Measuring sleptons at the ILC

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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!

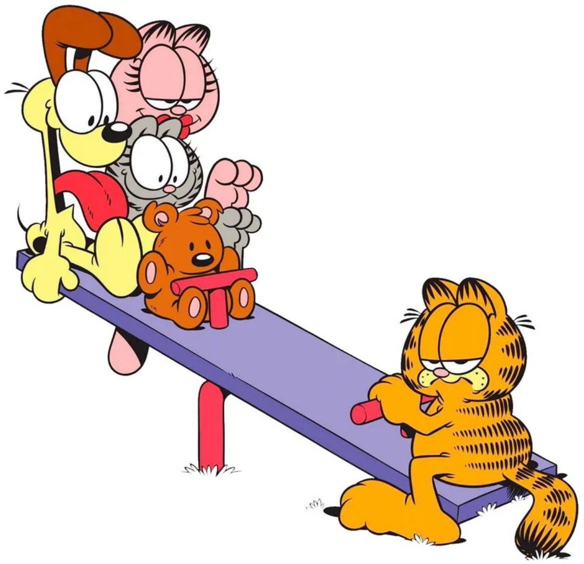
- Motivates searching for situations where SUSY can hide. Examples of these are compressed spectra and RPV.

Low-Scale Seesaw

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

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} - Y_\nu \left(\bar{L} \cdot \tilde{H}\, \nu_R \right) - \tfrac{1}{2} M_R \left(\bar{\nu}_R\, \nu_R^c \right)$$

$$m_\nu \sim \frac{v^2}{2} Y_\nu^*\, M_R^{-1}\, Y_\nu^\dagger$$



- 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.

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- 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 μ as low as possible → 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:

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

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

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

$$\mu \gtrsim 400\,\mathrm{GeV}$$

$$m_{\tilde{L}} \gtrsim 600\,\mathrm{GeV}$$

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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 $(M_5 = M_6 = 20\,\mathrm{GeV})$
  - Suppresses contribution to neutrinoless double beta decay
  - Keeps loop corrections to light neutrino masses under control

Sneutrino Sector

- Sneutrino mass matrix:

$$M^2_{\tilde{\nu}} = \begin{pmatrix} m^2_{\tilde{L}} + \frac{1}{2} m^2_Z \cos 2\beta & 0 \\ 0 & m^2_{\tilde{\nu}_R} + M^\dagger_R M_R \end{pmatrix}$$

- 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:

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

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$$\tilde{\tau}_1^- \to \tilde{\nu}_R\, W^-$$

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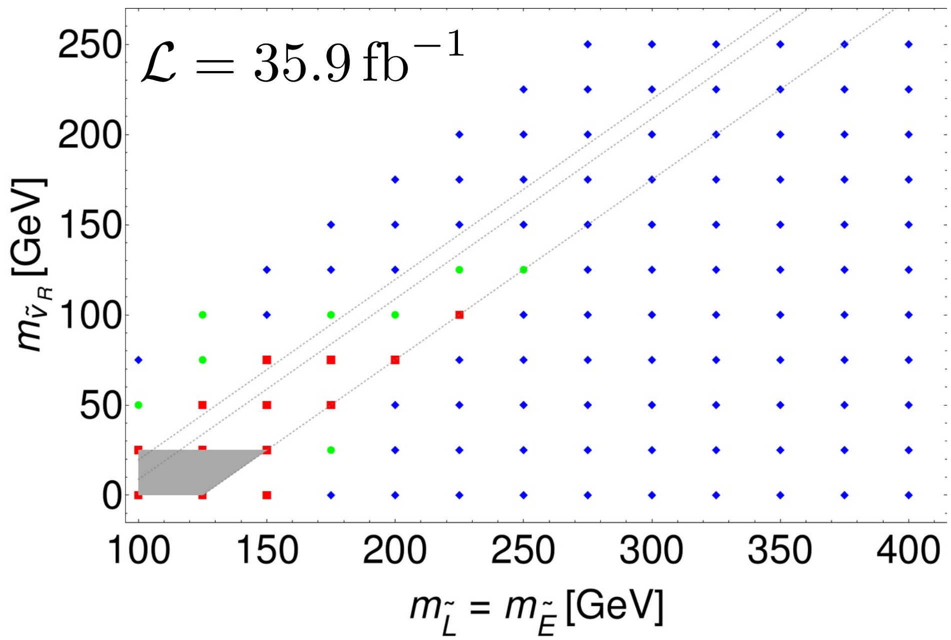
- Cascade decays (compressed):

