Prospects of chargino searches and measurements at the ILC

Teresa Núñez - DESY

On behalf of the ILD Concept Group

Chargino production at the ILC

M.T. Núñez Pardo de Vera¹, M. Berggren¹, J. List¹
¹ DESY

From light Higgsinos to test of unification

H. Baer¹, M. Berggren², K.Fujii³, J. List², S.-L. Lehtinen⁴,², T. Tanabe⁵, J. Yan³
¹ University of Oklahoma, ² DESY, ³ KEK, ⁴ University of Hamburg, ⁵ ICEPP


Photon-photon processes at the ILC and BSM signatures with small mass differences

Kollassery Swathi Sasikumar¹
¹ Hamburg University

DESY-THESIS-2021-002

SUSY 2021, 25-08-21
Introduction

- No evidence of SUSY in LHC data at 7, 8 and 13 GeV
- LHC SUSY exclusion/discovery limits are strongly model dependent
- Complementary nature of physics in e⁺e⁻ colliders offers interesting scenarios where SUSY can be discovered …
- … and highly model independent exclusion/discovery limits can be obtained

arXiv:2106.01676
Electroweak naturalness in simple SUSY models requires a cluster of four light Higgsinos:

\( \tilde{\chi}_1^\pm, \tilde{\chi}_1^0, \tilde{\chi}_2^0 \) compressed spectrum (10-20 GeV) around ~ 100-300 GeV

Challenging for LHC if other sparticles are heavy… but not for ILC:

- Electron-Positron collider at \( \sqrt{s} = 250\text{–}500 \text{ GeV} \) with energy upgradability (1 TeV)
- Electrons (80%) and positrons (30%) polarisations
- Well defined initial state: 4-Momentum and spin configuration
- Clean and reconstructable final state
- Hermetic detectors (almost 4\( \pi \) coverage)
- Triggerless operation

Searches for Higgsinos or Winos (charginos) at small mass differences and evaluation of precision of model parameter measurements
Chargino searches

- Compute lighter chargino pair production cross sections in a wide SUSY parameter space (only using MSSM as model and R-parity conservation)
- Determine case with lowest production cross sections
- Compare to cross section detection limits extrapolated from LEP results (in the worst scenario)

Cross section studies divided depending on:
  - chargino mixing: Higgsino-like, Wino-like and Mixed charginos
  - sneutrino mass scale: high (~1TeV), low (around kinematic limit)
Worst scenario for Wino and Higgsino-like charginos

Lower efficiencies reached in Wino-like case with sfermions masses close to kinematic limit

P(e-,e+)=(-80%,+30%)
Chargino searches: cross sections

Worst scenario for Wino and Higgsino-like charginos

Cross sections compared to limits from LEP extrapolated to 1.6 ab$^{-1}$ integrated luminosity (ILC500, $P(e^{-},e^{+})=(-80\%,+30\%)$), based on the dependency $\sigma_{\text{LIM}} \sim \frac{1}{\sqrt{L}}$, to obtain mass limits for chargino exclusion/discovery

Lower efficiencies reached in Wino-like case with sfermions masses close to kinematic limit
Chargino searches: mass exclusion limits

Higgsino

Wino

\[ \Delta M \text{ (GeV)} \]

\[ M_{\tilde{\chi}_1^+} \text{ (GeV)} \]

ATLAS-disappearing track
(PHYS-PUB-2017-019)

ILC500

ATLAS-model dependent
(CONF-2019-014)

Higgsino - MSSM

ATLAS-disappearing track
(arXiv:1712.02118)

Wino - MSSM

sfermion masses E_CMS/2
Higgsino

Wino

With high sfermion masses ...

... for $\Delta M > 3$ GeV exclusion and discovery reach a few 100 MeV apart from each other.

... for $m_{\pi} < \Delta M < 3$ GeV exclusion and discovery reach at most 5 GeV apart from each other.

