Measuring sleptons at the ILC

Joel Jones-Pérez
Pontificia Universidad Católica del Perú (PUCP)

Based on the following work:
N. Cerna, T. Faber, JJP, W. Porod (1705.06583)
N. Cerna, JJP, J. Masias, W. Porod (2102.06236)
Natural SUSY

- Searches for vanilla SUSY (for example, the CMSSM) have placed stringent bounds on SUSY masses.

- But SUSY cannot be too heavy! Little hierarchy problem!

- Motivates searching for situations where SUSY can hide. Examples of these are compressed spectra and RPV.
Low-Scale Seesaw

- The Type-I Seesaw is probably the most popular way of generating neutrino masses.

\[ \mathcal{L} = \mathcal{L}_{\text{SM}} - Y_\nu \left( \bar{L} \cdot \tilde{H} \nu_R \right) - \frac{1}{2} M_R \left( \bar{\nu}_R \nu_R^c \right) \]

\[ m_\nu \sim \frac{\nu^2}{2} Y_{\nu}^* \ M_R^{-1} \ Y_{\nu}^\dagger \]

- Searches for heavy neutrinos have been carried out at the LHC, but all compatible with background.
Low-Scale SUSY Seesaw

- What if we combine the MSSM and the Seesaw? Does that affect constraints on SUSY particles?

- For GUT-scale (s)neutrinos, LHC phenomenology is not too strongly affected.
Low-Scale SUSY Seesaw

- What if we combine the MSSM and the Seesaw? Does that affect constraints on SUSY particles?

- For GUT-scale (s)neutrinos, LHC phenomenology is not too strongly affected.

- What if we have a low-scale seesaw? We could have an R-sneutrino LSP!

- What if we want the model to be as natural as possible?
Our setup

• Set the R-sneutrino as the LSP.
• Keep $\mu$ as low as possible $\rightarrow$ Higgsino-like electroweakinos.
• Objective: Explore collider sensitivity to sleptons and / or electroweakinos (since R-sneutrinos couple exclusively to these sectors)
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Possible hierarchy:

$$m_{\tilde{\nu}_R}^2 < \mu < m_{\tilde{\nu}_L}^2, m_{\tilde{E}}^2$$

$$m_{\tilde{\nu}_R}^2 < m_{\tilde{\nu}_L}^2, m_{\tilde{E}}^2 < \mu$$
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\begin{align*}
    m_{\tilde{\nu}_R}^2 &< \mu < m_{\tilde{L}}^2, m_{\tilde{E}}^2 \\
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\end{align*}
\]

Strong constraints (2017, 13.3 fb\(^{-1}\)):

- $\mu \gtrsim 400$ GeV
- $m_{\tilde{L}} \gtrsim 600$ GeV
Our setup

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Possible hierarchy:

$$m^2_{\tilde{\nu}_R} < \mu < m^2_{\tilde{L}}, m^2_{\tilde{E}}$$

Strong constraints (2017, 13.3 fb$^{-1}$):

$$\mu \gtrsim 400 \text{ GeV}$$

$$m_{\tilde{L}} \gtrsim 600 \text{ GeV}$$
Neutrino Sector

• Keep heavy neutrino masses at the GeV scale
  ▶ R-sneutrino masses do not become too heavy
  ▶ Correlations between SUSY and heavy neutrino searches?

• Enhance Yukawas of two R-(s)neutrinos.
  ▶ Charged NLSP is not long-lived.
  ▶ Correlations between SUSY and heavy neutrino searches?

\[(Y_{\nu})_{ah} \sim \sqrt{\frac{2m_3 M_h}{v_u^2}} \cosh \gamma_{56}\]

• Set degenerate heavy neutrino masses, if enhanced \((M_5 = M_6 = 20\, \text{GeV})\)
  ▶ Suppresses contribution to neutrinoless double beta decay
  ▶ Keeps loop corrections to light neutrino masses under control
Sneutrino Sector

- Sneutrino mass matrix:

\[
M_{\tilde{\nu}}^2 = \begin{pmatrix}
    m_{\tilde{\nu}_L}^2 + \frac{1}{2} m_Z^2 \cos 2\beta & 0 \\
    0 & m_{\tilde{\nu}_R}^2 + M_R^\dagger M_R
\end{pmatrix}
\]