$$\tilde{\tau}_2^- \to \tilde{\tau}_1^- \, Z^*$$

$$\tilde{\tau}_2^- \to \tilde{\nu}_L \, W^{-*}$$

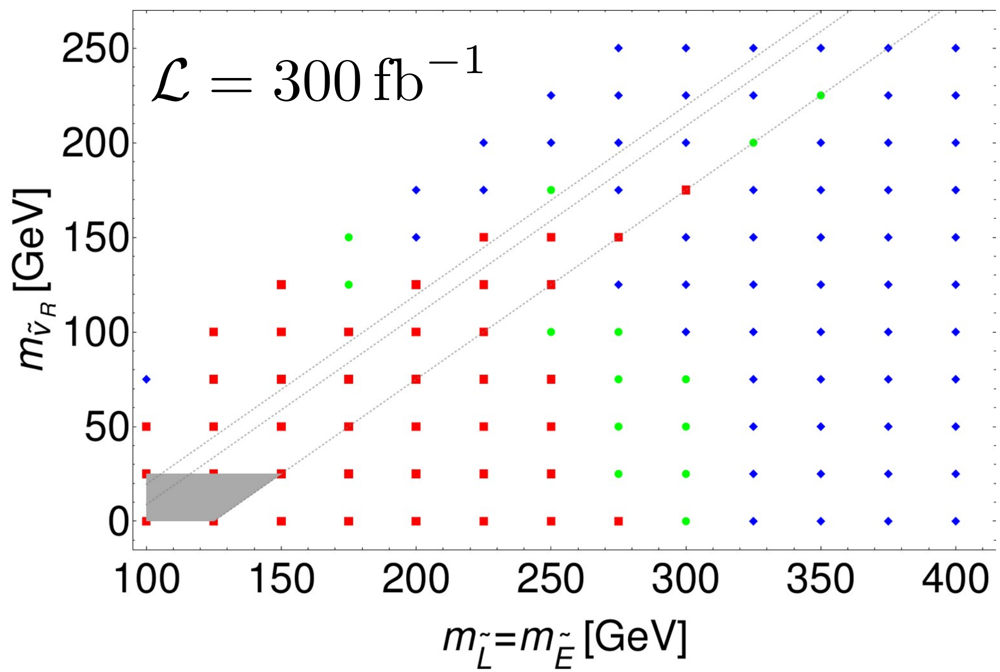
$$\tilde{\ell}_{L,R}^- \to \tilde{\nu}_L \, W^{-*}$$

Degenerate scenario at LHC:



