Signals from the $\tilde{\tau}_1 - \tilde{\chi}_1^0$ Co-annihilation Region in a Linear Collider

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Talk Outline

SUSY and Cosmology

Available mSUGRA parameter space with:
(a) Rare decay constraints
(b) Collider bounds
(c) Cosmological constraints

LC ($\sqrt{s} = 500$ and $800$ GeV) reach of the mSUGRA parameter space via $\tilde{\tau}_1^+\tilde{\tau}_1^-$ and $\tilde{\chi}_1^0\tilde{\chi}_2^0$

(i) Detailed study of signal and the background processes
(ii) Determination of SUSY masses in the dark matter allowed regions (in progress)

Conclusion
Linear Collider (LC) Program

- Physics
  - Higgs
  - Top quark mass
  - SUSY
  - ...

- LCs
  - 500 GeV
  - 800 GeV
  - ??? GeV

- Detector for precision measurements
  - Tracking
  - Calorimetry
  - ...

1. Supergravity models with $R$ parity invariance gives rise to a stable dark matter candidate:

The lightest neutralino: $\tilde{\chi}^0_1$

$mSUGRA$ (20 years ago...) = “Supersymmetrized SM” + Universality

2. This neutralino can give rise to the right amount of cold dark matter of the universe.

3. The relic density of these neutralinos is given by:

$$\Omega_{\tilde{\chi}^0_1} h^2 \sim \int_{0}^{x_f} dx (<\sigma_{\text{ann}} v>)^{-1}$$

where $\sigma_{\text{ann}}$ is calculated in terms of SUSY model parameters.
Experimental Constraints and Technical Issues

CLEO $b \rightarrow s \gamma$

$1.9 \times 10^{-4} < Br < 4.5 \times 10^{-4}$

LEP Higgs Mass

$M_{\text{Higgs}} > 114 \text{ GeV}/c^2$

LEP/Tevatron SUSY Mass Bounds

Relic Density Bounds

$0.094 < \Omega_{\chi_1^0} h^2 < 0.129$

[WMAP, Balloon Experiments such as BoomeranG, Maxima, DASI etc., Supernovae data, Radio Galaxy measurements]

Note: We do not assume Yukawa unification or proton decay as these depend on unknown physics beyond $M_G$.

$\rightarrow s \gamma$

Large $\tan \beta$ NLO correction [Degrassi et al., Carena et al.]

Higgs Mass

Two loop corrections [Haber et al., Carena et al., Heinemeyer et al.]

Relic Density

Inclusion of coannihilation $\tilde{\tau}_1 - \tilde{\chi}_1^0$ effects in relic density calculations [Ellis et al., Arnowitt et al., Gomez et al.]

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Signals from the Co-annihilation Region in a Linear Collider
mSUGRA: 4 Parameters +1 Sign

\begin{itemize}
\item \(m_{1/2}\) Common gaugino (spin=1/2) mass (GeV)
\item \(m_0\) Common scalar (spin=0) mass (GeV)
\item \(\tan \beta\) Ratio of 2 v.e.v.’s
\hspace{1cm} (2 Higgs doublets; \(H_u\) & \(H_d\))
\item \(\text{sign}(\mu)\) Sign of Higgs mixing parameter \(\mu\) (GeV)
\hspace{1cm} \(\rightarrow\) our nominal choice \(\mu > 0\)
\item \(A_0\) Trilinear \((\tilde{q}\tilde{q}h)\) coupling (GeV)
\hspace{1cm} \(\rightarrow\) our nominal choice \(A_0 = 0\)
\end{itemize}
CDM Allowed Region

$m_0$ vs. $m_{1/2}$ ($\tan \beta = 40, A_0 = 0$)

$\mu > 0$

$\tan \beta = 40$

$A_0 = 0$

$114$ GeV

$117$ GeV

$120$ GeV

$m_{\tilde{\chi}} > m_\tau$

$m_{\tilde{\chi}} < m_{\tau}$

$\tau \tau$

$\tilde{\chi}^0$

$\tilde{\chi}^0$

$\tilde{\tau}$

$\tilde{\tau}$

$\gamma$

$[0.094 < \Omega_{\tilde{\chi}^0_1} h^2 < 0.129]$ vs. $[0.07 < \Omega_{\tilde{\chi}^0_1} h^2 < 0.21]$

