LHC / ILC analysis for SUSY scenarios with heavy sfermions

Gudrid Moortgat-Pick

(K Desch, J Kalinowski, GMP, K Rolbiecki, WJ Stirling, JHEP 0612:007, 2006)

Outline

- Short introduction and expectations
- Case study: chosen scenario with heavy sfermions
- Numerical results: expectations for LHC
- Numerical results: ILC strategy and LHC/ILC interplay
- Conclusions and next steps
Short introduction and expectations

In which range do we expect SUSY?

- at least some light particles should be accessible at 500 GeV

- best possible tools needed to get maximal information out of only the part of the spectrum

To reveal the structure of the underlying physics, it is important to determine the parameters in a model-independent way and test all model assumptions experimentally

Soon we will have LHC data, but LHC/ILC interplay will be essential and both machines cover a large range of the parameter space!
Expectations, cont.

Expectations at the LHC:

- **Coloured SUSY partners:** discovery reach $m_{\tilde{q}, \tilde{g}} < 2-2.5$ TeV

- **Non-coloured partners:**
  a) via Drell-Yan $m_{\tilde{\chi}} < 250$ GeV
  b) via cascade decay chains

- **Parameter determinations:** in specific SUSY breaking models

At the ILC:

- direct production of all kind of SUSY particles up to kinematical limit $\sqrt{s}/2$

- indirect mass bounds due to high precision

- precise model-independent parameter determination

Particularly promising field for LHC/ILC interplay studies!
Tricky case with heavy sfermions

Feature of, for instance, focuspoint - inspired scenarios

- features: very heavy squarks, sleptons, heavy H, A but light SM-like h and light gluino and light charginos / neutralinos

- challenging for the LHC......but is the ILC then the right machine?

- some analysis done at LHC, but within mSUGRA and still difficult

Our approach: take a focuspoint-inspired scenario, but do not impose any assumption on the SUSY breaking mechanism and apply LHC / ILC analysis

How well is it possible to

- determine the underlying fundamental parameters?

- predict masses of heavier states?
Chosen scenario

MSSM parameters:

\[ M_1 = 60 \text{ GeV}, \ M_2 = 121 \text{ GeV}, \ M_3 = 322 \text{ GeV}, \ \mu = 540 \text{ GeV}, \ \tan \beta = 20 \]

Resulting masses:

<table>
<thead>
<tr>
<th>( m_{\tilde{\chi}_1^\pm} )</th>
<th>( m_{\tilde{\chi}_2^\pm} )</th>
<th>( m_{\tilde{\chi}_1^0} )</th>
<th>( m_{\tilde{\chi}_2^0} )</th>
<th>( m_{\tilde{\chi}_3^0} )</th>
<th>( m_{\tilde{\chi}_4^0} )</th>
<th>( m_{\tilde{g}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>117</td>
<td>552</td>
<td>59</td>
<td>117</td>
<td>545</td>
<td>550</td>
<td>416</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>( m_h )</th>
<th>( m_{H,A} )</th>
<th>( m_{H^\pm} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>119</td>
<td>1934</td>
<td>1935</td>
</tr>
</tbody>
</table>

- light gauginos/higgsinos, light gluino, light h but heavy H's, A

<table>
<thead>
<tr>
<th>( m_{\tilde{\nu}} )</th>
<th>( m_{\tilde{e}_R} )</th>
<th>( m_{\tilde{e}_L} )</th>
<th>( m_{\tilde{\tau}_1} )</th>
<th>( m_{\tilde{\tau}_2} )</th>
<th>( m_{\tilde{q}_R} )</th>
<th>( m_{\tilde{q}_L} )</th>
<th>( m_{\tilde{\ell}_1} )</th>
<th>( m_{\tilde{\ell}_2} )</th>
</tr>
</thead>
</table>

- heavy squarks and sleptons in the multi-TeV range
What is expected that LHC could do?

