Study of CDM–inspired cMSSM Scenarios at a 1 TeV Linear Collider

Marco Battaglia
UC Berkeley and LBNL
Introduction

✧ LC Physics and Cosmology connection becoming an important argument for sharpening the Linear Collider case;

✧ Offers an important opportunity to re-consider the LC potential for detailed exploration of New Physics responsible for CDM to define benchmark scenarios to optimise the detector design;

✧ This study represents a preliminary survey of the capabilities and experimental implications in slepton and Higgs analyses of CDM-inspired cMSSM scenarios;

✧ initiated as part of the activity of the US LC-Cosmo group and now becoming also embedded in the ALCPG Detector Design Study;

✧ Consider $\sqrt{s} = 0.5$ TeV and 1 TeV and including Circe beamstrahlung, events generated with Pythia 6.205+Isajet 7.67, detector simulation with Brahms, Lelaps and Fast Simulation; analysis with JAS-3 LCD Software;
Post-LEP & WMAP cMSSM

✧ cMSSM regions compatible with LEP and WMAP CDM constraints in co-annihilation ($\chi\ell$), rapid annihilation ($\chi\chi \rightarrow A$) and focus point regions;

✧ LC potential in testing CDM nature requires to follow reach and accuracy along these regions for different values of $(m_{1/2}, \tan \beta)$ and study experimental issues;

✧ This study addresses phenomenology along co-annihilation tail and in rapid annihilation funnel;

✧ Checking consistency of cMSSM with cosmology data requires precise determinations of $M_{\tilde{\ell}} - M_{\chi_1^0}$ or $M_{\chi}/M_A$ and $\tan \beta$ at LC.
Slepton Signatures in the post-WMAP cMSSM Parameter Space

✧ Slepton reconstruction at LC crucial for determining SUSY masses complementing the LHC reach;
✧ Testing SUSY nature of DM confronting cosmology data, crucial to accurately measure $M_{\tilde{\ell}} - M_\chi$ in co-annihilation region and $M_{\tilde{\tau}} - M_\chi$ in annihilation funnel.
✧ Distinctive $2 \ell + E_{\text{missing}}$ signature offers clean selection and fit to $E_\ell$ spectrum provides $M_{\tilde{\ell}}$ vs. $M_\chi$ reconstruction, $\tau$ tagging important;
✧ Typical LC mass accuracy in bulk region $\delta M_{\tilde{\ell}}/M_{\tilde{\ell}} \simeq 0.3 \%$ $\delta M_\chi/M_\chi \simeq 0.2 \%$
✧ Co-Annihilation and funnel regions present new challenges requiring detailed study of LC capabilities.
Slepton Signatures in the co-Annihilation Region

✧ Highest reach in $m_{1/2}$ from $e^+e^- \rightarrow \tilde{\ell}_R^+\tilde{\ell}_R^-$: LC at $\sqrt{s}=1$ TeV covers upper limit in $m_{1/2}$ for $\tan \beta = 5 - 10$ with $\sigma(e^+e^- \rightarrow \tilde{\ell}^+\tilde{\ell}^-) = \mathcal{O}(1-10 \text{ fb})$;
✧ along WMAP line $\tilde{\ell}_R$ becomes nearly degenerate with $\chi^0_1$: tuning $E_{\text{beam}}$ for sizeable $\sigma$ softens $E_{\ell}^{\text{min}}$.

$$E_{\ell}^{\text{min}} = \frac{1}{2}M_{\tilde{\ell}} \left(1 - \frac{M_{\chi^0_1}^2}{M_{\tilde{\ell}}^2}\right) \gamma \left(1 - \sqrt{1 - \frac{M_{\tilde{\ell}}^2}{E_{\text{beam}}^2}}\right);$$

\[ \tan \beta = 5 \]
\[ \tan \beta = 10 \]
✧ Lepton id. critical at lower endpoint due to:
1. Intrinsic Momentum Cut-off
2. $\gamma\gamma \to$ hadrons Background