$w_{\tilde{\chi}^0 < 11 \times 10^{-16}$

$m_{\tilde{\chi}^0} > m_\tau$

$m_{\tilde{\chi}^0} = 250$ GeV

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Signals from the Co-annihilation Region in a Linear Collider
CDM Allowed Region

$m_0$ vs. $m_{1/2}$ ($\tan\beta = 50, A_0 = 0$)

$A_0 = 0, \mu > 0$

$\tan\beta = 50$

$\chi_1^0, \chi_2^0$

$b \rightarrow s\gamma$

$\tilde{\chi}_1^0, \tilde{\chi}_2^0$

$\tilde{\tau}_1^+, \tilde{\tau}_1^-$

$a_\mu < 11 \times 10^{-10}$

$\Omega_{\tilde{\chi}_1^0}h^2 < 0.129$

WMAP (blue)

Previous Estimate (red)

$0.07 < \Omega_{\tilde{\chi}_1^0}h^2 < 0.21$
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Signals from the Co-annihilation Region in a Linear Collider

CDM Allowed Region and Kinematical Reach for $\tilde{\tau}_1^+\tilde{\tau}_1^- \& \tilde{\chi}_1^0\tilde{\chi}_1^0$

<table>
<thead>
<tr>
<th>$\tan\beta$</th>
<th>WMAP (blue)</th>
<th>Previous Estimate (red)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>$0.094 &lt; \Omega \tilde{\chi}_1^0 h^2 &lt; 0.129$</td>
<td>$0.07 &lt; \Omega \tilde{\chi}_1^0 h^2 &lt; 0.21$</td>
</tr>
<tr>
<td>40</td>
<td>$0.094 &lt; \Omega \tilde{\chi}_1^0 h^2 &lt; 0.129$</td>
<td>$0.07 &lt; \Omega \tilde{\chi}_1^0 h^2 &lt; 0.21$</td>
</tr>
<tr>
<td>10</td>
<td>$0.094 &lt; \Omega \tilde{\chi}_1^0 h^2 &lt; 0.129$</td>
<td>$0.07 &lt; \Omega \tilde{\chi}_1^0 h^2 &lt; 0.21$</td>
</tr>
</tbody>
</table>

- $A_0=0$, $\mu>0$, $\tan\beta=50$
- $A_0=0$, $\mu>0$, $\tan\beta=40$
- $A_0=0$, $\mu>0$, $\tan\beta=10$
Large \( \tan \beta \) scenario:

\( \tilde{\chi}_1^+ > 250 \text{ GeV}/c^2 \)
\( \tilde{\tau}_1 = \text{Next-to-LSP} \)

\( \rightarrow \text{No } \tilde{\chi}_1^+\tilde{\chi}_1^- [300 + 300 \text{ GeV}/c^2] \text{ production!} \)

\( \rightarrow \tilde{\tau}_1^+\tilde{\tau}_1^- [200+200 \text{ GeV}/c^2] \text{ and} \)
\( \tilde{\chi}_2^0\tilde{\chi}_1^0 [300+150 \text{ GeV}/c^2] \)

\( \rightarrow \tau\tau + E_{\text{miss}} \text{ final state} \)

Same final state in \( \tilde{\chi}_1^+\tilde{\chi}_1^- \) production/decay, BUT …
Importance of Active Mask at LC

\( \tau \tau + E_{\text{miss}} \) final state: 

BUT, both \( \tau \) jets could be very soft for small \( \Delta M \) (between \( \tilde{\tau}_1 \) and \( \tilde{\chi}_1^0 \)) in \( \tilde{\tau}_1^+ \tilde{\tau}_1^- \) production.

\[
\sigma (e^+ e^- \rightarrow e^+ e^- \tau \tau) \sim 27300 \text{ fb}
\]

for \( \theta(\tau) > 15^o \) and \( P_T(\tau) > 3 \text{ GeV/c} \)

\( \rightarrow \) Forward \( e^+ e^- \) tagging

\( \rightarrow \) Active mask
\(e^+e^- \rightarrow e^+e^- \tau\tau\)