Constrained mainly by multi-lepton searches

Ruled out   Allowed   Ambiguous

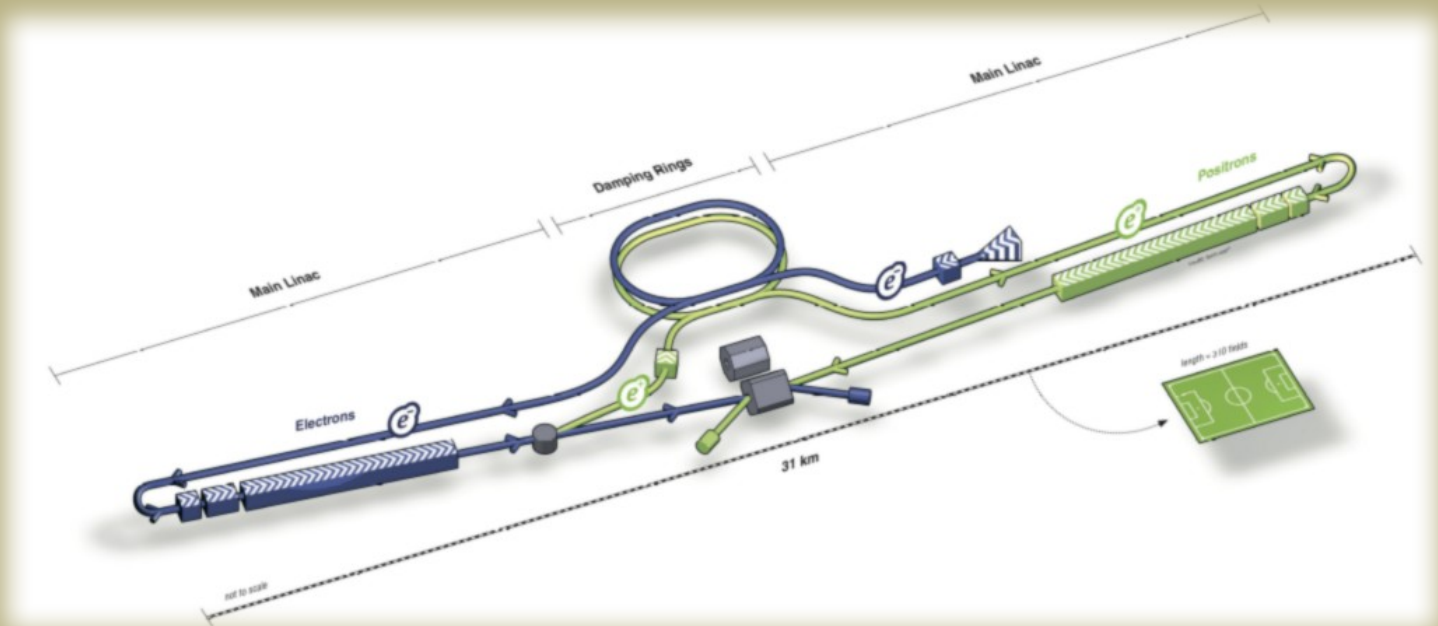


Projection at the end of LHC lifetime has a hard time extending the reach above 250 GeV.

CMS Collaboration (1709.05406)

CheckMATE (1709.05406 [hep-ph])

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:

$$\tilde{\tau}_1^- \to \tilde{\nu}_R \, W^- \qquad \tilde{\nu}_L \to \tilde{\nu}_R \, Z \qquad \tilde{\nu}_L \to \tilde{\nu}_R \, h$$

- The hadronic decays of the SM bosons lead to final states with **four jets and missing energy**.
- We consider Type **B** polarization $(e_R^- \, e_L^+)$

Sleptons at a 1 TeV ILC

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

Scenario	SE
No cuts	14713
$E_{\text{miss}} > 50$ GeV	12941
Exactly four jets with $E > 20$ GeV	4740
Exactly two reconstructed SM bosons	869
$E_{\text{lepton}} < 25$ GeV	862
$\|\cos(\theta_{\text{miss}})\| < 0.99$	758
Efficiency (%)	5.2

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

Suehara, List (0906.5508 [hep-ph])

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$E_{\text{miss}} > 50$ GeV	12941	12997
Exactly four jets with $E > 20$ GeV	4740	3770
Exactly two reconstructed SM bosons	869	1092
$E_{\text{lepton}} < 25$ GeV	862	1084
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Efficiency (%)	5.2	6.3