In principle: all squarks should be kinematically accessible

- stops: \( BR(\tilde{t}_{1,2} \rightarrow \tilde{g} t) \sim 66\% \)

  background t large, no new interesting channels open in decays

- other quarks: decay mainly via gluino and q, but reconstruction of heavy squarks at 2 TeV difficult

- assume: mass resolution of squarks with uncertainty of \(~50\) GeV

Light gluino: perfect for LHC (high rates, several decays)

<table>
<thead>
<tr>
<th>Mode</th>
<th>BR</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tilde{g} \rightarrow \tilde{\chi}_2^0 b \bar{b} )</td>
<td>14.4%</td>
</tr>
<tr>
<td>( \tilde{g} \rightarrow \tilde{\chi}^-_1 q u \bar{d} )</td>
<td>10.8%</td>
</tr>
<tr>
<td>( \tilde{\chi}_1^+ \rightarrow \tilde{\chi}_1^0 q u \bar{d} )</td>
<td>33.5%</td>
</tr>
<tr>
<td>( \tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \ell^+ \ell^- )</td>
<td>3.0%</td>
</tr>
<tr>
<td>( \tilde{t}_{1,2} \rightarrow \tilde{g} t )</td>
<td>66%</td>
</tr>
<tr>
<td>( \tilde{\chi}_1^- \rightarrow \tilde{\chi}<em>1^0 \ell^- \bar{\nu}</em>\ell )</td>
<td>11.0%</td>
</tr>
</tbody>
</table>

- clear dilepton edge from neutralino decay \( \delta(m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^-}) \sim 0.5 \) GeV

- decay via chargino less promising (escaping \( \nu \), 3-body decay)
**What is expected at the ILC (500)?**

Kinematically only two light neutralinos and light chargino accessible

- in reality: light neutralino production below 1 fb .......

<table>
<thead>
<tr>
<th>( \sigma(\tilde{\chi}_i \tilde{\chi}_j)/\text{fb} )</th>
<th>( \sqrt{s} = 350 \text{ GeV} )</th>
<th>( \sqrt{s} = 500 \text{ GeV} )</th>
<th>( \sqrt{s} = 800 \text{ GeV} )</th>
<th>( \sqrt{s} = 1300 \text{ GeV} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tilde{\chi}_1 \tilde{\chi}_2 )</td>
<td>0.58</td>
<td>0.08</td>
<td><strong>0.93</strong></td>
<td>0.07</td>
</tr>
<tr>
<td>( \tilde{\chi}_1 \tilde{\chi}_3 )</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( \tilde{\chi}_1 \tilde{\chi}_4 )</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( \tilde{\chi}_2 \tilde{\chi}_3 )</td>
<td>0.06</td>
<td>0.05</td>
<td><strong>0.49</strong></td>
<td>0.05</td>
</tr>
<tr>
<td>( \tilde{\chi}_2 \tilde{\chi}_4 )</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( \tilde{\chi}_3 \tilde{\chi}_3 )</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( \tilde{\chi}_3 \tilde{\chi}_4 )</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( \tilde{\chi}_4 \tilde{\chi}_4 )</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( \tilde{\chi}_1^+ \tilde{\chi}_2^- )</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( \tilde{\chi}_2^+ \tilde{\chi}_2^- )</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

- light pure \( \tilde{\chi}_1^0 \sim \tilde{B} \), \( \tilde{\chi}_2^0 \sim \tilde{W} \): production suppressed by heavy \( \tilde{\epsilon}_L, \tilde{\epsilon}_R \) exchange
- heavier \( \tilde{\chi}_3^0, \tilde{\chi}_4^0 \sim \tilde{H} \) with specific CP-phases: rather high rates!
- heavy pair \( \tilde{\chi}_2^+ \tilde{\chi}_2^- \sim \tilde{H} \): also high rates!
**Promising channel: light chargino**

So forget light neutralino production at ILC(500) for today ...