... for $\Delta M < m_{\pi}$ exclusion and discovery are a few MeV apart from each other.
Even in the particular case with sfermion masses close to the kinematic limit …

… for $\Delta M > 3$ GeV exclusion is guaranteed up to $M_{\tilde{\chi}^\pm_1} = 246$ GeV and discovery up to 243 GeV

… for $m_{\pi} < \Delta M < 3$ GeV exclusion is guaranteed up to $M_{\tilde{\chi}^\pm_1} = 225$ GeV and discovery up to 205 GeV

… for $\Delta M < m_{\pi}$ exclusion and discovery are guaranteed up to few MeV from the kinematic limit
Chargino searches: Conclusions

**Improvements at the ILC**

- **Polarisation** (increases signal/background ratio)
- **No trigger** (increases detection efficiency and allows ‘redundant’ analysis) but …
  ISR needed for gamma-gamma background suppression
- **Smaller beam size** (increases detection efficiency by releasing ISR requests -> observation of decay length for soft events)

**General comments**

- **Loop corrections** are not included (**chargino pair production** cross sections can change up to 20%)
- Low sfermions masses not taken into account in LEP analysis, they would imply:
  - changes in chargino branching ratios and decay topology
  - sfermion production and possible discovery
  The drop in cross section due to sfermions masses depends on the beam energy, can be shifted.
- **ISR request close to kinematic limits could cause unknown effects**
From Light Higgsinos to test of unification

Examine the capability of the ILC to make precision measurements of superparticle properties offering the possibility to make important predictions of SUSY breaking and fundamental particle physics and providing insights into the nature of dark matter and cosmology.

Three benchmark scenarios

ILC1 & ILC2:
- Natural models from NUHM2
- Gaugino mass unification at GUT scale

nGMM1:
- Natural generalized mirage mediation model
- Gaugino mass unification at mirage scale

Two channels

Light Higgsino masses ~150 GeV and mass differences 4-20 GeV
Direct measurement of masses and cross sections

Extracted from kinematic distributions in both channels under study

Chargino channel

Neutralino channel
Direct measurement of masses and cross sections

Extracted from kinematic distributions in both channels under study

Chargino and neutralino masses measured to less than 1% precision

σ x BR up to a few % precision, depending on channel and beam polarisation
Fitting fundamental parameters and testing gaugino mass unification

Extraction of both GUT-scale and weak-scale parameters with two different approaches (4 and 10 free parameters), extrapolation of these to the GUT-scale

Input parameters:
- Four Higgsino masses
- Four polarised total cross sections from chargino and neutralino
- Higgs observables with ILC precision:
  > Mass of the lightest CP-even Higgs boson
  > Higgs decay branching ratios
Fitting fundamental parameters: GUT scale

Strongly dependent on underlying SUSY breaking scheme

None of the benchmarks can be excluded as NUMH2 model

Not underlying models (NUHM1, CMSSM): interpretations ruled out at 95% CL with only 0.1% total integrated luminosity
Fitting fundamental parameters: Weak scale

Check if it possible to constrain a comprehensive set of parameters from observables of Higgsino sector alone

Parameters entering Higgsino sector in tree and loop level

Clear electroweakinos and heavy Higgs bosons mass predictions

Changes in parameters entering at loop level the Higgsino sector do not affect heavier Higgsino predictions

Rest of sfermions masses less constrained but upper limits can be obtained

Provides important information for a future hadron colliders
Fitting fundamental parameters: Weak scale

Only tree level Higgsino sector parameters

Heavier electroweakinos mass precisions improved up to 1.6% - 3%

Changes in fixed parameters keeps predictions within 1σ uncertainties
Testing gaugino mass unification

MSSM RGEs used to evolve fitted parameters to higher energy scales and check unification hypothesis

- Test gaugino mass unification in different models
- Study impact of experimental improvements

- pMSSM-10 weak scale parameters extracted at Q=10GeV
- Scan around extracted values using corresponding PDF within +/- 1σ
- Calculate running parameters at different energy scales
Testing gaugino mass unification: ILC1

Assuming NUHM2 model, prediction of physical gluino mass can be obtained: $m_g = 1467 \pm 80 \text{ GeV}$

$Q_{\text{unif}}$ and $M_{1/2}$ in agreement with GUT scale model fit (same for ILC2)
Testing gaugino mass unification: nGMM1

Differences with ILC1 & ILC2:
• Underlying model unifies at intermediate scale
• $M_1$ and $M_2$ determination at weak scale much less accurate

Even in pessimistic scenario gaugino mass unification at GUT scale can be rejected

Improving precision and using hypothetical gluino mass shows unification at intermediate scale
Effect of $\gamma \gamma \rightarrow$ low $p_T$ hadron overlay on Higgsino analysis

- e+e- beams are accompanied by real and virtual photons
- At = 500 GeV 1.05 low $p_T$ hadron events/Bunch crossing expected

- A new developed track grouping algorithm facilitates an effective separation of signal and overlay tracks (based on impact parameter)

- Event selection criteria were adapted

- Key observables like the chargino mass and polarized cross section can be measured with few percent uncertainty

- Even with statistical uncertainties worsening due to presence of overlay to about ~3%, the obtained results are highly precise
Conclusions

• We show the ILC discovering reach for SUSY in the chargino channel within the worst scenario and in very conservative conditions. Mass limits up to few GeV below the kinematic limit have been found.