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

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

ST: $m_{\tilde{E}_3} = m_{\tilde{L}_3}$

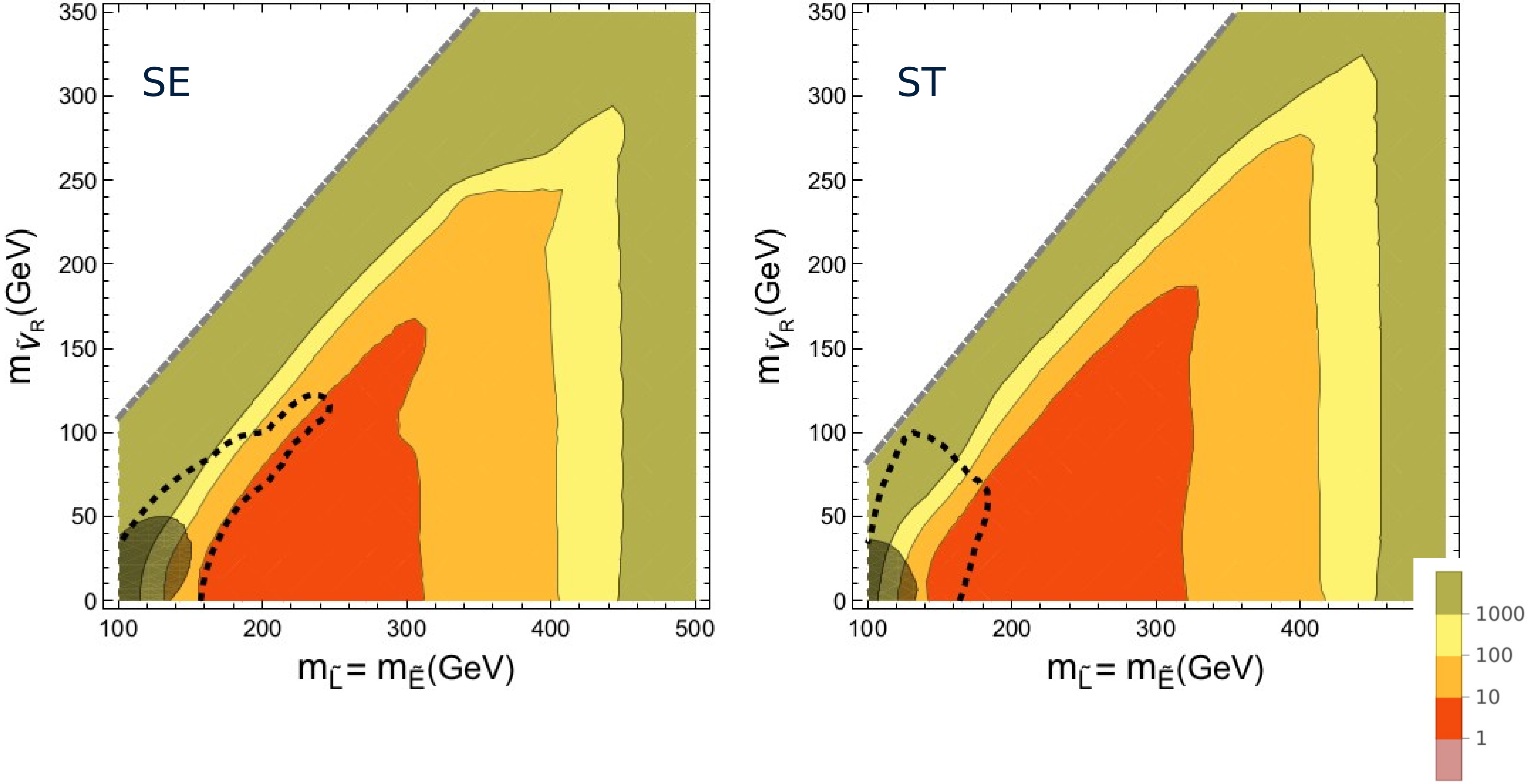
All background: 417 events

Efficiency: 0.08%

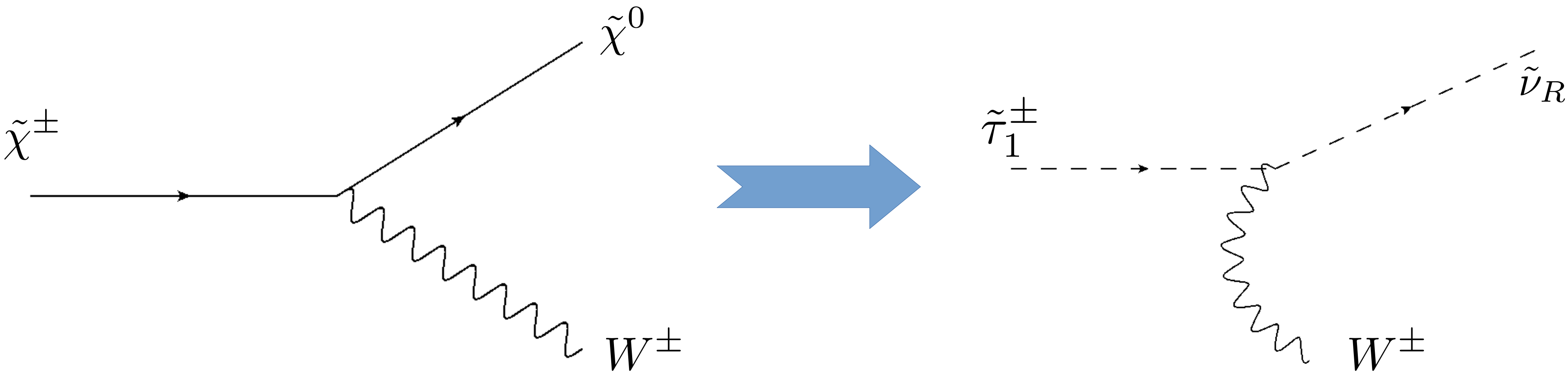
Main sources: $t\,\bar{t}$, $Z\,W^+W^-$, $2\nu\,W^+W^-$

Suehara, List (0906.5508 [hep-ph])

Required luminosity (fb^{-1}) at ILC to get 5σ



Slepton Mass Reconstruction: Endpoint Method



Reconstruct W boson and measure its energy.