**Energy MC (GeV)**

- \(1^0 < \theta(e^{+/−}) < 5.8^0\)
- \(\theta(e^+) > 3^0, \theta(e^-) > 3^0\)
- \(\theta(e^+/-) > 3^0, \theta(e^-/+)<3^0\)
- \(\theta(e^+) < 3^0, \theta(e^-) < 3^0\)

100 GeV
Monte Carlo

Event Generator plus Beam Bremsstrahlung

SUSY: ISAJET v7.69

\[ e^+e^- \rightarrow \widetilde{\chi}_2^0 \widetilde{\chi}_1^0 \rightarrow \widetilde{\tau}_1^+ \widetilde{\tau}_1^- \rightarrow \tau \tau + E^{\text{miss}} \]

SM : WPHACT v2.02pol

(all 4 fermion final states (SM4f) and \( \gamma \gamma \) process with \( e^+/e^- \) polarization)

\[ e^+e^- \rightarrow \nu_e \nu_e \tau \tau, \nu_\mu \nu_\mu \tau \tau, \nu_\tau \nu_\tau \tau \tau; ee \tau \tau, eeqq (\gamma \gamma \text{ process}) \]


Tau Decay: TAUOLA v2.6

Detector Simulation & Event Analysis:

Package LCD Root v3.5

FAST MC using LD Mar01 detector parameterization, Jet Finder, …
### Optimization of Event Selection Cuts

<table>
<thead>
<tr>
<th>$\tilde{\chi}_1^0 \tilde{\chi}_2^0$ at $Pol = +0.9$ (LH)</th>
<th>$\tilde{\tau}_1^+ \tilde{\tau}_1^-$ at $Pol = -0.9$ (RH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\text{jet}} \geq 2 \ (E_{\text{jet}} &gt; 3 \text{ GeV}; \text{JADE } Y \geq 0.0025)$</td>
<td>$N_{\text{jet}} \geq 2 \ (E_{\text{jet}} &gt; 3 \text{ GeV}; \text{JADE } Y \geq 0.0025)$</td>
</tr>
<tr>
<td>$\tau_h$ ID ($N_{\text{track}} = 1, 3; q = \pm 1$)</td>
<td>$\tau_h$ ID ($N_{\text{track}} = 1, 3; q = \pm 1$)</td>
</tr>
<tr>
<td>$-q \times \cos \theta_{\text{jet}} &lt; 0.7$</td>
<td>$</td>
</tr>
<tr>
<td>Missing $P_T &gt; 5 \text{ GeV}/c$</td>
<td>Missing $P_T &gt; 5 \text{ GeV}/c$</td>
</tr>
<tr>
<td>$-0.8 - \cos \theta(j_2, P_{\text{vis}}) &lt; 0.7$</td>
<td>$-0.6 - \cos \theta(j_2, P_{\text{vis}}) &lt; 0.6$</td>
</tr>
<tr>
<td>Acoplanarity $&gt; 40^\circ$</td>
<td>Acoplanarity $&gt; 40^\circ$</td>
</tr>
<tr>
<td>No EM clusters in $5.8^\circ &lt; \theta &lt; 25.8^\circ$ with $E &gt; 2 \text{ GeV}$</td>
<td>No EM clusters in $5.8^\circ &lt; \theta &lt; 25.8^\circ$ with $E &gt; 2 \text{ GeV}$</td>
</tr>
<tr>
<td>No electrons in $\theta &gt; 25.8^\circ$ with $P_T &gt; 1.5 \text{ GeV}/c$</td>
<td>No electrons in $\theta &gt; 25.8^\circ$ with $P_T &gt; 1.5 \text{ GeV}/c$</td>
</tr>
<tr>
<td>Beam mask: $2^\circ(1^\circ) - 5.8^\circ$</td>
<td>Beam mask: $2^\circ(1^\circ) - 5.8^\circ$</td>
</tr>
<tr>
<td>No EM clusters with $E &gt; 100 \text{ GeV}$</td>
<td>No EM clusters with $E &gt; 100 \text{ GeV}$</td>
</tr>
</tbody>
</table>

**Note:** $\cos(25.8^\circ) = 0.9, \cos(5.8^\circ) = 0.995$

July 29, 2004 Signals from the Co-annihilation Region in a Linear Collider
$\sigma$ vs. $\Delta M$

