The stop co-annihilation region at the ILC

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1. Introduction
2. Detecting light stops
3. Parameter determination
4. Dark matter prediction
Introduction
Electroweak Baryogenesis

**Sakharov conditions:**

- Baryon number violation
  - In Standard Model and extensions through non-perturbative sphaleron processes

- C and CP violation
  - CP violation in Standard Model through CKM phase not sufficient to explain baryon asymmetry $\eta_{BBN} \sim 6 \times 10^{-10}$

- Non-equilibrium
  - Strongly first order electroweak phase transition necessary
    \[
    \frac{v(T_c)}{T_c} > 1
    \]

  - In Standard Model: $\frac{v(T_c)}{T_c} \approx \frac{g^2}{4\pi\lambda} \text{ with } \lambda \propto \frac{M_H^2}{v^2}$
    
    $\rightarrow$ not fulfilled for $M_H \gtrsim 40$ GeV
Electroweak Baryogenesis and Supersymmetry

**EW baryogenesis:**
- new boson degrees of freedom with strong Higgs coupling
- new sources for CP violation

Supersymmetry provides natural framework for EW baryogenesis

Carena, Quirós, Wagner ’96

Higgs potential modified by scalar top (stop) $\tilde{t}_1$:

Each stop has six degrees of freedom (3 color, 2 charge),
coupling $\mathcal{O}(1)$ to Higgs

$$\frac{v(T_C)}{T_C} \approx \frac{g^2 + 2y_{\tilde{t}}^2}{4\pi \lambda}$$

- Higgs masses up to 120 GeV
- Lightest stop must have mass below top quark
Electroweak Baryogenesis and CP violation

CP violating source needed to generate chiral charge asymmetry

→ particle currents coupling to the Higgs background

In Standard Model:
CP-violating CKM processes suppressed by Yukawa couplings $m_q^2/M_W^2$

Supersymmetry: Carena, Quirós, Riotto, Vilja, Wagner ’97
Additional contribution from stop and chargino currents

\[ \alpha \text{Im}(A_t \mu) \quad \alpha \text{Im}(M_2 \mu) \]

Higgs bound $M_{h_0} \gtrsim 114$ GeV: one stop eigen-state heavy

⇒ Charginos are dominant source if they are light

Phase can be rotated into $\mu$ parameter only
Dark matter

Evidence for dark matter from many sources:

- Rotation curves of galaxies
- Supernovae Ia redshift
- CMB
- Gravitational lensing
- Large scale structure

\(\sim 85\%\) of matter in universe is \textcolor{red}{dark}\.
Dark matter and Supersymmetry

Dark matter has to be stable and weakly interacting

Supersymmetry has natural dark matter candidate:

- lightest neutralino $\tilde{\chi}^0_1$ stable for R-parity conservation

- Dark matter particles freeze out when expanding universe cools
- After freeze-out dark matter particles annihilate
- Annihilation cross-section

$$\tilde{\chi}^0_1 \tilde{\chi}^0_1 \rightarrow X$$

suppressed due to chirality conversation

→ Too large relic density in many SUSY scenarios
Co-annihilation

Mass of SUSY particle $\tilde{X}$ close to lightest neutralino $\tilde{\chi}_1^0$

- Freeze-out of $\tilde{X}$ and $\tilde{\chi}_1^0$ at roughly same temperature
- Annihilation in parallel (co-annihilation)
- Reduction of total dark matter density

In framework of EW baryogenesis:
Co-annihilation with scalar top
**Typical parameter regions**

Carena, Balázs, Wagner ’04

**Green:** Relic density consistent with WMAP

Co-annihilation for
\[ \Delta m \lesssim 30 \text{ GeV} \]

Difficult for searches at Tevatron

LHC will have similar difficulties

(possible additional channel: \( pp \rightarrow \tilde{g}\tilde{g} \rightarrow \tilde{t}_1 \tilde{t}_1 \tilde{t}\tilde{t} \))
Detecting light stops
Light stop signature

Dominant decay for small mass differences $\Delta m = m_{\tilde{t}_1} - m_{\tilde{\chi}^0_1}$: $\tilde{t}_1 \rightarrow c \tilde{\chi}^0_1$

Assume 100% branching ratio for $\tilde{t}_1 \rightarrow c \tilde{\chi}^0_1$

Signature at linear collider: $e^+e^- \rightarrow \tilde{t}_1 \tilde{t}^*_1 \rightarrow c \bar{c} \tilde{\chi}^0_1 \tilde{\chi}^0_1$

Two (soft) charm jets plus missing energy

Discrimination from background requires detector simulation

- Event generation with Pythia
- Detector effects with fast simulation
- Include beamstrahlung with Circe