✧ Momentum cut-off $p_t^{\text{min}}$ defined by radius $R_{\text{det}}$ of ECAL, HCAL and Muon Chambers and solenoidal field $B$:

$$p_t^{\text{min}}[\text{GeV}] = \frac{R_{\text{det}}[m]}{0.3B[\text{Tesla}]}$$

<table>
<thead>
<tr>
<th>$B$ [Tesla]</th>
<th>$R_{\text{det}}$ [m]</th>
<th>$p_t^{\text{min}}$ (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>$R_{\text{det}}[m]$</td>
<td>$p_t^{\text{min}}$ (GeV)</td>
</tr>
<tr>
<td>$\mu$ $\mu$Ch</td>
<td>4.2</td>
<td>$\mu$ $\mu$Ch</td>
</tr>
<tr>
<td>$\mu$ HCAL</td>
<td>2.0</td>
<td>$\mu$ HCAL</td>
</tr>
<tr>
<td>e ECAL</td>
<td>1.5</td>
<td>e ECAL</td>
</tr>
<tr>
<td>e dE/dx</td>
<td>0.7</td>
<td>e dE/dx</td>
</tr>
</tbody>
</table>

✧ $\gamma\gamma \to$ hadrons bkg becomes relevant if only one lepton can be tagged

Wired Display of $e^+e^- \to \tilde{\mu}_R^+\tilde{\mu}_R^-$ at 1 TeV at lower endpoint

$\tan \beta = 5$, $m_{1/2} = 600$, $m_0 = 118$
✧ Study co-annihilation tail with Micromegas and SSARD;
✧ define 3 study points at $\tan \beta = 5$ to track the slepton phenomenology at 1 TeV LC;

<table>
<thead>
<tr>
<th>Masses at Study Points</th>
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</thead>
<tbody>
<tr>
<td>$m_{1/2} = 600$</td>
</tr>
<tr>
<td>$M_{\tilde{\ell}_L}$</td>
</tr>
<tr>
<td>$M_{\tilde{\ell}_R}$</td>
</tr>
<tr>
<td>$M_{\chi_1^0}$</td>
</tr>
<tr>
<td>$m_{1/2} = 800$</td>
</tr>
<tr>
<td>$M_{\tilde{\ell}_L}$</td>
</tr>
<tr>
<td>$M_{\tilde{\ell}_R}$</td>
</tr>
<tr>
<td>$M_{\chi_1^0}$</td>
</tr>
<tr>
<td>$m_{1/2} = 950$</td>
</tr>
<tr>
<td>$M_{\tilde{\ell}_L}$</td>
</tr>
<tr>
<td>$M_{\tilde{\ell}_R}$</td>
</tr>
<tr>
<td>$M_{\chi_1^0}$</td>
</tr>
</tbody>
</table>

![Graph showing the relationship between $m_{1/2}$ and $m_0$.]
Lepton Momentum

Lepton Momentum Spectrum in
\[ e^+e^- \rightarrow \tilde{\ell}_R^+\tilde{\ell}_R^- \rightarrow \ell^+\chi_1^0\ell^-\chi_1^0 \] at 1 TeV for \( \tan \beta = 5 \) (\( \ell = e, \mu \))

\[ m_{1/2} = 600 \text{ GeV} \]
\[ m_{1/2} = 800 \text{ GeV} \]
\[ m_{1/2} = 950 \text{ GeV} \]

✧ Lepton ld momentum acceptance cuts into lower endpoint for \( m_{1/2} > 500 \text{ GeV} \).
Electron Id with $dE/dx$ in TPC

$\diamond$ $dE/dx$ in TPC useful to recover low-momentum electrons:

$$\sigma(dE/dx) = 0.045 \times \sqrt{\frac{1.68 \text{[m]}}{0.3B|T|p_t[\text{GeV}]}}$$