500 GeV Linear Collider, $P = -0.9$ (R.H.)

- $m_0 = 203 \sim 220$
- $m_{1/2} = 360$
- $A_0 = 0$
- $\tan\beta = 40$
- $\mu > 0$

$\sigma B(\tau^0 h)^2$ (fb) vs. $\Delta M$ (GeV)
$\Delta M$ vs. $m_0$

\[ \Delta M = 0.952 \, m_0 - 190 \]
**N_{event} vs. ΔM**

500 GeV Linear Collider, \( P = -0.9 \) (R.H.)

- **2° Mask**
  - ISAJET 7.69
  - \( m_0 = 203 \sim 220 \)
  - \( m_{1/2} = 360 \)
  - \( A_0 = 0 \)
  - \( \tan \beta = 40 \)
  - \( \mu > 0 \)

- \( \chi^0_1 \), \( \chi^0_2 \), \( \tau_1 \tau_1 \)

Event counts vs. \( \Delta M \) for 500 GeV Linear Collider, \( P = -0.9 \) (R.H.)

- N = 122
- N = 33

\( N_{event} @ 500 \text{ fb}^{-1} \)
Mass Determination

- Choose an effective mass of $j_1, j_2$ and $E^{\text{miss}}$, $M(j_1,j_2,E^{\text{miss}})$, as a discriminator.
- Prepare three templates of the distribution of the effective mass for $\tilde{\chi}_1^0 \tilde{\chi}_2^0$, $\tilde{\tau}_1 \tilde{\tau}_1$ and SM.
- Fit a MC sample of 500 fb$^{-1}$ with the three templates to extract each contribution.
Validation of Templates

$M_{\text{eff}} \equiv M(j_1,j_2,E^{\text{miss}})$

High Stat. “Data”
SM + SUSY
$(m_0 = 205, \Delta M = 4.76 \text{ GeV})$

High Stat. “Data”
SM + SUSY
$(m_0 = 210, \Delta M = 9.53 \text{ GeV})$

High Stat. “Data”
SM + SUSY
$(m_0 = 220, \Delta M = 18.98 \text{ GeV})$

2° Mask

$\tilde{\chi}_1^0 \tilde{\chi}_2^0 = 5^{+3}_{-3} \ (15)$
$\tilde{\tau}_1^+ \tilde{\tau}_1^- = 104^{+16}_{-16} \ (122)$
SM = 409$^{+10}_{-10} \ (378)$

$\tilde{\chi}_1^0 \tilde{\chi}_2^0 = 25^{+8}_{-8} \ (26)$
$\tilde{\tau}_1^+ \tilde{\tau}_1^- = 786^{+20}_{-20} \ (787)$
SM = 383$^{+21}_{-21} \ (378)$

$\tilde{\chi}_1^0 \tilde{\chi}_2^0 = 27^{+8}_{-8} \ (29)$
$\tilde{\tau}_1^+ \tilde{\tau}_1^- = 1282^{+19}_{-19} \ (1283)$
SM = 387$^{+19}_{-19} \ (378)$
\[ \Delta M = 1.882 - 0.07485 M_{\text{eff}} + 0.01075 M_{\text{eff}}^2 \]
Numerical Results