- LR mixing very small! Mass eigenstates will be almost pure \( \tilde{\nu}_L \) or \( \tilde{\nu}_R \)

- For simplicity, new sources of LNV are set to zero, and all parameters are assumed real. Soft masses are taken diagonal.
Slepton Sector

- Slepton hierarchy mainly from D-Terms:

\[ m_{\tilde{\nu}_R} < m_{\tilde{\tau}_1} \sim m_{\tilde{\nu}_L} < m_{\tilde{\ell}_L, \tilde{\ell}_R} < m_{\tilde{\tau}_2} \]
**Slepton Sector**

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  \[ m_{\tilde{\nu}_R} < m_{\tilde{\tau}_1} \sim m_{\tilde{\nu}_L} < m_{\tilde{\ell}_L, \tilde{\ell}_R} < m_{\tilde{\tau}_2} \]

- Decays into R - sneutrinos and on-shell bosons:
  \[ \tilde{\tau}_1^- \rightarrow \tilde{\nu}_R W^- \]
  \[ \tilde{\nu}_L \rightarrow \tilde{\nu}_R Z \]
  \[ \tilde{\nu}_L \rightarrow \tilde{\nu}_R h \]
**Slepton Sector**

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  \[ \tilde{\tau}_1^- \rightarrow \tilde{\nu}_R W^- \quad \tilde{\nu}_L \rightarrow \tilde{\nu}_R Z \]
  \[ \tilde{\nu}_L \rightarrow \tilde{\nu}_R h \]

- **Cascade decays (compressed):**

  \[ \tilde{\tau}_2^- \rightarrow \tilde{\tau}_1^- Z^* \]
  \[ \tilde{\tau}_2^- \rightarrow \tilde{\nu}_L W^{-*} \]
  \[ \tilde{\ell}_{L,R} \rightarrow \tilde{\nu}_L W^{-*} \]
Measuring sleptons at the ILC

Degenerate scenario at LHC:

Constrained mainly by multi-lepton searches

Projection at the end of LHC lifetime has a hard time extending the reach above 250 GeV.
Prospects at the ILC
Sleptons at a 1 TeV ILC

- The $e^+ e^-$ collisions would produce slepton pairs.
- Our analysis will be tailored for stau and L-snu production, leading to:

  $$\tilde{\tau}_1^- \rightarrow \tilde{\nu}_R W^- \quad \tilde{\nu}_L \rightarrow \tilde{\nu}_R Z \quad \tilde{\nu}_L \rightarrow \tilde{\nu}_R h$$

- The hadronic decays of the SM bosons lead to final states with **four jets and missing energy**.
- We consider Type B polarization $(e^-_R e^+_L)$
Measuring sleptons at the ILC

Sleptons at a 1 TeV ILC

Cutflow, 500 fb⁻¹ integrated luminosity, 300 GeV slepton mass

<table>
<thead>
<tr>
<th>Scenario</th>
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<tbody>
<tr>
<td>No cuts</td>
<td>14713</td>
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<td>$E_{\text{miss}} &gt; 50$ GeV</td>
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| Efficiency (%)                              | 5.2  |

SE: $m_{\tilde{E}_1} = m_{\tilde{L}_1}$
Sleptons at a 1 TeV ILC

Cutflow, 500 fb\(^{-1}\) integrated luminosity, 300 GeV slepton mass

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SE: \(m_{\tilde{E}_1} = m_{\tilde{L}_1}\)

ST: \(m_{\tilde{E}_3} = m_{\tilde{L}_3}\)
## Sleptons at a 1 TeV ILC

Cutflow, 500 fb$^{-1}$ integrated luminosity, 300 GeV slepton mass

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Efficiency (%) | SE: 5.2 | ST: 6.3

All background: 417 events

Efficiency: 0.08%

Main sources: $t \bar{t}$, $Z W^+ W^-$, $2\nu W^+ W^-$

SE: $m_{\tilde{E}_1} = m_{\tilde{L}_1}$

ST: $m_{\tilde{E}_3} = m_{\tilde{L}_3}$
Measuring sleptons at the ILC

Required luminosity ($fb^{-1}$) at ILC to get $5\sigma$
Slepton Mass Reconstruction: Endpoint Method