Generate SM background from various sources

Assume $\mathcal{L} = 500 \text{ fb}^{-1}$ at $\sqrt{s} = 500 \text{ GeV}$. 
Signal and Background

<table>
<thead>
<tr>
<th>process</th>
<th>cross-section [pb]</th>
<th>$P(e^-)/P(e^+)$ = 0/0</th>
<th>-80%/+60%</th>
<th>+80%/-60%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{t}_1 \tilde{t}<em>1$, $m</em>{\tilde{t}_1}$ = 120 GeV</td>
<td>0.115</td>
<td>0.153</td>
<td>0.187</td>
<td></td>
</tr>
<tr>
<td>$m_{\tilde{t}_1}$ = 140 GeV</td>
<td>0.093</td>
<td>0.124</td>
<td>0.151</td>
<td></td>
</tr>
<tr>
<td>$m_{\tilde{t}_1}$ = 180 GeV</td>
<td>0.049</td>
<td>0.065</td>
<td>0.079</td>
<td></td>
</tr>
<tr>
<td>$m_{\tilde{t}_1}$ = 220 GeV</td>
<td>0.015</td>
<td>0.021</td>
<td>0.026</td>
<td></td>
</tr>
<tr>
<td>$W^+W^-$</td>
<td>8.55</td>
<td>24.54</td>
<td>0.77</td>
<td></td>
</tr>
<tr>
<td>ZZ</td>
<td>0.49</td>
<td>1.02</td>
<td>0.44</td>
<td></td>
</tr>
<tr>
<td>$W e\nu$</td>
<td>6.14</td>
<td>10.57</td>
<td>1.82</td>
<td></td>
</tr>
<tr>
<td>$eeZ$</td>
<td>7.51</td>
<td>8.49</td>
<td>6.23</td>
<td></td>
</tr>
<tr>
<td>$q\bar{q}$, $q \neq t$</td>
<td>13.14</td>
<td>25.35</td>
<td>14.85</td>
<td></td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>0.55</td>
<td>1.13</td>
<td>0.50</td>
<td></td>
</tr>
<tr>
<td>$\gamma\gamma$, $p_t &gt; 5$ GeV</td>
<td>936</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$- = L$
$+ = R$

$\sin \theta_{\tilde{t}} = 0.5$

Large Standard Model backgrounds!
**Reduction of background**

**Preselection:**

1. $4 < N_{\text{chargedtracks}} < 50$
2. $p_t > 5$ GeV
3. $|\cos \theta_{\text{Thrust}} < 0.8|$
4. $|p_{\text{long,tot}}/p_{\text{tot}}| < 0.9$
5. $E_{\text{vis}} < 0.75 \sqrt{s}$
6. $m_{\text{inv}} < 200$ GeV

Most backgrounds (color) strongly reduced

Signal (black) to $\sim 70\%$
Effect of preselection for various signal parameters

for $m_{\tilde{t}_1} = 140$, 180, 220 GeV

and $\Delta m = 20$, 40, 80 GeV

Signal efficiencies after pre-selection 65–75%
Reduction of background

Preselection:
1. $4 < N_{\text{charged tracks}} < 50$
2. $p_t > 5$ GeV
3. $|\cos \theta_{\text{Thrust}}| < 0.8$
4. $|p_{\text{long,tot}}/p_{\text{tot}}| < 0.9$
5. $E_{\text{vis}} < 0.75 \sqrt{s}$
6. $m_{\text{inv}} < 200$ GeV

Selection:
1. $N_{\text{jets}} = 2$
   (Durham $y_{\text{cut}} = 0.003$)
2. $E_{\text{vis}} < 0.4 \sqrt{s}$
3. $\cos \phi_{\text{aco}} > -0.9$
4. $|\cos \theta_{\text{Thrust}}| < 0.7$
5. $p_t > 12$ GeV
6. $3500 \text{ GeV}^2 < m_{\text{inv}}^2 < 8000 \text{ GeV}^2$, c-tagging
### Remaining background levels

<table>
<thead>
<tr>
<th>Background</th>
<th>$N_{\text{evt}}$ generated</th>
<th>$N_{\text{evt}}$ after selection</th>
<th>scaled to 500 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^+W^-$</td>
<td>210,000</td>
<td>10</td>
<td>145</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>30,000</td>
<td>30</td>
<td>257</td>
</tr>
<tr>
<td>$W\nu\nu$</td>
<td>210,000</td>
<td>624</td>
<td>5044</td>
</tr>
<tr>
<td>$eeZ$</td>
<td>210,000</td>
<td>3</td>
<td>36</td>
</tr>
<tr>
<td>$q\bar{q}$, $q \neq t$</td>
<td>350,000</td>
<td>10</td>
<td>200</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>180,000</td>
<td>25</td>
<td>38</td>
</tr>
<tr>
<td>$\gamma\gamma$</td>
<td>8,000,000</td>
<td>0</td>
<td>$&lt; 164$</td>
</tr>
</tbody>
</table>