Use only (light) chargino production, provides high rates

- subsequent decays: \( \tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 e^- \bar{\nu}_e, \tilde{\chi}_1^0 \mu^- \bar{\nu}_\mu, \tilde{\chi}_1^0 d \bar{u}, \tilde{\chi}_1^0 s \bar{c} \)

Due to very limited information, use two energies and polarized beams!

<table>
<thead>
<tr>
<th>( \sqrt{s}/\text{GeV} )</th>
<th>( (P_{e^-}, P_{e^+}) )</th>
<th>( \sigma(\tilde{\chi}_1^+ \tilde{\chi}_1^-)/\text{fb} )</th>
<th>( \sigma(\tilde{\chi}<em>1^+ \tilde{\chi}<em>1^-) B</em>{slc} e</em>{slc}/\text{fb} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>350</td>
<td>(−90%, +60%)</td>
<td>6195.5</td>
<td>1062.5±4.0</td>
</tr>
<tr>
<td></td>
<td>(+90%, −60%)</td>
<td>85.0</td>
<td>14.6±0.7</td>
</tr>
<tr>
<td>500</td>
<td>(−90%, +60%)</td>
<td>3041.5</td>
<td>521.6±2.3</td>
</tr>
<tr>
<td></td>
<td>(+90%, −60%)</td>
<td>40.3</td>
<td>6.9±0.4</td>
</tr>
</tbody>
</table>

uncertainties: efficiency 50%, 1\( \sigma \) stat. uncertainties, \( \Delta P / P = 0.5\% \)

- to separate background WW: use semileptonic chargino decay channel, since mass constraints applicable
Mass measurements at LHC+ILC

Expected chargino mass resolution:

- in the continuum: up to 0.5 GeV
- threshold scan:

\[ m_{\tilde{\chi}_1^\pm} = 117.1 \pm 0.1 \text{ GeV} \]

Neutralino mass resolution:

- use either energy \( \tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 \ell^- \bar{\nu}_\ell \) or invariant mass distribution

\[ m_{\tilde{\chi}_1^0} = 59.2 \pm 0.2 \text{ GeV} \]

- together with LHC mass information \( \delta(m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}) \sim 0.5 \text{ GeV} \): 

\[ m_{\tilde{\chi}_2^0} = 117.1 \pm 0.5 \text{ GeV} \]
Determine fundamental parameters

On which parameters depend the process?

- Parameters in the gaugino/higgsino: $M_1, M_2, \mu, \tan \beta$

- But heavy virtual particles: $m_{\tilde{\nu}}, m_{\tilde{l}}, m_{\tilde{q}L}, m_{\tilde{q}R}$
Strategy, 1st step

Use measured masses and polarized cross sections

Analytical conversion and derive / fit parameters

→ do $\chi^2$ test for $M_1$, $M_2$, $\mu$ and $m_\tilde{\nu}$

→ BR not sensitive to heavy slepton masses

→ was necessary to fix $\tan\beta$ (took several values) to get convergence of fit! (strong correlations among parameters)

Results:

→ contradiction to theory for $\tan\beta < 1.7$

→ $450 \leq \mu \leq 750$ GeV, $1800 \leq m_\tilde{\nu}_e \leq 2210$ GeV

$59.4 \leq M_1 \leq 62.2$ GeV, $118.7 \leq M_2 \leq 127.5$ GeV,

$M_1$, $M_2$ good (~5%), but $\mu$ and $m_\tilde{\nu}$ rather weak (~16%) (limited info)
Strategy, 1st step

Masses and cross sections are not enough to constrain five parameter space due to strong correlations.

Allowed ranges migrate with change of $\tan \beta$.

Need another observable to get better constraints.
Strategy, 2\textsuperscript{nd} step -- spin correlations

Which further observable could be used?