Reconstruct $W$ boson and measure its energy.
Min / max values of $W$ boson energy: \textbf{endpoints}, $E_{B-}$, $E_{B+}$
Slepton Mass Reconstruction: Endpoint Method

\[ m_{\tilde{\ell}} = \frac{2E_{\text{beam}}}{E_{B^+} + E_{B^-}} E'_B \]

Boson energy in slepton rest frame
Measuring sleptons at the ILC

Slepton Mass Reconstruction: Endpoint Method

\[ m_{\ell} = \frac{2E_{\text{beam}}}{E_{B+} + E_{B-}} E'_B \]

Boson energy in slepton rest frame

\[ E'_B = \frac{1}{\sqrt{2}} \sqrt{(E_{B+} + E_{B-} + m_B^2) \pm \sqrt{(E_{B+}^2 - m_B^2)(E_{B-}^2 - m_B^2)}} \]
Slepton Mass Reconstruction: Endpoint Method

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m_{\tilde{\ell}} = \frac{2E_{\text{beam}}}{E_{B^+} + E_{B^-}} E'_B
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\[ m_{\tilde{\ell}} = \frac{2E_{\text{beam}}}{E_{B+} + E_{B-}} E'_{B} \]

Boson energy in slepton rest frame

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Need two datasets, for example, decays into W and Z bosons.
Require that both datasets reproduce same LSP mass:

\[ m_{\tilde{\nu}_{R}} = \sqrt{m_{\tilde{\ell}}^{2} + m_{B}^{2} - 2E'_{B}m_{\tilde{\ell}}} \]
Measuring sleptons at the ILC

Slepton Mass Reconstruction: Light Staus with 500 fb\(^{-1}\)

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<td>(m_{\tilde{\tau}_1}) (GeV)</td>
<td>296.91 ± 10.69</td>
<td>294.47</td>
</tr>
<tr>
<td>(m_{\tilde{\nu}_L}) (GeV)</td>
<td>293.32 ± 3.61</td>
<td>293.37</td>
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<td>101.14 ± 1.36</td>
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Slepton Mass Reconstruction: Light Selectrons with 500 fb^{-1}

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<td>$m_{\tilde{\nu}_L}$ (GeV)</td>
<td>293.63 ± 3.12</td>
<td>293.37</td>
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<td>$m_{\tilde{\nu}_R}$ (GeV)</td>
<td>100.52 ± 1.65</td>
<td>101.98</td>
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Conclusions

● The LHC is not really sensitive to SUSY models where\[ m_{\tilde{\nu}_R}^2 < m_{\tilde{L}}^2 = m_{\tilde{E}}^2 < \mu \], single slepton families constrained to be heavier than \( \sim 150 \) GeV.

● A 1 TeV run of the ILC can probe a much larger part of the parameter space, most of it leading to a discovery with less than 1000 fb\(^{-1}\).

● Endpoint method can reconstruct masses with 500 fb\(^{-1}\), as long as sleptons decay into on-shell SM bosons.
Thanks!
Backup
Parameter scan set up in Amazon Web Service
Measuring sleptons at the ILC

Neutrino Sector

After diagonalizing the neutrino mass matrix:

3 active $\nu_L$  \quad 3 light $\nu_1$ \quad \begin{pmatrix} U_{aL} & U_{ah} \\ U_{sL} & U_{sh} \end{pmatrix}

3 sterile $\nu_R$  \quad 3 heavy $\nu_h$

Using a Casas-Ibarra parametrization, we can reconstruct the Yukawa matrices:

$$Y_\nu = -i \sqrt{2} \frac{\nu_u}{\nu_u} U_{PMNS}^* H^* m_\ell^{1/2} (m_\ell R^\dagger + R^T M_h) M_h^{-1/2} \bar{H}$$

$$H \sim I \quad \bar{H} \sim I$$

Complex orthogonal matrix

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Casas, Ibarra (hep-ph/0103065)
Donini, Hernandez, Lopez-Pavon, Maltoni, Schwetz (1205.5230 [hep-ph])
Yukawa couplings can be enhanced by taking a large $\gamma_{56}$.

