Exploring Supersymmetry in Future \(e^+e^-\) Colliders

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on behalf of ILD, SiD, CLICpd groups
**LC detector concepts for MC**

- **ILD concept**
  - Time projection chamber
  - 3.5T magnetic field

- **SiD concept**
  - Silicon tracker
  - 5T magnetic field

Adapt ILC detectors for higher energy initial studies (CLIC_ILD & CLIC_SID)

- Larger inner radius of VTX first layer
- Larger HCAL
- Stronger magnetic field (CLIC_ILD only: 4T)

All works in this talk are done in realistic full MC simulation using geometries of ILD, SiD, CLIC_ILD or CLIC_SiD
SUSY in LC

Colored sector
- Naturally heavy in light of LHC data
- May be accessible in a multi-TeV LC
- For some parameters low energy squarks still alive

Gaugino sector
- Should be light
- Direct production is difficult in hadron colliders
- Many properties are accessible in LC “Window to SUSY world”

Slepton sector
- Light sleptons still alive
- Long-lived stau also accessible in LC

Higgs (light/heavy)
- Structure of Higgs doublet can be accessible in TeV LC
- Precision study of light Higgs also gives constraints on SUSY
Colored sector
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Gaugino sector
- Should be light
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- Many properties are accessible in LC
  “Window to SUSY world”

Higgs (light/heavy)
- Not covered in this talk:
  See F. Simon’s presentation in Friday

Gravitino
Virtually no model-independent constraints by LHC in gaugino sector

Part of following studies may use benchmark points which are already excluded, but they are easily applicable for parameters with too heavy colored sector to be seen in LHC.

**Gaugino sector**

- Chargino/Neutralino mass fit
- Spin determination
- WIMP + ISR
- Neutralino decay (RPV)
Chargino/Neutralino study

- Detector benchmark (ILC LoI, CLIC CDR) for W/Z/H separation in particle flow
- Mass & cross section measurement

$m(\chi^\pm_1) \sim m(\chi^0_2) \sim 217 \text{ GeV}$, $m(\chi^0_1) \sim 116 \text{ GeV}$ (ILD, SiD 500 GeV)
$m(\chi^\pm_1) \sim m(\chi^0_2) \sim 643 \text{ GeV}$, $m(\chi^0_1) \sim 340 \text{ GeV}$ (CLIC 3TeV)

1-3\% cross section accuracy can be obtained.
Chargino/Neutralino mass fit

500 GeV 500 fb⁻¹

ILD

SiD

CLIC

3 TeV 2 ab⁻¹

fit -> edge -> mass

template -> $\chi^2$

both (template & fit)

<table>
<thead>
<tr>
<th></th>
<th>ILD(fit)</th>
<th>SiD(template)</th>
<th>CLIC(tmpl.)</th>
<th>CLIC(fit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m(\chi^{\pm})$</td>
<td>1.4%</td>
<td>0.2%</td>
<td>1.0%</td>
<td>1.1%</td>
</tr>
<tr>
<td>$\Delta m(\chi^0)$</td>
<td>0.5%</td>
<td>0.5%</td>
<td>1.1%</td>
<td>1.5%</td>
</tr>
<tr>
<td>$\Delta m(\chi^0_1)$</td>
<td>0.7%</td>
<td>0.1%</td>
<td>0.9%</td>
<td>0.9%</td>
</tr>
</tbody>
</table>
Chargino/Neutralino mass fit

ILD(fit) | SiD(template) | CLIC(tmpl.) | CLIC(fit)
---|---|---|---
$\Delta m(\chi^{\pm}_{1})$ | 1.4% | 0.2% | 1.1%
$\Delta m(\chi^{0}_{2})$ | 0.5% | 0.5% | 1.1%
$\Delta m(\chi^{0}_{1})$ | with correlation: 0.7% | without correlation: 0.1% | 0.9% | 0.9%
Chargino/Neutralino mass fit

500 GeV 500 fb⁻¹
ILD

3 TeV 2 ab⁻¹
CLIC

ILD(fit) SiD(template) CLIC(tmpl.) CLIC(fit)

fit -> edge -> mass template -> $\chi^2$ both (template & fit)

$D_{m(\frac{c}{2})}$
$D_{m(0 \pm 1)}$

0.5% 0.5% 1.1% 1.5%

0.7% 0.1% 0.9% 0.9%

with correlation without correlation

$\sim 1 \%$ mass resolution is obtained.
Spin determination

Obtaining $\chi^\pm$ spin by production angle and threshold scan

Threshold scan

Production angle

Template fit using 2D distribution of two solutions

Scalar $\chi^\pm$ can be separated with $> 4.9 \sigma$

Fermion (SUSY) $\chi^\pm$ can be well separated with $3 \times 50 \text{ fb}^{-1}$ statistics