Min / max values of W boson energy: **endpoints**, E_{B-}, E_{B+}

Suehara, List (0906.5508 [hep-ph])

Slepton Mass Reconstruction: Endpoint Method

$$m_{\tilde{\ell}} = \frac{2E_{\mathrm{beam}}}{E_{B+} + E_{B-}} E'_B$$

Boson energy in slepton rest frame

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$$E'_B = \frac{1}{\sqrt{2}} \sqrt{(E_{B+} E_{B-} + m_B^2) \pm \sqrt{(E_{B+}^2 - m_B^2)(E_{B-}^2 - m_B^2)}}$$

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Need two datasets, for example, decays into *W* and *Z* bosons.

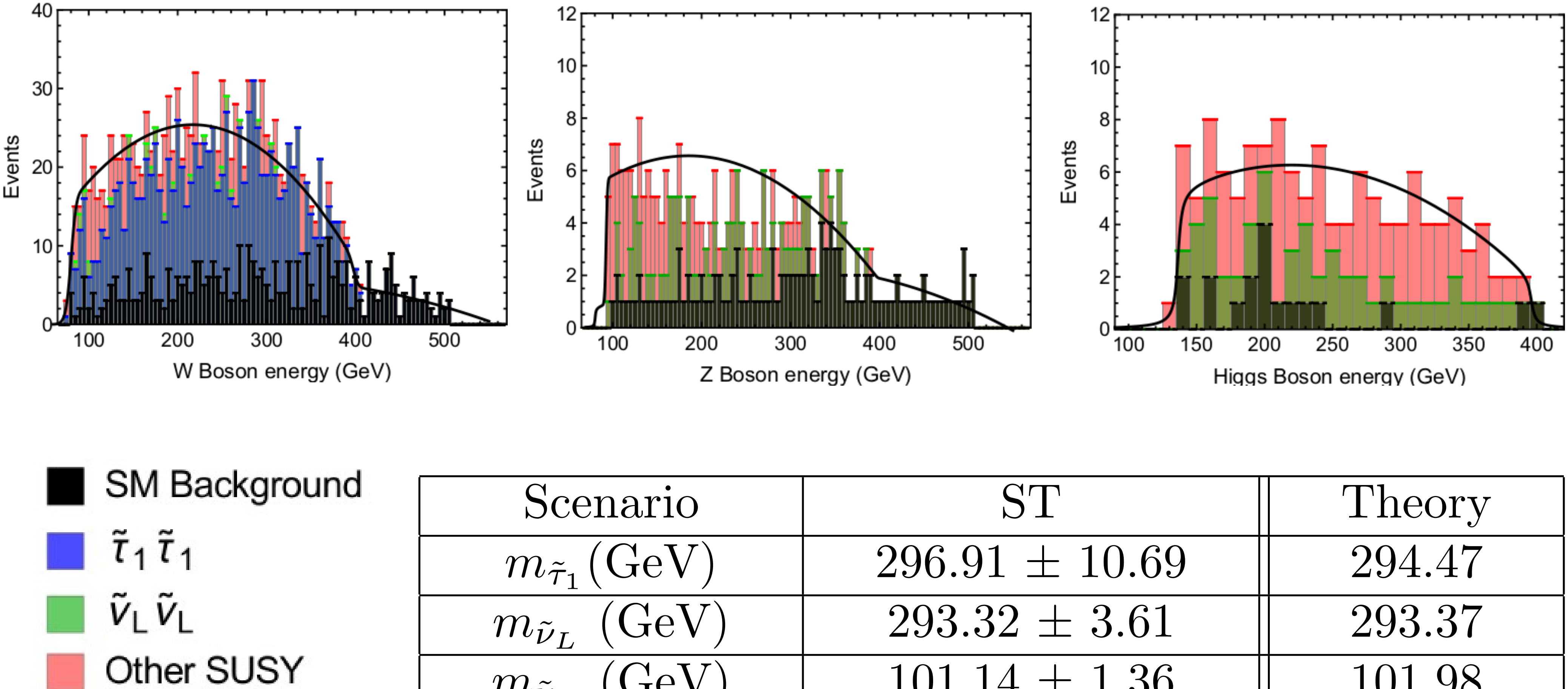
Require that both datasets reproduce same LSP mass:

$$m_{\tilde{\nu}_R} = \sqrt{m_{\tilde{\ell}}^2 + m_B^2 - 2E'_B m_{\tilde{\ell}}}$$