\[(Y_{\nu})_{a5} = \pm (Z_{a}^{\text{NH}})^{*} \sqrt{\frac{2m_{3}M_{5}}{v_{u}^{2}}} \cosh \gamma_{56} e^{\pm i\rho_{56}}\]

\[(Y_{\nu})_{a6} = -i(Z_{a}^{\text{NH}})^{*} \sqrt{\frac{2m_{3}M_{6}}{v_{u}^{2}}} \cosh \gamma_{56} e^{\pm i\rho_{56}}\]

With this, the mass matrix gets a structure similar to the inverse seesaw.
Neutrino Sector

For definiteness, we set:

\[ M_5 = M_6 \]  
(So we do not exceed 0νββ)

\[ M_{5,6} = 20 \text{ GeV} \]  
(So they do not contribute much to R-sneutrino masses)

\[ \gamma_{56} = 8 \]  
(So we do not exceed LFV)

Neutrino sector is **fixed**.
Sneutrino Sector

We need to add new soft SUSY breaking terms:

\[ \nu^{soft} = \nu^{soft}_{\text{MSSM}} + (m^2_{\tilde{\nu}_R})_{ij} \tilde{\nu}^*_{R,i} \tilde{\nu}_{R,j} + \frac{1}{2} (B_{\tilde{\nu}})_{ij} \tilde{\nu}_{R,i} \tilde{\nu}_{R,j} + (T_{\nu})_{ij} \tilde{L}_i \cdot H_u \tilde{\nu}_{R,j} \]
Sneutrino Sector

We need to add new soft SUSY breaking terms:

\[
\mathcal{V}^{soft} = \mathcal{V}^{soft}_{\text{MSSM}} + (m_{\tilde{\nu}_R}^2)_{ij} \tilde{\nu}^*_R,i \tilde{\nu}_R,j + \frac{1}{2} (B_{\tilde{\nu}})_{ij} \tilde{\nu}_R,i \tilde{\nu}_R,j \\
+ (T_{\nu})_{ij} \tilde{L}_i \cdot H_u \tilde{\nu}_R,j
\]

Additional simplifications:

\( T_\nu \) Assumed proportional to \( Y_\nu \), so negligible

\( B_{\tilde{\nu}} \) New source of LNV, taken equal to zero for this work
MSSM Slepton Sector

D-Term contribution to mass splitting:

\[(m_{\tilde{\ell}}_L - m_{\tilde{\nu}}_L)_D \approx \frac{(\sin^2 \theta_W - 1)m_Z^2 \cos 2\beta}{2m_{\tilde{\ell}}_L} > 0\]

\[m_{\tilde{e}}_L > m_{\tilde{\nu}}_{eL}\] \[m_{\tilde{\mu}}_L > m_{\tilde{\nu}}_{\mu L}\]
Measuring sleptons at the ILC

MSSM Slepton Sector

D-Term contribution to mass splitting:

\[(m_{\tilde{\ell}_L} - m_{\tilde{\nu}_L})_D \approx \frac{(\sin^2 \theta_W - 1)m_Z^2 \cos 2\beta}{2m_L} > 0\]

\[m_{\tilde{e}_L} > m_{\tilde{\nu}_{eL}} \quad m_{\tilde{\mu}_L} > m_{\tilde{\nu}_{\mu L}}\]

Same contribution, assuming \[m_{\tilde{L}}^2 = m_{\tilde{E}}^2\]

\[(m_{\tilde{\ell}_R} - m_{\tilde{\nu}_L})_D \approx \frac{(-\sin^2 \theta_W - \frac{1}{2})m_Z^2 \cos 2\beta}{2m_L} > 0\]

\[m_{\tilde{e}_R} > m_{\tilde{\nu}_{eL}} \quad m_{\tilde{\mu}_R} > m_{\tilde{\nu}_{\mu L}}\]
MSSM Slepton Sector

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\[m_{\tilde{e}_L} > m_{\tilde{\nu}_e L} \quad m_{\tilde{\mu}_L} > m_{\tilde{\nu}_{\mu} L} \]

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\[m_{\tilde{e}_R} > m_{\tilde{\nu}_e L} \quad m_{\tilde{\mu}_R} > m_{\tilde{\nu}_{\mu} L} \]