• The capability of the ILC for measuring SUSY observables with precision enough to make relevant SUSY related predictions has been studied and confirmed.

• Improvement on the experimental results are clearly reflected on the predictions.

• The predictions extracted from direct SUSY measurements can have an important role in future accelerator designs and upgrades.

• The interplay between ILC and LHC/HL-LHC SUSY measurements can improve considerably the results of both analysis.

• Light Higgsinos can be measured at the ILC even in the presence of $\gamma\gamma \rightarrow \text{low } p_T \text{ hadron overlay}$.
Backup slides
Chargino searches: cross sections

\( \sqrt{s} = 500 \text{ GeV}, \text{ ISR photon} \)

ILC experimental conditions

Lower cross sections for Higgsino-like case

\[ \text{P}(e^-, e^+) = (-80\%, +30\%) \]

With \( \mathcal{L} = 1.6 \text{ ab}^{-1} \) will be used for the study
Chargino searches: cross sections

**Low sfermion masses**

- Affects Wino case via destructive interference of t-channel
- No effect on Higgsino due to weakly coupling to sneutrino

\[
P(e^-, e^+) = (-80\%, +30\%)
\]

* Limit selectron mass \( < M_{\tilde{\chi}_1^±} \)
Chargino searches: extrapolated data

Combined LEP chargino studies

- Data taken at up to ~208 GeV center-of-mass energy, accumulated luminosity ~800 pb⁻¹
- No signal found, limits derived at 95%CL in the context of MSSM (R parity conservation) focused in the region with small $\Delta M = M_{\tilde{\chi}_1^\pm} - M_{\text{LSP}}$
- Two cases considered:
  - Higgsino-like
  - Wino-like (high sfermion masses)
- Three topologies for the analysis of chargino decays:
  - prompt decays into leptons, leptons + jets, jets via $W^*$ ($\Delta M > 3\text{GeV}$)
  - soft decays with a ISR requested on trigger ($\pi$ mass < $\Delta M < 3\text{GeV}$)
  - events with tracks displaying kinks, impact parameters offset or heavy stable charged particles ($\Delta M < \pi$ mass)
Chargino searches: extrapolated data

**Combined LEP chargino studies**

- Data taken at up to ~208 GeV center-of-mass energy, accumulated luminosity ~800 pb\(^{-1}\)
- No signal found, limits derived at 95%CL in the context of MSSM (R parity conservation) focused in the region with small \(\Delta M = M_{\tilde{\chi}^\pm_1} - M_{\text{LSP}}\)
- Two cases considered:
  - Higgsino-like
  - Wino-like (high sfermion masses)
- Three topologies for the analysis of chargino decays:
  - prompt decays into leptons, leptons + jets, jets via \(W^*\) (\(\Delta M > 3\text{GeV}\))
  - soft decays with a ISR requested on trigger (\(\pi\) mass < \(\Delta M < 3\text{GeV}\))
  - events with tracks displaying kinks, impact parameters offset or heavy stable charged particles (\(\Delta M < \pi\) mass)

Cross sections compared to limits from LEP extrapolated to 1.6 fb\(^{-1}\) integrated luminosity (ILC500, \(P(e^-, e^+) = (-80\%, +30\%)\)) based on the dependency \(\sigma_{\text{LIM}} \sim \frac{1}{\sqrt{L}}\)
Chargino searches:

Comparison to extrapolated limits

Low efficiency in \( \pi \) mass \(<\) DM \(<\) 3 GeV region due to ISR trigger requirement
Chargino searches:

Comparison to extrapolated limits

Cross section limits extracted and extrapolated to 1.6 fb$^{-1}$ integrated luminosity (ILC500, $P(e-, e^+)$=(-80%,+30%)) based on the dependency $\sigma_{\text{lim}} \sim \frac{1}{\sqrt{L}}$
**Benchmark scenarios**

**ILC1 & ILC2:**
- Natural models from NUHM2
- Gaugino mass unification at GUT scale

**nGMM1:**
- Natural generalized mirage mediation model
- Gaugino mass unification at mirage scale (between EW and GUT scales)