$m(\chi^\pm) \sim 232 \text{ GeV}$, $m(\chi^0) \sim 44 \text{ GeV}$, $\sigma = 40 \text{ fb}$

500 GeV

500 fb$^{-1}$

PRD 84, 115003 (2011)
LSP-pair production w/ ISR

$m(\chi^0_1) \sim 100$ GeV case


$\sigma \sim 60$ fb in $(P_e^-, P_e^+) = (0.8, -0.3)$

$m(\chi^0_1) \sim 150, 200$ GeV case

arXiv:1006.3551

$\sigma \sim 30$ fb in $(P_e^-, P_e^+) = (0.8, -0.3)$ (150)

$\sigma \sim 11$ fb in $(P_e^-, P_e^+) = (0.8, -0.3)$ (200)

Template fit for mass determination

$\Delta m(\chi^0_1) \sim 3-4\%$

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Bilinear R-Parity violating SUSY

Motivated by
- cosmology (gravitino DM) \[ arXiv:1007.5007 \]

Signal signature
- \( \tilde{\chi}_1^0 \to W + l \)
- lifetime of \( \tilde{\chi}_1^0 \) \( \to \) displaced vertices

Full ILD simulation
- search for 2W+2l
- no assumptions on neutralino mass or lifetime

Production cross section of neutralino pairs @ ILC

Measurement of neutrino mixing

\[ \int L \ dt = 26 \text{ fb}^{-1} \]

assumptions: \( \varepsilon_\mu = 0.8 \pm 1\% \)
\( \varepsilon_\tau = 0.3 \pm 1\% \)
\( \varepsilon_W = 0.7 \pm 1\% \)

blue: precision @ ILC
red: current uncertainties \[ PDG2012 \]

500 GeV
Slepton sector

- smuon/stau (500 GeV)
- selectron/smuon/sneutrino (3 TeV)
- Long-lived stau (500 GeV)

Model-independent constraints by LHC are also very weak in slepton sector.
Light smuon/stau

**smuon** ILD LoI

\[ m(\text{smuL}) = 184 \text{ GeV}, \ m(\chi^0_1) = 98 \text{ GeV}, \ 54.32 \text{fb} \]

\[ \Delta m(\chi^0_1) : 1.1\% \]
\[ \Delta m(\text{smuL}) : 0.2\% \]
\[ \Delta \sigma: 2.5\% \]

**stau** ILD LoI, arXiv:0908.0876v2

\[ m(\text{stau1}) = 108 \text{ GeV} \]
\[ m(\text{stau2}) = 195 \text{ GeV} \]

\[ \Delta m(\text{stau1}): 1.1 \Delta m(\chi^0_1) \text{ GeV} \]
\[ \Delta m(\text{stau2}): +11-5 + 18 \Delta m(\chi^0_1) \text{ GeV} \]

\[ \Delta P: 9\% (\pi) \ 5\% (\rho) \]
### Heavy Sleptons

#### CLIC CDR

**Note:** LCD-Note-2011-018

<table>
<thead>
<tr>
<th>Process</th>
<th>Decay Mode</th>
<th>$\sigma$ (fb)</th>
<th>$m_{\tilde{\ell}}$ (GeV)</th>
<th>$m_{\tilde{\chi}<em>1^0}$ or $m</em>{\tilde{\chi}_1^\pm}$ (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+e^- \rightarrow \tilde{\mu}_R^+ \tilde{\mu}_R^-$</td>
<td>$\mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0$</td>
<td>0.71 ± 0.02</td>
<td>1014.3 ± 5.6</td>
<td>341.8 ± 6.4</td>
</tr>
<tr>
<td>$e^+e^- \rightarrow \tilde{e}_R^+ \tilde{e}_R^-$</td>
<td>$e^+e^-\tilde{\chi}_1\tilde{\chi}_1^0$</td>
<td>6.20 ± 0.05</td>
<td>1001.6 ±</td>
<td>340.6 ± 6.1</td>
</tr>
<tr>
<td>$e^+e^- \rightarrow \tilde{e}_L^+ \tilde{e}_L^-$</td>
<td>$e^+e^-\tilde{\chi}_1\tilde{\chi}_1^0$</td>
<td>2.77 ± 0.20</td>
<td>1096.4 ± 3.9</td>
<td>644.8 ± 3.7</td>
</tr>
<tr>
<td>$e^+e^- \rightarrow \tilde{\nu}_e \tilde{\nu}_e$</td>
<td>$e^+e^-\tilde{\chi}_1\tilde{\chi}_1^\pm$</td>
<td>13.24 ± 0.32</td>
<td>1096.4 ± 3.9</td>
<td>644.8 ± 3.7</td>
</tr>
</tbody>
</table>