L - sneutrinos are lighter than charged sleptons
MSSM Slepton Sector

Decay modes for selectrons, smuons:
MSSM Slepton Sector

F-Term contribution to stau mass splitting:

\[
(m_{\tilde{\tau}} - m_{\tilde{\nu}_L})_F \approx \pm \frac{m_{\tau} \mu \tan \beta}{2m_{\tilde{L}}} \\
m_{\tilde{\tau}_1} \sim m_{\tilde{\nu}_{\tau L}} \\
m_{\tilde{\tau}_2} > m_{\tilde{\nu}_{\tau L}}
\]
MSSM Slepton Sector

F-Term contribution to stau mass splitting:

\[
(m_{\tilde{\tau}} - m_{\tilde{\nu}_L})_F \approx \pm \frac{m_\tau \mu \tan \beta}{2m_{\tilde{L}}} \quad m_{\tilde{\tau}_1} \sim m_{\tilde{\nu}_{\tau L}}
\]

\[
m_{\tilde{\tau}_2} > m_{\tilde{\nu}_{\tau L}}
\]

Different decay mode for $\tilde{\tau}_1$
Slepton Production at the LHC

Drell-Yan production favours $\tilde{\nu}_L \tilde{\ell}_L$ initial state

Cross-section at the LHC (13 TeV), according to MadGraph.

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Slepton Decay modes:

Selectrons, smuons:

Charged slepton starts a small cascade, involving L-sneutrino and very soft fermions.

Final states have $Z$ / $h$ pairs, and missing energy due to R-sneutrino. Evaluated in CheckMATE.
Measuring sleptons at the ILC

Search for selectrons at LHC:

\[ \mathcal{L} = 35.9 \text{ fb}^{-1} \]

Constrained mainly by multi-lepton searches (CMS 1709.05406)

- Ruled out
- Allowed
- Ambiguous
Measuring sleptons at the ILC

Search for selectrons at LHC:

**Projection at the end of LHC lifetime has a hard time extending the reach above ~175 GeV.**

$\mathcal{L} = 35.9 \text{ fb}^{-1}$

$\mathcal{L} = 300 \text{ fb}^{-1}$

Constrained mainly by multi-lepton searches (CMS 1709.05406)
Search for selectrons at LHC:

Constrained mainly by multi-lepton searches (CMS 1709.05406)

Projection at the end of LHC lifetime has a hard time extending the reach above \( \sim 175 \) GeV.
Measuring sleptons at the ILC

Slepton Decay modes:

Staus:

Lightest stau decays directly into R-sneutrino.

Final states have $Z / h + W$, and missing energy due to R-sneutrino.
Search for staus at LHC:

$$m_{\tilde{\nu}_R}^2 = 0$$

$\mathcal{L} = 35.9$ fb$^{-1}$

Multi-lepton searches by CMS still most sensitive.

- Ruled out
- Allowed
- Ambiguous
Search for staus at LHC:

\[ m^{2}_{\tilde{\nu}_R} = 0 \]

Multi-lepton searches by CMS still most sensitive.

For stau masses above 150 GeV, there are no constraints.
Sleptons at the ILC

- The $e^+ e^-$ collisions would produce slepton pairs.

- Cross-section at the ILC (1 TeV), according to WHIZARD.

- Type B polarization. 
  $\left( e_R^- e_L^+ \right)$
Getting the endpoints

1. Group all events into W-like, Z-like, and h-like datasets:

\[
\chi^2_W(m_1, m_2) = \frac{(m_1 - m_W)^2 + (m_2 - m_W)^2}{\sigma^2}
\]

\[
\chi^2_Z(m_1, m_2) = \frac{(m_1 - m_Z)^2 + (m_2 - m_Z)^2}{\sigma^2}
\]

\[
\chi^2_h(m_1, m_2) = \frac{(m_1 - m_h)^2 + (m_2 - m_h)^2}{\sigma^2}
\]
Getting the endpoints

2. Generate a SM distribution from MC events, by fitting parameters:

\[
\int_{E_{SM-}}^{\infty} \left( a_2 E'^2 + a_1 E' + a_0 \right) V(E' - E, \sigma_{SM}, \Gamma_{SM}) dE'
\]