- Forward-backward asymmetry of the final lepton / quark

( angle between incoming beam and final lepton or quark )

Dependent on spin correlations of decaying chargino:

- amplitude squared:

\[ e^- + e^+ \rightarrow \tilde{\chi}_1^+ + \tilde{\chi}_1^- \quad \text{and} \quad \tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 + \ell^- + \nu \]

\[ |T|^2 = |\Delta_f_1|^2 |\Delta_f_2|^2 \sum_{\text{fin.sp.}} (P^{\lambda_f_1} P^{\lambda_f_2} P^{\lambda_f_1'} P^{\lambda_f_2'}) \times (Z^{\lambda_f_1} Z^{\lambda_f_2}) \times (Z^{\lambda_f_1} Z^{\lambda_f_2'}) \]

\[ |T|^2 \sim PD_i D_j + \sum_a^P \sum_a^D D_j + \sum_b^P \sum_b^D D_i + \sum_{ab}^P \sum_a^D \sum_b^D \]

- cross section \( A_{fb}(l^-) \)
- \( A_{fb}(l^+) \)
- \( A_{fb}(l^+l^-) \)

'new contributions'
How important are spin correlations?

Impact of the 'new contributions' on $A_{fb}$:

- strong influence of spin correlations: $A_{fb}$ within [5%, 20%]
- and also sensitivity to heavy sneutrino mass!
**Strategy, 2nd step -- leptonic $A_{fb}$**

- use measured masses, cross sections and leptonic $A_{fb}$

- since decay also depends on unknown left slepton mass, use SU(2) relation:

\[
m_{\tilde{e}_L}^2 = m_{\tilde{\nu}_e}^2 + m_Z^2 \cos(2\beta)(-1 + \sin^2 \theta_W)
\]

- include also statistical and polarization uncertainty for $A_{fb}$:

<table>
<thead>
<tr>
<th>$\sqrt{s}$/GeV</th>
<th>$(P_e^-, P_e^+)$</th>
<th>$A_{FB}(\ell^-)/%$</th>
<th>$A_{FB}(\tilde{e})/%$</th>
</tr>
</thead>
<tbody>
<tr>
<td>350</td>
<td>$(-90%, +60%)$</td>
<td>4.42±0.29</td>
<td>4.18±0.74</td>
</tr>
<tr>
<td></td>
<td>$(+90%, -60%)$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>500</td>
<td>$(-90%, +60%)$</td>
<td>4.62±0.41</td>
<td>4.48±1.05</td>
</tr>
<tr>
<td></td>
<td>$(+90%, -60%)$</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

- use only (- +) values due to statistical uncertainty
Strategy, 2\textsuperscript{nd} step -- results

Results:

- do $\chi^2$ test:

$$\chi^2_{A_{FB}} = \chi^2 + \sum_i \left( \frac{A_{FB}(i) - A_{FB}(i)^{th}}{\Delta A_{FB}(i)} \right)^2$$

- not necessary to fix $\tan\beta$ any more !!!

- $59.7 \leq M_1 \leq 60.35$ GeV, $119.9 \leq M_2 \leq 122.0$ GeV,
- $500 \leq \mu \leq 610$ GeV, $14 \leq \tan \beta \leq 31$
- $1900 \leq m_{\tilde{\nu}_e} \leq 2100$ GeV

Improvements:

- constraints for multi-TeV sneutrino mass by factor 2, up to 5\% accuracy !
- accuracy of $M_1$, $M_2$ by factor 5
- accuracy of $\mu$ by factor 1.6 and $\tan \beta$ now included!
Strategy, 2\textsuperscript{nd} step -- mass predictions

Due to rather precise parameter determination:

- use these allowed parameters and predict, for instance, the possible ranges for the masses of the heavier chargino and neutralino states

\begin{align*}
506 & < m_{\tilde{\chi}_3^0} < 615 \text{ GeV} \\
512 & < m_{\tilde{\chi}_4^0} < 619 \text{ GeV} \\
514 & < m_{\tilde{\chi}_2^\pm} < 621 \text{ GeV}
\end{align*}

- Obviously 1.3 TeV as 2\textsuperscript{nd} ILC energy stage would be sufficient

Rather precise parameter determination important and possible at 500 GeV (even in such tricky scenarios with limited information only)