Suehara, List (0906.5508 [hep-ph])

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

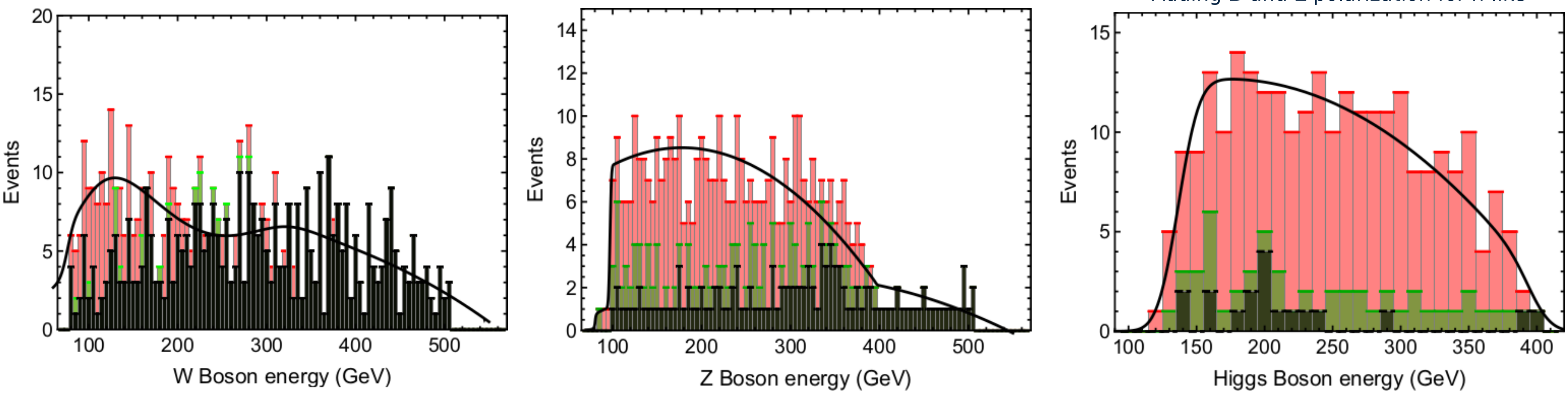
Adding **B** and **L** polarization for h-like

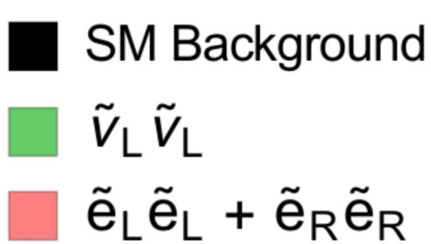


Scenario	ST	Theory
$m_{\tilde{\tau}_1}$ (GeV)	296.91 ± 10.69	294.47
$m_{\tilde{\nu}_L}$ (GeV)	293.32 ± 3.61	293.37
$m_{\tilde{\nu}_R}$ (GeV)	101.14 ± 1.36	101.98

Slepton Mass Reconstruction: Light Selectrons with 500 fb^{-1}

Adding **B** and **L** polarization for h-like





Scenario	SE	Theory
$m_{\tilde{\nu}_L}$ (GeV)	293.63 ± 3.12	293.37
$m_{\tilde{\nu}_R}$ (GeV)	100.52 ± 1.65	101.98

Conclusions

- The LHC is not really sensitive to SUSY models where $m^2_{\tilde{\nu}_R} < m^2_{\tilde{L}} = m^2_{\tilde{E}} < \mu$, single slepton families constrained to be heavier than ~ 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