Largest remaining background from $e^+e^- \rightarrow W^\pm e^\mp \nu$

Distributions in thrust, acoplanarity, jet angles, etc. similar to signal

Only cut in window around $m_{\text{inv}} \sim M_W$ and c-tagging effective
**Signal efficiency**

<table>
<thead>
<tr>
<th>$\Delta m$</th>
<th>$m_{\tilde{t}_1} = 120$ GeV</th>
<th>140 GeV</th>
<th>180 GeV</th>
<th>220 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>80 GeV</td>
<td>10%</td>
<td>15%</td>
<td>19%</td>
<td></td>
</tr>
<tr>
<td>40 GeV</td>
<td>10%</td>
<td>20%</td>
<td>24%</td>
<td></td>
</tr>
<tr>
<td>20 GeV</td>
<td>17%</td>
<td>21%</td>
<td>28%</td>
<td>35%</td>
</tr>
<tr>
<td>10 GeV</td>
<td>19%</td>
<td>20%</td>
<td>19%</td>
<td>35%</td>
</tr>
<tr>
<td>5 GeV</td>
<td>2.5%</td>
<td>1.1%</td>
<td>0.3%</td>
<td>0.1%</td>
</tr>
</tbody>
</table>

Typical signal event number remaining after selectron for 500 fb$^{-1}$, depending on $m_{\tilde{t}_1}$ and $\theta_{\tilde{t}}$: $N_{\text{sig}} \sim \mathcal{O}(10^3) - \mathcal{O}(10^4)$

→ same order as remaining background

Signal efficiency deteriorates for very small $\Delta m$
Stop discovery reach at linear collider

From simulations:
Background numbers $B$ and
signal efficiencies $\epsilon$
with theor. cross-section $\sigma$
yields signal number $S = \epsilon\sigma$

Green region: $\frac{S}{\sqrt{S + B}} > 5$

Light green:
decay $t \to \tilde{t}_1\tilde{\chi}_1^0$ open
(not yet studied)

Detection of light stops
possible for $\Delta m \sim \mathcal{O}(5\text{GeV})$

Cover complete
co-annihilation region
Parameter determination
Sample parameter point

Point with light stop, gauginos, selectron and CP violation
→ Use existing studies where possible

\[ M_1 = 112.6 \text{ GeV} \quad M_{u3}^2 = -992 \text{ GeV}^2 \]
\[ M_2 = 225 \text{ GeV} \quad M_{q3} = 4200 \text{ GeV} \]
\[ |\mu| = 320 \text{ GeV} \quad A_t = -1050 \text{ GeV} \]
\[ \phi_\mu = 0.2 \quad \tan \beta = 5 \]

1st/2nd generation squarks heavy

→ Consistent with $\epsilon$ and $n$ EDM, $m_{h_0}$ bound, baryogenesis

Sparticle masses:
\[ m_{\tilde{\chi}_1^0} = 107.2 \text{ GeV} \quad m_{\tilde{t}_1} = 122.5 \text{ GeV} \quad \cos \theta_{\tilde{t}} = 0.0105 \]
\[ \Omega_{\text{CDM}} h^2 \approx 0.112 \]
Stop parameters

Use $e^+ e^- \rightarrow \tilde{t}_1 \tilde{t}_1^*$ cross-section measurements for two different beam polarizations:

$P(e^-)/P(e^+) = -80% / +60%$

$+80% / -60%$

$\mathcal{L} = 250 \text{ fb}^{-1}$ each

Systematic errors:

- $\delta m_{\tilde{\chi}_1^0} = 0.1 \text{ GeV}$
- $\delta P/P = 0.5%$
- backgr. $\delta B/B = 0.3%$
- $\delta \mathcal{L}/\mathcal{L} = 5 \times 10^{-4}$
- $\tilde{t}_1$ hadroniz./fragment.: $\sim 1%$
- charm tagging/fragm.: $0.5%$
- detector calibration: $0.5%$
- beamstrahlung

Result: $m_{\tilde{t}_1} = 122.5 \pm 1.0 \text{ GeV}$

$|\cos \theta_{\tilde{t}}| < 0.074$

$\Rightarrow |\sin \theta_{\tilde{t}}| > 0.9972$
Chargino/Neutralino parameters

Mass measurements:

- Heavy 1st/2nd generation squarks
  → Neutralino masses from squark cascades at LHC difficult

- Lightest neutralino $\tilde{\chi}^0_1$ mass from selectron and other decays at ILC
  $\rightarrow \delta m_{\tilde{\chi}^0_1} = 0.11$ GeV