<table>
<thead>
<tr>
<th>mSUGRA</th>
<th>500 GeV</th>
<th>2σ Mask</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{1/2}$</td>
<td>$m_0$</td>
<td>$M(\tau_1)$</td>
</tr>
<tr>
<td>(GeV)</td>
<td>(GeV)</td>
<td>(GeV/c^2)</td>
</tr>
<tr>
<td>360</td>
<td>203</td>
<td>145.14</td>
</tr>
<tr>
<td>360</td>
<td>204</td>
<td>146.29</td>
</tr>
<tr>
<td>360</td>
<td>205</td>
<td>147.24</td>
</tr>
<tr>
<td>360</td>
<td>206</td>
<td>148.20</td>
</tr>
<tr>
<td>360</td>
<td>207</td>
<td>149.16</td>
</tr>
<tr>
<td>360</td>
<td>208</td>
<td>150.12</td>
</tr>
<tr>
<td>360</td>
<td>209</td>
<td>151.08</td>
</tr>
<tr>
<td>360</td>
<td>210</td>
<td>152.04</td>
</tr>
<tr>
<td>360</td>
<td>211</td>
<td>153.00</td>
</tr>
<tr>
<td>360</td>
<td>212</td>
<td>153.95</td>
</tr>
<tr>
<td>360</td>
<td>213</td>
<td>154.90</td>
</tr>
<tr>
<td>360</td>
<td>214</td>
<td>155.86</td>
</tr>
<tr>
<td>360</td>
<td>215</td>
<td>156.81</td>
</tr>
<tr>
<td>360</td>
<td>216</td>
<td>157.76</td>
</tr>
<tr>
<td>360</td>
<td>217</td>
<td>158.70</td>
</tr>
<tr>
<td>360</td>
<td>218</td>
<td>159.65</td>
</tr>
<tr>
<td>360</td>
<td>219</td>
<td>160.59</td>
</tr>
<tr>
<td>360</td>
<td>220</td>
<td>161.55</td>
</tr>
</tbody>
</table>
$\chi^2$ Test Procedures

Prepare “500 fb$^{-1}$ experimental” data including $\tilde{\chi}\tilde{\chi}$ and $\tilde{\tau}_1\tilde{\tau}_1$ events at a specific mSUGRA point (e.g., $m_0 = 210$).

Fit the data with the $M_{\text{eff}}$ template for SM and various templates for $\tilde{\chi}\tilde{\chi}$ and $\tilde{\tau}_1\tilde{\tau}_1$ ($m_0 = 202 \sim 220$).

Find the template that gives a minimum $\chi^2$:

$$\chi^2 = \sum_i \left( \frac{N_i^{\text{data}} - \sum_{j_{\text{MC}}} (C_{j_{\text{MC}}} \cdot F_i^{j_{\text{MC}}})}{\sigma_i^{\text{data}}} \right)^2$$

$N_i^{\text{data}} = \text{number of events in } i\text{-th bin; } j_{\text{MC}} = \text{SM, } \chi\chi \text{ or } \tau_1\tau_1; F_i = \text{shape from MC}$

$C_{j_{\text{MC}}} = \text{normalization factor (free parameters)}$
χ² Test

"Experimental Data" (500 fb⁻¹)

\[ m_0 = 210 \]
\[ (\Delta M = 9.53 \text{ GeV}) \]

\( \chi^2 \) value suggests the data sample likely contains "\( m_0 = 210 \)" SUSY events.

\[ m_0 = 210 \]
\[ (\Delta M = 9.53 \text{ GeV}) \]

Fitted with Templates

\[ m_0 = 210 \]

Fitted with Templates

\[ m_0 = 211 \]
Finding $\chi^2$ (minimum)

2° Mask

"Experimental Data" (500 fb$^{-1}$)
$\ m_0 = 210 \ (\Delta M = 9.53 \ GeV)$
$\ m_{1/2} = 360$

Compared to

Templates (high statistics samples)
$\ m_0 = 203 - 220$
$\ m_{1/2} = 360$

Preliminary Result

$9.5^{+1.0}_{-1.0} \ GeV$

fit $\chi^2$/n.d.f. ($\Delta M$) / P(e$^-$) = -0.9

Real $\Delta M$ is 9.53

Data $m_0 = 210$
All plots are preliminary.

With 500 fb⁻¹, it \((m_0 = 205)\) is hard to distinguish from 204 and 206.

More details (see the next slide)
Data $m_0 = 205$

- **2° Mask**
  - Fitted with Templates ($m_0 = 204$)

- **1° Mask?**
  - (see the next slide)

- **2γ events** make the mass determination very difficult.

- **Fitted with Templates**
  - ($m_0 = 205$)
  - ($m_0 = 206$)
  - $\chi^2 / \text{ndf}$: 75.33 / 54
  - # of XX: $-20.45 \pm 10.98$
  - # of ST: $67.04 \pm 15.11$
  - # of SM: $377.6 \pm 0.0$

- $\gamma$ events make the mass determination very difficult.