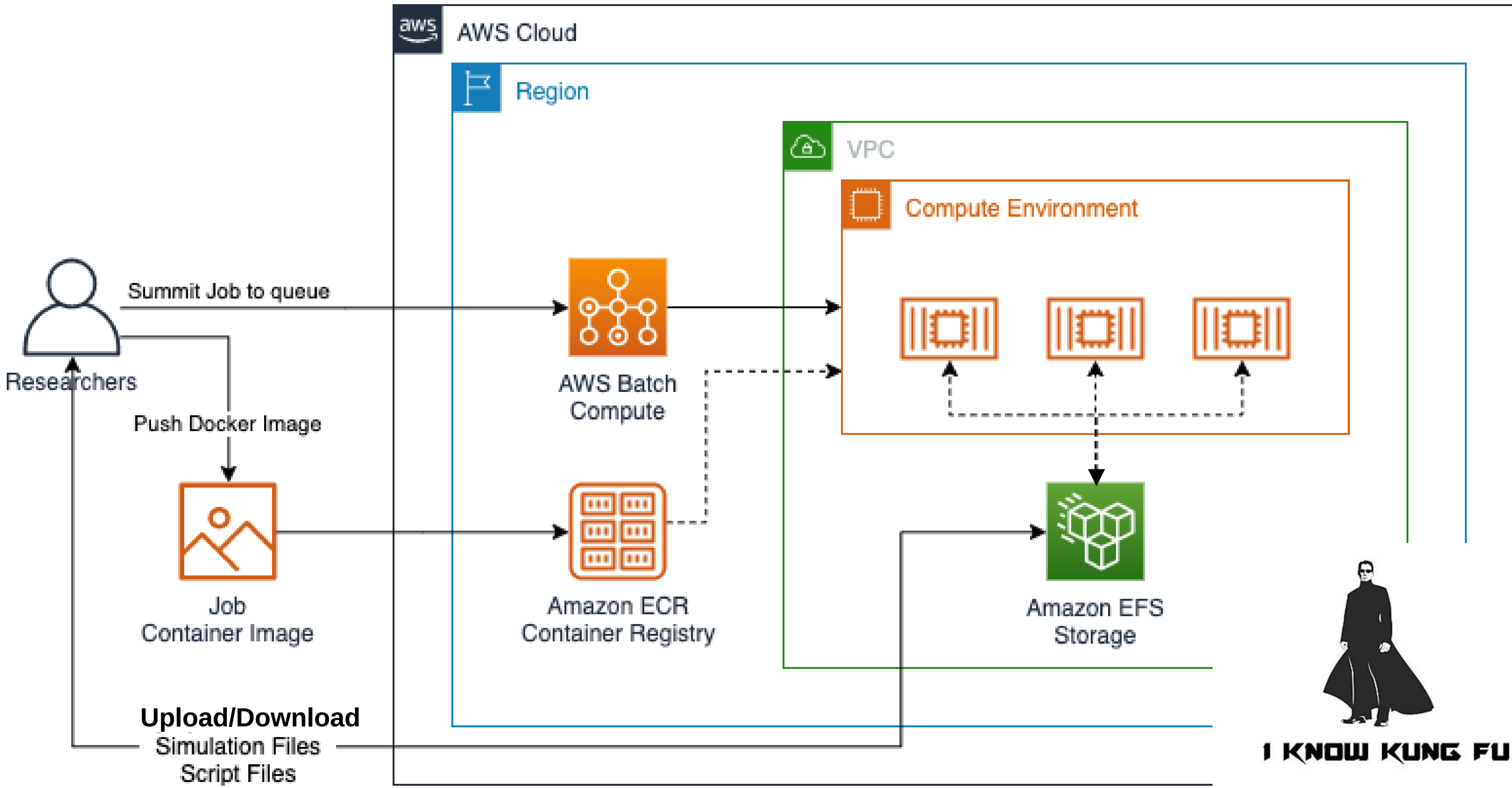


Image Credit: Gabriel Paredes

Neutrino Sector

After diagonalizing the neutrino mass matrix:

3 active ν_L ⟷ 3 light ν_l

3 sterile ν_R 3 heavy ν_h

$$U = \begin{pmatrix} U_{a\ell} & U_{ah} \\ U_{s\ell} & U_{sh} \end{pmatrix}$$

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

$$Y_\nu = -i\frac{\sqrt{2}}{v_u} U^*_{\mathrm{PMNS}} H^* m_\ell^{1/2} \left(m_\ell R^\dagger + R^T M_h \right) M_h^{-1/2} \bar{H}$$

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

Complex orthogonal matrix

Casas, Ibarra (hep-ph/0103065)

Donini, Hernandez, Lopez-Pavon, Maltoni, Schwetz (1205.5230 [hep-ph])

Neutrino Sector

Yukawa couplings can be enhanced by taking a large γ_{56}.

$$(Y_\nu)_{a5} = \pm(Z_a^{\mathrm{NH}})^* \sqrt{\frac{2m_3 M_5}{v_u^2}} \cosh\gamma_{56}\, e^{\mp i\rho_{56}}$$

$$(Y_\nu)_{a6} = -i(Z_a^{\mathrm{NH}})^* \sqrt{\frac{2m_3 M_6}{v_u^2}} \cosh\gamma_{56}\, e^{\mp i\rho_{56}}$$