3. Generate 100 samples of SM background using SM distribution. Implement statistical errors by modifying number of events in each bin using a Poisson distribution.
Getting the endpoints

4. For each SM sample, fit the sum of SUSY and SM spectra:

\[ f(E; E_{B-}, E_{B+}, b_{0-2}, \sigma_1, \Gamma_1) \]

\[ = f_{SM}(E; E_{SM-}, a_{0-2}, \sigma_{SM}, \Gamma_{SM}) \]

\[ + \int_{E_{B-}}^{E_{B+}} (b_2 E'^2 + b_1 E' + b_0) V(E' - E, \sigma_1, \Gamma_1) dE' \]

5. Get endpoints from fit. Use 100 samples to get average and standard deviation.

6. For h-like events, background is negligible. Divide into subsets.
Measuring sleptons at the ILC

Required luminosity (fb$^{-1}$) at ILC to get 5$\sigma$

![Diagram showing required luminosity for sleptons at the ILC](image-url)
Measuring sleptons at the ILC

Slepton Mass Reconstruction: Degenerate Soft Masses with 500 fb$^{-1}$

Adding B and L polarization for h-like

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Non-thermal R-Sneutrino Dark Matter

Maximum dark matter mass: 0.7 - 250 GeV
Non-thermal R-Sneutrino Dark Matter

Maximum dark matter mass: 0.7 - 250 GeV

Too small thermal relic density (L-sneutrino NLSP)

Too small thermal relic density (Higgsino NLSP)
Non-thermal R-Sneutrino Dark Matter

Maximum dark matter mass: 0.7 – 250 GeV

- Too small thermal relic density (L-sneutrino NLSP)
- Too small thermal relic density (Higgsino NLSP)
- Too small thermal relic density (Higgsino NLSP)
- Would require a negative soft mass
- Ruled out by LHC (Higgsino lighter than L-slepton)

Measuring sleptons at the ILC

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SARAH, SPheno, micrOMEGAs
Non-thermal R-Sneutrino Dark Matter

Maximum dark matter mass: 0.7 – 250 GeV

Too small thermal relic density (L-sneutrino NLSP)

Too small thermal relic density (Higgsino NLSP)

Would require a negative soft mass

Ruled out by LHC (Higgsino lighter than L-slepton)

LHC @ 300 fb⁻¹
Non-thermal R-Sneutrino Dark Matter

Maximum dark matter mass: 0.7 – 250 GeV

\( \tau_{NLSP} \lesssim 1 \text{ s} \)
\( \tau_{NLSP} \lesssim 10^4 \text{ s} \)
\( \tau_{NLSP} \lesssim 10^5 \text{ s} \)
\( \tau_{NLSP} \lesssim 10^6 \text{ s} \)
Non-thermal R-Sneutrino Dark Matter

Gets worse when adding annihilation in plasma:

\[ (Y_\nu)_{a4} \sim \sqrt{\frac{2m_1 M_4}{v_u^2}} \]

\[ m_{\tilde{L}} = 323 \text{ GeV} \]

\[ m_{\tilde{\nu}_{R5,6}} = 302 \text{ GeV} \]
Measuring sleptons at the ILC

\[ m_{\tilde{\nu}_R}^2 < \mu < m_{\tilde{L}}^2 = m_{\tilde{E}}^2 \]

Chargino production:

\[ pp \rightarrow \tilde{\chi}^+ \tilde{\chi}^- \rightarrow \ell^+ \ell^- \tilde{\nu}_R \tilde{\nu}_R^* \]

Scenario 1:
\[ \mu = m_{\tilde{\nu}_R} + 25 \text{ GeV} \]

Scenario 2:
\[ \mu = 400 \text{ GeV} \]
Measuring sleptons at the ILC

\[ m_{\tilde{\nu}_R}^2 < \mu < m_{\tilde{L}}^2 = m_{\tilde{E}}^2 \]

Scenario 1

\[ \mathcal{L} = 13.3 \text{ fb}^{-1} \]

Very strong constraints on slepton mass!

\[ \mu = m_{\tilde{\nu}_R} + 25 \text{ GeV} \]
Measuring sleptons at the ILC

μ = 400 GeV

If electroweakinos are heavy, we have weak constraint!