okada for preparation of this talk. He especially thanks M.M.Nojiri for theoretical explanation of $\tilde{\tau}$ and figures in ref.[3]. He also thanks members of the JLC study group for continuous encouragement of this work.

References

[1] J.Ellis and S.Rudaz, *Phys. Lett.* **128B**,248(1983); L.E.Ibáñez, C.Lopez and C.Muñoz, *Nulc. Phys.* **B256**,218(1985); A.Bouquet, J.Kaplan and C.A.Savoy, *Nulc. Phys.* **B262**,299(1985); M.Drees and M.M.Nojiri, *Nulc. Phys.* **B369**,54(1992);

[2] For reviews, see H.E.Haber and G.L.Kane, *Phys. Rep.* **117**,75(1985)

[3] M.M.Nojiri, KEK-TH-425

[4] Y.S.Tsai, *Phys. ReV.* **D4**,2821(1971); T.Hagiwara, S.-Y.Pi, and A.I.Sanda, *Ann. of Physics* **106**,134(1977); H.Kühn and F.Wagner, *Nucl. Phys.* **B236**,16(1984); K.Hagiwara, A.D.Martin and D.Zeppenfeld, *Phys. Lett.* **B235**, 198(1989); A.Rougé, *Z.Phys.* **C48**,75(1990); B.K.Bullock, K.Hagiwara and A.D.Martin, *Phys. Rev. Lett.* **67**,3055(1989) and *Nucl. Phys.* **B395**,499(1993)

[5] J.F.Gunion and H.E.Haber, *Nucl.Phys* **B272**,1(1986). Errata UCD-92-31

[6] T.Tsukamoto, K.Fujii, H.Murayama, M.Yamaguchi, and Y.Okada, KEK Preprint 93-146 to be published in *Phys. Rev.* **D**