$dE/dx$ vs. $p$  

$|dE/dx_e - dE/dx_\pi|/\sigma$

$\diamond$ TPC with 200 samplings and 4.5% resolution should ensure $>4\sigma$ $e/\pi$ separation over the interesting momentum window.
Electron Momentum Spectrum in
\[ e^+e^- \rightarrow \tilde{\nu}_R\tilde{\nu}_R \rightarrow e^+\chi_1^0e^-\chi_1^0 \] at 1 TeV for \( \tan \beta = 5 \) (with \( dE/dx \) Id)

\[ m_{1/2} = 600 \text{ GeV} \quad m_{1/2} = 800 \text{ GeV} \quad m_{1/2} = 950 \text{ GeV} \]

✧ Electron \( dE/dx \) Id recovers sensitivity to lower endpoint almost to upper \( m_{1/2} \) edge.
Slepton Mass Fit

✧ Extract $\tilde{\ell}_R$ mass from $\chi^2$ fit to full lepton momentum distribution;
✧ include beamstrahlung and momentum resolution effects;
✧ impose $\chi^0$ mass (will add as syst. uncertainty);

$$m_{1/2} = 800 \text{ GeV}, \sqrt{s} = 1 \text{ TeV}$$

PRELIMINARY SLEPTON MASS
ACCURACY AT 1 TeV FOR
500 fb$^{-1}$

<table>
<thead>
<tr>
<th>$m_{1/2}$ (GeV)</th>
<th>$\delta M_{\tilde{\ell}_R}$ (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>0.07</td>
</tr>
<tr>
<td>800</td>
<td>0.10</td>
</tr>
<tr>
<td>950</td>
<td>0.06</td>
</tr>
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Studies of CDM-inspired cMSSM scenarios at a 1 TeV LC
M. Battaglia
Soft lepton spectrum also affects reconstruction of stau decays;

Lepton Momentum Spectrum in
\[ e^+ e^- \rightarrow \tilde{\tau}^+ \tilde{\tau}^- \rightarrow \ell^+ X \chi_1^0 \ell^- X \chi_1^0 \text{ at 1 TeV for } \tan \beta = 5 \]

- \( m_{1/2} = 600 \text{ GeV} \)
- \( M_{\tilde{\tau}_1} = 253.6 \text{ GeV} \)
- \( M_{\tilde{\tau}_2} = 428.0 \text{ GeV} \)
- \( m_{1/2} = 800 \text{ GeV} \)
- \( M_{\tilde{\tau}_1} = 332.3 \text{ GeV} \)
- \( M_{\tilde{\tau}_2} = 563.7 \text{ GeV} \)
- \( m_{1/2} = 950 \text{ GeV} \)
- \( M_{\tilde{\tau}_1} = 396.8 \text{ GeV} \)
- \( M_{\tilde{\tau}_2} = 668.4 \text{ GeV} \)
Estimate rate from $\gamma\gamma \rightarrow$ hadrons background

<table>
<thead>
<tr>
<th></th>
<th>TESLA 0.8 TeV</th>
<th>NLC 1.0 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{L}$ (fb BX$^{-1}$)</td>
<td>$2.7 \times 10^{-9}$</td>
<td>$1.3 \times 10^{-9}$</td>
</tr>
<tr>
<td>$N_{\gamma\gamma}$ BX$^{-1}$</td>
<td>0.40</td>
<td>0.27</td>
</tr>
<tr>
<td>$N_{\gamma\gamma}$ 500 fb$^{-1}$</td>
<td>$0.75 \times 10^{11}$</td>
<td>$1.05 \times 10^{11}$</td>
</tr>
</tbody>
</table>

$\gamma\gamma \rightarrow$ hadrons sample for NLC at 1 TeV;

Suppress $\gamma\gamma \rightarrow$ hadrons bkg using event shape and kinematical variables;

Assume $\epsilon(\pi \rightarrow \ell) \approx 0.10$ at low $p$

![Graph](chart.png)