#### Graphs

- **Graph 1:** $e^+e^- \rightarrow \tilde{\mu}_R^+ \tilde{\mu}_R^-$
  - $M_{\tilde{\mu}} = 1014.29 \pm 5.57$
  - $M_{\tilde{\chi}^0} = 341.75 \pm 6.38$, $\chi^2$/ndf = 24.5/45

- **Graph 2:** $e^+e^- \rightarrow \tilde{e}_R^+ \tilde{e}_R^-$
  - $M_{\tilde{\epsilon}} = 1001.59 \pm 5.28$
  - $M_{\tilde{\chi}^0} = 340.59 \pm 6.08$, $\chi^2$/ndf = 21.6/45

- **Graph 3:** $e^+e^- \rightarrow \tilde{\nu}_e \tilde{\nu}_e$
  - $M_{\tilde{\nu}} = 1001.64 \pm 3.98$
  - $M_{\tilde{\chi}^0} = 644.75 \pm 3.66$, $\chi^2$/ndf = 35.6/35

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Taikan Suehara, ICHEP2012 in Melbourne, 5th July 2012 page 15
Long-lived stau

Yamaura et al., LCWS11 talk
for m(stau) = 150 GeV,
• m(stau) can be determined by dE/dx at TPC and TOF
  -> ~1.4% resolution
• gravitino life can be measured by tuning sqrt(s) for staus to be stopped at HCAL ~ 2.4%

Katayama et al., KILC12 talk
m(stau) = 120 GeV, σ = 136 fb

\[ \Delta m(\text{stau}) : 1.4\% \]
\[ \Delta \tau(\text{stau}) : 2.1\% \]
\[ \Delta m(\text{gravitino}) : 4\% \]
Colored sector

- squark (3 TeV)
- degenerate sbottom (500 GeV)
Light-flavor Squarks

<table>
<thead>
<tr>
<th>$m_{\tilde{u}<em>R}, m</em>{\tilde{c}_R}$</th>
<th>$m_{\tilde{d}<em>R}, m</em>{\tilde{s}_R}$</th>
<th>$m_{\chi}$</th>
<th>combined cross section</th>
</tr>
</thead>
<tbody>
<tr>
<td>1125.7 GeV</td>
<td>1116.1 GeV</td>
<td>328.3 GeV</td>
<td>1.47 fb</td>
</tr>
</tbody>
</table>

$$M_C = \sqrt{(E_{q,1} + E_{q,2})^2 - (\vec{p}_{q,1} - \vec{p}_{q,2})^2}$$
$$= \sqrt{2(E_1 E_2 + \vec{p}_1 \cdot \vec{p}_2)},$$

$M_C$: independent of the CM energy

$\Delta m(squark) : 0.5\%$
$\Delta \sigma : 4.9\%$

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Sbottom co-annihilation

Sbottom-neutralino co-annihilation: small mass difference between sbottom and $\chi_1^0$, difficult to discover in LHC

with $\theta_{b\text{min}}$

$> 3\sigma$ separation is obtained with 20 GeV mass difference

$\sim 2\sigma$ separation with 10 GeV
Summary

• Still a lot of room to explore SUSY with LC!
  – In case of “discovery” at LHC: many properties of SUSY can be revealed
  – In case of “non-discovery” at LHC: many possibilities of SUSY to be revealed

• Many realistic full simulation have been performed & ongoing

• ILD, SiD and CLICpd groups are in very close cooperation to realize a linear collider
References

• Websites
  – ILD http://www.ILCILD.org/
  – SiD https://www.silicondetector.org/display/SiD/home
  – CLICpd http://lcd.web.cern.ch/lcd/

• LoI / CDR
  – ILD LoI arXiv:1006.3396
  – SiD LoI arXiv:0911.0006
  – CLIC CDR: https://edms.cern.ch/document/1180032

• Others
  – LCD Notes
Common Simulation Framework

ILD framework

Common features:
• Geant4-based full simulation
• Realistic detector geometry (incl. gaps, electronics, etc.)
• Common persistency (LCIO) compatible data format
• Common generator samples of SM bkg. and signals

• Mokka MC simulator (g4-based)
• Marlin C++-based reconstruction framework
  • Digitization
  • Tracking, PFA, flavor tagging

SiD framework

• slic MC simulator (g4-based)
• org.lcsim Java-based reconstruction framework
  • Digitization, Tracking, PFA
  • Flavor tagging in Marlin

CLIC application
• Use adapted geometry: CLIC_ILD & CLIC_SID
• Overlaying $\gamma\gamma$ to hadron background (severe in multi-TeV env.)