- **Fitted with Templates**
  - ($m_0 = 205$)
  - $\chi^2 / \text{ndf}$: 64.51 / 54
  - # of XX: $-20.36 \pm 10.76$
  - # of ST: $99.22 \pm 18.44$
  - # of SM: $377.6 \pm 0.0$

- **Fitted with Templates**
  - ($m_0 = 206$)
  - $\chi^2 / \text{ndf}$: 68.9 / 54
  - # of XX: $-28.9 \pm 11.5$
  - # of ST: $80.23 \pm 16.55$
  - # of SM: $377.6 \pm 0.0$
Finding $\chi^2$ (minimum)

**1° Mask**

“Experimental Data” (500 fb$^{-1}$)

$m_0 = 205$ ($\Delta M = 4.76$ GeV)

$m_{1/2} = 360$

Compared to

*Templates (high statistics samples)*

$m_0 = 203 - 220$

$m_{1/2} = 360$

---

**Preliminary Result**

$4.74^{+0.97}_{-1.03}$ GeV

<table>
<thead>
<tr>
<th>fit $\chi^2$/n.d.f. ($\Delta M$) / $P(e^-) = 0.9$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data $m_0 = 205$</td>
</tr>
</tbody>
</table>

Real $\Delta M$ is 4.76
### 500-GeV LC Performance

#### Preliminary Results

<table>
<thead>
<tr>
<th>$m_0 (\Delta M)$</th>
<th>(500 fb$^{-1}$)</th>
<th>$\Delta M$ (&quot;500 fb$^{-1}$ experiment&quot;)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$N_{\tilde{n}\tilde{n}}$</td>
<td>2° Mask</td>
</tr>
<tr>
<td>205 (4.76 GeV)</td>
<td>122</td>
<td>Not determined</td>
</tr>
<tr>
<td>210 (9.53 GeV)</td>
<td>787</td>
<td>9.5$^{+1.1}_{-1.0}$ GeV</td>
</tr>
<tr>
<td>213 (12.37 GeV)</td>
<td>1027</td>
<td>12.5$^{+1.4}_{-1.4}$ GeV</td>
</tr>
<tr>
<td>215 (14.27 GeV)</td>
<td>1138</td>
<td>14.5$^{+1.1}_{-1.4}$ GeV</td>
</tr>
<tr>
<td>220 (18.98 GeV)</td>
<td>1283</td>
<td>19.0$^{+2.0}_{-2.0}$ GeV</td>
</tr>
</tbody>
</table>
500-GeV LC Requirements

- $\mathcal{L} = 500 \text{ fb}^{-1}$ (both LH and RH beams)
- $1^{\circ}$ active mask
- Good central calorimeter + tracking systems for low $P_T$ $\tau$'s
- $e^+e^- \rightarrow ee ee$ or $ee \mu\mu$ as calibration
Conclusion

[1] We investigated the cosmologically allowed mSUGRA parameter space using other possible experimental constraints, e.g., collider bounds, rare decay bounds.

→ Only $\tilde{\chi}_1^0 \tilde{\chi}_2^0$ and $\tau_1 \tau_1$ production are kinematically allowed at 500-GeV and 800-GeV LCs.

[2] We considered various points ($\Delta M = 5$-20 GeV) in the parameter space at $m_{1/2} = 360$.

→ Importance of “active mask” to detect forward electron/positron to suppress $\gamma \gamma$ events especially for the small $\Delta M$ cases.

→ $1^o$ mask will be effective at 500-GeV LC.
Conclusion (Cont’d)

[4] Beam polarization for $e^-$:
   - LH polarization to enhance the $\tilde{\chi}_1^0 \tilde{\chi}_2^0$ production.
   - RH polarization to reduce the SM ($\nu \nu \tau \tau$) events and to study the $\tilde{\tau}_1 \tilde{\tau}_1$ production. In this channel, we have the maximum reach for $m_{1/2}$ in the allowed region.

[5] We proposed to use $M(j_1j_2,E^{\text{miss}})$ to extract the contributions from $\tilde{\chi}_1^0 \tilde{\chi}_2^0$, $\tilde{\tau}_1 \tilde{\tau}_1$, and SM events. Our preliminary result shows that it is possible to measure the difference between $\tilde{\chi}_1^0$ and $\tilde{\tau}_1$ masses separately in a SUSY model.

[6] The parameter space needs to be probed in details for 800-GeV LC.