<table>
<thead>
<tr>
<th>Masses (GeV)</th>
<th>ILC1</th>
<th>ILC2</th>
<th>nGMM1</th>
</tr>
</thead>
<tbody>
<tr>
<td>neu1</td>
<td>103</td>
<td>148</td>
<td>151</td>
</tr>
<tr>
<td>Chi1+-</td>
<td>117</td>
<td>157.8</td>
<td>159</td>
</tr>
<tr>
<td>Neu2</td>
<td>124</td>
<td>158.3</td>
<td>156</td>
</tr>
<tr>
<td>Neu3</td>
<td>267</td>
<td>539</td>
<td>1530</td>
</tr>
<tr>
<td>Gluino</td>
<td>1560</td>
<td>2830</td>
<td>2860</td>
</tr>
</tbody>
</table>

Cross sections at $\sqrt{s} = 500$ GeV several hundreds fb
Software tools and observables

- Whizard1.95 for event generation
- ILD-specific software based on Geant4 for simulation and reconstruction
- Beam spectrum, ISR and γγ “pile-up” included
- $\sqrt{s} = 500$ GeV and $\mathcal{L} = 500$ fb$^{-1}$ simulation results scaled to operation scenarios

Processes studied:

$$e^+ e^- \rightarrow \tilde{\chi}^+_1 \tilde{\chi}^-_1 \rightarrow \tilde{\chi}^0_1 q \bar{q} \tilde{\chi}^0_1 e \nu_e (\mu \nu_\mu)$$
$$e^+ e^- \rightarrow \tilde{\chi}^0_1 \tilde{\chi}^0_2 \rightarrow \tilde{\chi}^0_1 \tilde{\chi}^0_1 e^+ e^- (\mu^+ \mu^-)$$

Observables:

- three masses ($\tilde{\chi}^{\pm}_1$, $\tilde{\chi}^0_1$, $\tilde{\chi}^0_2$)
- four cross sections

Masses from kinematical distributions (maximum invariant mass -> mass splittings, maximum dilepton/dijet energy -> absolute masses)

Cross sections from counting events after fitting overall shape

Chargino and neutralino channels studied independently
Higgs branching rations
Fitting fundamental parameters: GUT scale

Strongly dependent on underlying SUSY breaking scheme

Fit to NUMH2 model

<table>
<thead>
<tr>
<th></th>
<th>ILC1 best fit (true)</th>
<th>ILC2 best fit (true)</th>
<th>nGMM1 best fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{1/2}$</td>
<td>556.7 (568.3)</td>
<td>1194 (1200)</td>
<td>2407</td>
</tr>
<tr>
<td>$\mu$</td>
<td>105.3 (115.0)</td>
<td>150.7 (150.0)</td>
<td>155.6</td>
</tr>
<tr>
<td>$\tan\beta$</td>
<td>11.4 (10.0)</td>
<td>16.0 (15.0)</td>
<td>10.0</td>
</tr>
<tr>
<td>$m_A$</td>
<td>968 (1000)</td>
<td>1008 (1000)</td>
<td>1603</td>
</tr>
<tr>
<td>$M_0$</td>
<td>7685 (7025)</td>
<td>4788 (5000)</td>
<td>3422</td>
</tr>
<tr>
<td>$A_0$</td>
<td>-11064 (-10427)</td>
<td>-7663 (-8000)</td>
<td>-7409</td>
</tr>
<tr>
<td>$\chi^2$</td>
<td>0.0011 (0.0013)</td>
<td>0.02848 (0.0007)</td>
<td>0.233</td>
</tr>
</tbody>
</table>
Fitting fundamental parameters: predicting SUSY spectrum

Clear electroweakinos and heavy Higgs bosons mass predictions (ILC1 & ILC2)

- Gluino mass firmly predicted (GUT check)

- Rest of sfermions masses less constrained but upper limits can be obtained

Provides important information for a future hadron colliders
Fitting fundamental parameters: predicting SUSY spectrum

Provides important information for a future hadron colliders

Clear electroweakinos and heavy Higgs bosons mass predictions

Gluino mass firmly predicted (GUT check)

Rest of sfermions masses less constrained but upper limits can be obtained
Fitting fundamental parameters: Weak scale

- Check if it possible to constrain a comprehensive set of parameters from observables of Higgsino sector alone
- Study influence of parameters in which Higgsino sector enters at loop level
- Investigate precision achievable when fitting only tree level Higgsino parameters

Two models used: pMSSM-10, pMSSM-4

Fit parameters Higgsino sector
Fitting fundamental parameters: Weak scale

Weak-scale parameters

- Check if it possible to constrain a comprehensive set of parameters from observables of Higgsino sector alone
- Study influence of parameters in which Higgsino sector enters at loop level
- Investigate precision achievable when fitting only tree level Higgsino parameters