- might be important input for future upgrade strategies ...
Strategy, 3\textsuperscript{rd} step -- also hadronic $A_{fb}$

Redo analysis without assuming SU(2) relation between slepton masses

- squark masses constrained from LHC
- strategy as before: use masses, cross sections, leptonic $A_{fb}$

Include also $A_{fb}$ from hadronic distribution:

- charm identification needed: assume c-tag efficiency of 40% for selection efficiency of 50%

Results (without using SU(2) relation):

\begin{align*}
59.45 & \leq M_1 \leq 60.80 \text{ GeV}, \\
118.6 & \leq M_2 \leq 124.2 \text{ GeV}, \\
420 & \leq \mu \leq 770 \text{ GeV} \\
1900 & \leq m_{\tilde{\nu}_e} \leq 2120 \text{ GeV}, \\
m_{\tilde{e}_L} & \geq 1500 \text{ GeV}, \\
11 & \leq \tan \beta \leq 60.
\end{align*}

- again precise parameter determination and constraints for msn
- no upper bound for msel, but consistent with SU(2) relation!
Conclusions and next steps

Tricky scenario: only few particles accessible at LHC/ILC

Study done without assuming a SUSY breaking scheme!

Forward-backward asymmetries of the final leptons/quarks: sensitivity to heavy virtual particles

- get tight constraints even for masses in the multi-TeV range!

Rather accurate parameter determination possible with $A_{fb}$

- allows to predict masses of heavier charginos/neutralinos

Next steps: a) $\chi^0$-channels, b) $\chi^\pm$: $A_{fb}(l^+l^-), A_{fb}(jl)$

LHC / ILC(500): neither of these colliders alone can resolve such a challenging scenario with multi-TeV squarks and sleptons  --> both LHC and ILC required a.s.a.p. ... !
LHC / ILC interplay

If fundamental parameters determined: allows mass predictions for heavier particles

- significant increase of sensitivity for searches at the LHC and unique identification of particles in decay chain

- Powerful test of the model


<table>
<thead>
<tr>
<th></th>
<th>$M_1$</th>
<th>$M_2$</th>
<th>$\mu$</th>
<th>$\tan \beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
<td>99.1</td>
<td>192.7</td>
<td>352.4</td>
<td>10</td>
</tr>
<tr>
<td>LC\textsubscript{500}</td>
<td>$99.1 \pm 0.2$</td>
<td>$192.7 \pm 0.6$</td>
<td>$352.8 \pm 8.9$</td>
<td>$10.3 \pm 1.5$</td>
</tr>
<tr>
<td>LHC+LC\textsubscript{500}</td>
<td>$99.1 \pm 0.1$</td>
<td>$192.7 \pm 0.3$</td>
<td>$352.4 \pm 2.1$</td>
<td>$10.2 \pm 0.6$</td>
</tr>
</tbody>
</table>

- strong improvement in parameter determination via interplay!
**NMSSM versus MSSM**

SUSY scenario in the NMSSM: Higgs and light particle sector (neutralino / chargino) show no hints for model distinction measured at ILC (500 GeV): \[ m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_{1,2}^0}, \sigma(e^+e^- \rightarrow \tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^0\tilde{\chi}_2^0) \]

- Consistent within MSSM-analysis
- Predictions:

\[
\begin{align*}
  m_{\tilde{\chi}_3^0} &= [352, 555] \text{ GeV} \rightarrow \text{pure higgsino} \\
  m_{\tilde{\chi}_4^0} &= [386, 573] \text{ GeV} \rightarrow \text{larger gaugino comp.} \\
  m_{\tilde{\chi}_2^\pm} &= [450, 600] \text{ GeV}
\end{align*}
\]

\[ \Rightarrow \tilde{\chi}_3^0 \text{ not accessible at LHC} \]

**S Hesselbach, GMP, F Franke, H Fraas, 2005**

Model inconsistency determined via LHC/ILC