Evts/500 fb$^{-1}$

<table>
<thead>
<tr>
<th>$2 \ell + E_{\text{missing}}$</th>
<th>1.5 - 2.5 GeV</th>
<th>2.5 - 5 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1 \ell + E_{\text{missing}}$</td>
<td>$\sim 22k$</td>
<td>$\sim 7k$</td>
</tr>
</tbody>
</table>

Important to tag fwd electrons down to small angles to suppress $\gamma\gamma \rightarrow$ hadrons.
The $A^0$ Annihilation Funnel

✧ In rapid annihilation $\chi\chi \rightarrow A^0$ funnel, $\Omega_{CDM}$ controlled by $R = 2M_{\chi}/M_A$ and $\tan \beta$;

✧ estimate required accuracy on $M_A$, $M_{\chi}$;

✧ Scan of $(m_0, m_{1/2}, \tan \beta)$ with Micromegas, imposing $M_h > 111.5$ GeV and $0.093 < \Omega_{CDM} h^2 < 0.129$ to determine $\Delta \Omega_{CDM}/\Delta R$ (agrees with sc DarkSusy);

$$\Delta \Omega_{CDM}/\Delta R = 2 - 5$$

$$\delta R = 2 \frac{\delta M_{\chi}}{M_{\chi}} \oplus \frac{\delta M_A}{M_A}$$

→ must determine $M_{\chi}$ and $M_A$ to $\mathcal{O}(0.5\%)$ or better to ensure $\Omega_{CDM}$ accuracy comparable to next generation of satellites (PLANCK), assuming theory uncertainty $\simeq \mathcal{O}(1\%)$. 

$\Omega_{CDM} h^2$ vs. $2M_{\chi}/M_A$

For $\mu > 0$ in $\tan \beta \pm 1$ slices
The $A$ Boson at the LHC

Cosmologically interesting region within sensitivity of heavy Higgs search at the LHC:

- $M_A$ Mass determination accuracy at LHC critically depends on accessibility to $A^0 \rightarrow \mu^+ \mu^-$ channel which is at the borderline for part of CDM-favoured region.
$m_0=340.00 \text{ GeV} \quad m_1/2=400.00 \text{ GeV} \quad \tan \beta=51$

$A=0 \quad Sgn(\mu)=+1 \quad M_{top}=178 \text{ GeV}$

<table>
<thead>
<tr>
<th>Mass (GeV)</th>
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<tbody>
<tr>
<td>$M_{h^0}$</td>
</tr>
<tr>
<td>$M_{A^0}$</td>
</tr>
<tr>
<td>$M_{\chi^0}$</td>
</tr>
<tr>
<td>$M_{\tilde{\tau}_1}$</td>
</tr>
</tbody>
</table>

**Analysis strategy**

- Determine at 0.5 TeV:
  - $M_{\tilde{\tau}_1}$ by threshold scan and $\Delta M = M_{\tilde{\tau}_1} - M_{\chi}$
  - by $\tilde{\tau}_1 \to \tau \chi$ jet kinematics to extract $M_{\chi}$

- Estimate at 0.5 TeV:
  - $M_A$ using $\frac{\text{BR}(h^0 \to b\bar{b})}{\text{BR}(h^0 \to W^+W^-)}$, $\frac{\text{BR}(h^0 \to b\bar{b})}{\text{BR}(h^0 \to c\bar{c})}$

- Determine 1.0 TeV:
  - $M_A$ with $e^+e^- \to H^0 A^0 \to b\bar{b}b\bar{b}, b\bar{b}\tau\bar{\tau}$. 