Two models used: pMSSM-10, pMSSM-4

Fit parameters Higgsino sector

ILC2 shows same behaviour
Fitting fundamental parameters: Weak scale

Weak-scale parameters

- Check if it possible to constrain a comprehensive set of parameters from observables of Higgsino sector alone
- Study influence of parameters in which Higgsino sector enters at loop level
- Investigate precision achievable when fitting only tree level Higgsino parameters

Two models used: pMSSM-10, pMSSM-4

Fit parameters Higgsino sector

nGMM1 constrains less M1 and M2 due to worse experimental resolution and larger M1 and M2 absolute values
Fitting fundamental parameters: Weak scale

Improvement fit parameters by using mass differences

\[ \Delta \chi^2 \]

\[ M_2 \text{ [GeV]} \]

\[ nGMM1 \]

pMSSM-10 nGMM1

Hypothetical gluino mass from LHC (11% precision)
Fitting fundamental parameters: Weak scale

Constraints for parameters of colored sector can be obtained

Hypothetical gluino mass measurement from LHC with 11% precision improves M3 precision accordingly, not significant effect on the rest.
Fitting fundamental parameters: Weak scale

**pMSSM-10 ILC2**

- ILC2 predictions overestimate sfermions masses but still within 1σ

**pMSSM-10 nGMM1**

- Improvement by using mass differences

**Fit with absolute masses**

- pMSSM-4 fit predicts heavier electroweakino masses within an 1σ uncertainty (~150 GeV) with not improved fit

- M3 only constrained via its loop effects on Higgsino sector, since gluino probably outside LHC reach
Dark Matter in Higgsino fits

Fits to MSSM parameters allows extraction of WIMP Dark Matter related observables

Thermally produced WIMP relic density
Dark Matter in Higgsino fits

Fits to MSSM parameters allows extraction of WIMP Dark Matter related observables

Thermally produced WIMP relic density

Agreement model with fit values

Such measurement would confirm possible underabundance of Higgsino-like WIMPs
Dark Matter in Higgsino fits

Fits to MSSM parameters allows extraction of WIMP Dark Matter related observables

Thermally produced WIMP relic density

Other dark matter observables fitted within 1%-10% precision

Interplay of ILC results with indirect WIMP detection rates could offer confirmation of multicomponent dark matter
Testing gaugino mass unification: ILC1
Testing gaugino mass unification: ILC2

Assuming NUHM2 model and that $M_3$ unifies, prediction of physical gluino mass can be obtained: $m_g = 2872 \pm 605$ GeV

Possible to verify that $M_1$ and $M_2$ unify at GUT scale
Testing gaugino mass unification: ILC2

Assuming NUHM2 model and that M3 unifies, prediction of physical gluino mass can be obtained: \( m_g = 2872 \pm 605 \) GeV

Possible to verify that \( M_1 \) and \( M_2 \) unify at GUT scale
Testing gaugino mass unification: nGMM1

IlC I20 scenario, pessimistic

M\(_1\) [GeV]

M\(_2\)

M\(_3\)

Q [GeV]

pMSSM-10 fit to nGMM1

IlC I20 scenario, full sim

\(\tilde{g}\) from HL-LHC

M\(_1\)

M\(_2\)

M\(_3\)

Q [GeV]

pMSSM-4 + M\(_3\) fit to nGMM1

M\(_{1/2}\) [GeV]

0.01

0.02

0.03

0.04

\(\log_{10}(Q [\text{GeV}])\)

\(10^{-4}\)

\(10^{-3}\)

\(10^{-2}\)

\(10^{-1}\)

\(10^{0}\)

\(10^{1}\)

\(10^{2}\)

\(10^{3}\)

\(10^{4}\)

\(10^{5}\)

\(10^{6}\)

\(10^{7}\)

\(10^{8}\)

\(10^{9}\)

\(10^{10}\)

\(10^{11}\)

\(10^{12}\)

\(10^{13}\)

\(10^{14}\)

\(10^{15}\)

\(10^{16}\)

\(10^{17}\)

\(10^{18}\)
Effect of $\gamma\gamma \rightarrow$ low $p_T$ hadron overlay on Higgsino analysis

$M_{\tilde{\chi}_1^\pm}^{\text{fit}} = 164.9 \pm 2.7$ GeV

$M_{\tilde{\chi}_1^\pm}^{\text{fit}} = 160.3 \pm 3.8$ GeV