- Other neutralino/chargino masses from ILC threshold scans
  LHC/ILC report '04

Most studies performed in SPS1a scenario
→ Scale errors with different cross-sections in our scenario

<table>
<thead>
<tr>
<th>$\tilde{\chi}^0_1$</th>
<th>$\tilde{\chi}^0_2$</th>
<th>$\tilde{\chi}^0_3$</th>
<th>$\tilde{\chi}^\pm_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta m$</td>
<td>0.11</td>
<td>2.5</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.12 GeV</td>
<td></td>
</tr>
</tbody>
</table>
Cross-section measurements

\[ e^+e^- \rightarrow \tilde{\chi}_1^+\tilde{\chi}_1^- \quad P(e^-)/P(e^+) = -80\%/+60\% \text{ and } +80\%/-60\% \]

at \( \sqrt{s} = 500 \text{ GeV} \)

Note: Light stop opens decay \( \tilde{\chi}_1^+ \rightarrow \tilde{t}_1\bar{b} \)
with experimentally unknown BR

→ Use only cross-section ratios for \( \sigma(e^+e^- \rightarrow \tilde{\chi}_1^+\tilde{\chi}_1^-) \)

Systematic errors in cross-sections:

- chargino/neutralino masses
- selectron/sneutrino masses in t-channel
- \( \delta P/P = 0.5\% \)

Experimental efficiency extrapolated from analysis for \( e^+e^- \rightarrow \tilde{\chi}_1^0\tilde{\chi}_2^0 \)

M. Ball '02
Chargino/Neutralino comprehensive analysis

Use $\chi^2$ fit to extract fundamental SUSY parameters:

\[
M_1 = 112.6 \pm 0.2 \text{ GeV} \quad |\phi_\mu| < 1.0 \\
M_2 = 225.0 \pm 0.7 \text{ GeV} \quad \tan \beta = 5^{+0.5}_{-2.6} \\
|\mu| = 320.0 \pm 3.3 \text{ GeV}
\]

Large correlation between \( \tan \beta \) and \( \phi_\mu \)

→ Not problematic for dark matter determination
Dark matter prediction
Computation of $\Omega_{\text{CDM}}$ from collider results

Use program by D. Morrissey for calculating $\Omega_{\text{CDM}}$

Balázs, Carena, Menon, Morrissey, Wagner ’04

Use inputs and propagate errors from
- Stop sector
- Chargino/neutralino sector
- Higgs sector

Account for correlations by using $\chi^2$ fit

$1\sigma$ constraints from ILC/LHC measurements:
$0.086 < \Omega_{\text{CDM}} h^2 < 0.143$

dominated by error on $m_{\tilde{t}_1}$

WMAP/SDSS (95% CL):
$0.095 < \Omega_{\text{CDM}} h^2 < 0.129$
Different SUSY scenarios

ILC measurements could lead to different conclusions:

- Agreement with cosmological observations (A,C,E)
- SUSY predicts too little DM (B) → other sources?
- SUSY predicts too much DM (D,E) → constraints on parameters, revision of model of universe?
Conclusions

- ILC can cover complete stop-neutralino co-annihilation scenario
  Can explore mass differences down to
  \[ \Delta m = m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} \sim \mathcal{O}(5 \text{ GeV}) \]

- Prediction of \( \Omega_{\text{CDM}} \) in MSSM from collider measurements with precision comparable to cosmological measurements

Future avenues:

- Further refinements of the experimental analysis
- Analyze different dark matter scenarios
- Investigate effect of radiative corrections
Maybe at one point we will be able to figure out what this is
C-tagging – Concept

Vertex identification followed by a Neural Network optimization

Vertex identification:

As a maximum in track overlapping (product of probability density tubes defined using the track parameters) 3 cases:

1. Only primary vertex
2. 1 secondary vertex
3. >1 secondary vertex

Neural Network (NN):

Data for training: 255000 $\tilde{t}_1\tilde{t}_1^*$ events, $m_{\tilde{t}_1} = 120–220$ GeV, $\Delta m = 5, 10, 20$ GeV
240000 $W_{\ell\nu}$ events, the most resilient background
C-tagging – Neural Network Input

**Vertex Case 1:** NN input variables:
- impact parameters and their significance (impact parameter / error) of 2 most significant tracks
- track momenta
- joint probability in $r$-$\phi$ plane and $z$ direction

**Cases 2/3:** NN input variables: **all of case 1 plus:**
- decay length and its significance of secondary vertex
- number/momenta of tracks associated to 2$^{\text{nd}}$ vertex
- $p_t$-corrected mass of 2$^{\text{nd}}$ vertex
  (corrected for neutral hadrons and $\nu$’s), $p_t$ distribution relative 2$^{\text{nd}}$ vertex direction