**Micromegas Scan for $Sgn(\mu)=+1$**
$e^+e^- \rightarrow \tilde{\tau}_1\tilde{\tau}_1$ at 0.5 TeV

✧ Extract $M_\chi$ from $\tilde{\tau}_1 \rightarrow \tau \chi$, which is accessible at $\sqrt{s}=0.5$ TeV;

✧ Threshold scan to determine $M_{\tilde{\tau}_1}$:
\[
\frac{\Delta \sigma}{\Delta M_{\tilde{\tau}_1}} = 0.6 \text{ fb/GeV}
\]

✧ Irreducible SM Bkg $e^+e^- \rightarrow \tau \tau \nu \nu$

$E_{\text{missing}} > 350$ GeV $\sigma_{SM} \approx 6.5$ fb

✧ 2 point scan:
425 GeV - 500 GeV with $200 + 300$ fb$^{-1}$

$$\delta M/M \approx 0.5 \%$$
✧ Use $\tilde{\tau}_1 \tilde{\tau}_1$ production to determine $\Delta M = M_{\tilde{\tau}_1} - M_\chi$;

✧ Tag $\tau$ jets using multiplicity and lepton content and pair with charge;

✧ Reject SM bkg with combination of cuts on $E_{\text{missing}}$, $\theta_{JJ}$ and shape variables;

✧ Define estimator for $\Delta M$ from $M_{JJ E_{\text{missing}}}$ and fit data to templates for different $\Delta M$ values;

$$\delta \Delta M \simeq 1 \text{ GeV}$$

$$\delta M_\chi / M_\chi \simeq 1 \%$$

✧ May also use $e^+ e^- \rightarrow \chi_1 \chi_2^0$ but $\sigma \simeq 1 \text{ fb.}$
Beyond LHC, the 0.5 TeV LC data would show that the Higgs sector is non minimal through precise measurements of $h^0$ branching fractions and may already provide some constraints on the $A^0$ mass;

- in particular $R_{bW} = \frac{BR(h^0 \rightarrow b\bar{b})}{BR(h^0 \rightarrow W^+W^-)}$ has a sensitivity of 0.02 GeV$^{-1}$;
- underlying heavy quark mass uncertainties are significantly reduced using moments of spectral distribution in s.l. $b$ decays from $B$-factory and CDF data to $\delta BR(h \rightarrow b\bar{b})/BR < 1\%$ and $\delta BR(h \rightarrow c\bar{c})/BR < 10\%$;

- Combined analysis of $h^0$ branching fractions should give ($M_A \pm 15$) GeV;
\[ e^+e^- \rightarrow H^0 A^0 \rightarrow b\bar{b}b\bar{b} \text{ at } 1 \text{ TeV} \]

✧ Select hadronic events with no significant \( E_{\text{missing}} \) and force 4-jet reconstruction; 
✧ reject background with selection on discriminant based on \( \Phi_{jj} \), \( y_{34} \), \( \text{Thrust} \) and \( M_{jj1} - M_{jj2} \) cuts; 
✧ apply parametric b-tagging for di-jet and kinematic fit; 
✧ Consider SM \( e^+e^- \rightarrow Z^0Z^0 \), \( W^+W^- \) and \( b\bar{b}b\bar{b} \) (5 fb) and inclusive SUSY background.
✧ Obtain $\epsilon_{\text{signal}} \simeq 0.30 \simeq \delta M \simeq = 1.5$ GeV 

$$\frac{\delta M}{M} = 0.5\%$$

with fast simulation, preliminary results using Lealps agree;
✧ Need to include full 4-$f$ background and overlay $\gamma\gamma \to \text{hadrons}$ events which may distort jet reconstruction significantly.
Conclusions

✧ CDM-inspired cMSSM presents important challenges for experimentation at LC;

✧ typical LC $\mathcal{O}(0.1 \%)$ accuracy on slepton masses appears realisable along co-annihilation tail;

✧ but co-annihilation region at small $M_{\tilde{\ell}} - M_{\tilde{\chi}_1^0}$ characterised by low lepton momenta which requires to extend acceptance of lepton ld, in particular at low $\tan \beta$ and careful study of $\gamma\gamma$ Bkg rejection;

✧ Achieving few % precision on predicting $\Omega h^2$ from SUSY measurements requires accuracies of $\mathcal{O}(0.5 \%)$ for individual masses;

✧ complete analyses of benchmark points along co-annihilation tail and in the annihilation funnel will clarify the LC impact on testing CDM nature in a quantitative way and underline their implications on detector design.