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 $0\nu\beta\beta$)

$$M_{5,6} = 20 \text{ GeV}$$

(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:

$$\begin{aligned}\mathcal{V}^{soft} &= \mathcal{V}^{soft}_{\mathrm{MSSM}} + (m^2_{\tilde{\nu}_R})_{ij}\tilde{\nu}^*_{R,i}\tilde{\nu}_{R,j} + \frac{1}{2}(B_{\tilde{\nu}})_{ij}\tilde{\nu}_{R,i}\tilde{\nu}_{R,j} \\ &\quad + (T_\nu)_{ij}\,\tilde{L}_i \cdot H_u\,\tilde{\nu}_{R,j}\end{aligned}$$

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$$+(T_\nu)_{ij}\,\tilde{L}_i\cdot H_u\,\tilde{\nu}_{R,j}$$

Additional simplifications:

T_ν Assumed proportional to Y_ν, 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:

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

$$m_{\tilde{e}_L} > m_{\tilde{\nu}_{eL}}$$

$$m_{\tilde{\mu}_L} > m_{\tilde{\nu}_{\mu L}}$$

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Same contribution, assuming $m^2_{\tilde{L}} = m^2_{\tilde{E}}$

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

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

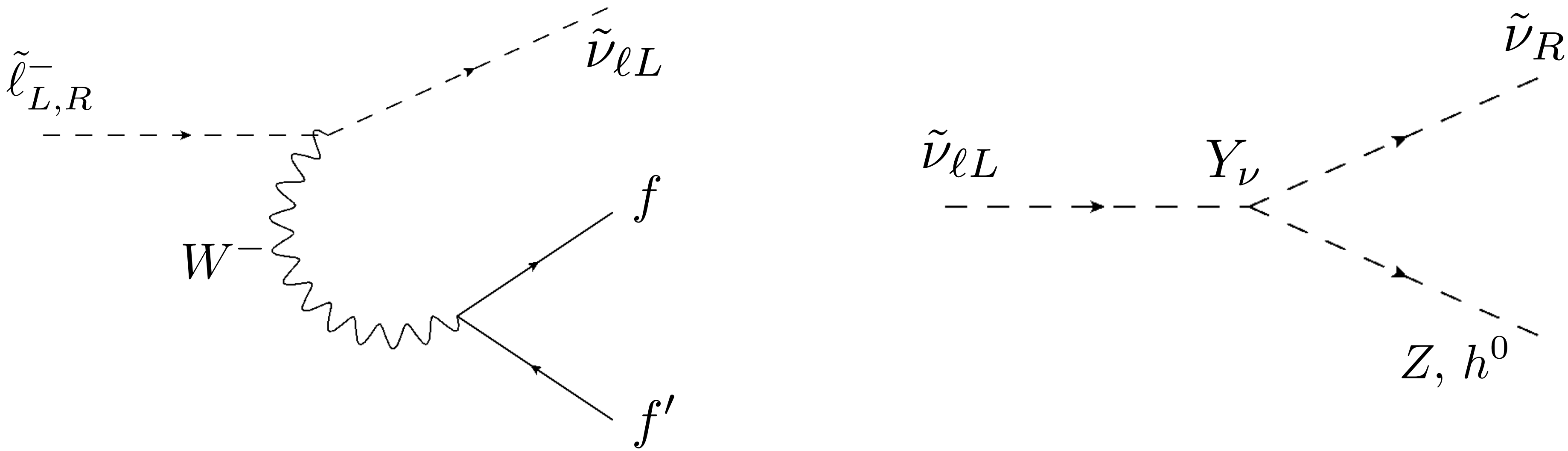
$$(m_{\tilde{\ell}_R} - m_{\tilde{\nu}_L})_D \approx \frac{(-\sin^2\theta_W - \frac{1}{2})m_Z^2 \cos 2\beta}{2m_{\tilde{L}}} > 0$$

$$m_{\tilde{e}_R} > m_{\tilde{\nu}_{eL}} \qquad m_{\tilde{\mu}_R} > m_{\tilde{\nu}_{\mu L}}$$

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:

$$(m_{\tilde{\tau}} - m_{\tilde{\nu}_L})_F \approx \pm \frac{m_\tau \, \mu \, \tan\beta}{2 m_{\tilde{L}}}$$

$$m_{\tilde{\tau}_1} \sim m_{\tilde{\nu}_\tau L}$$

$$m_{\tilde{\tau}_2} > m_{\tilde{\nu}_\tau L}$$

MSSM Slepton Sector

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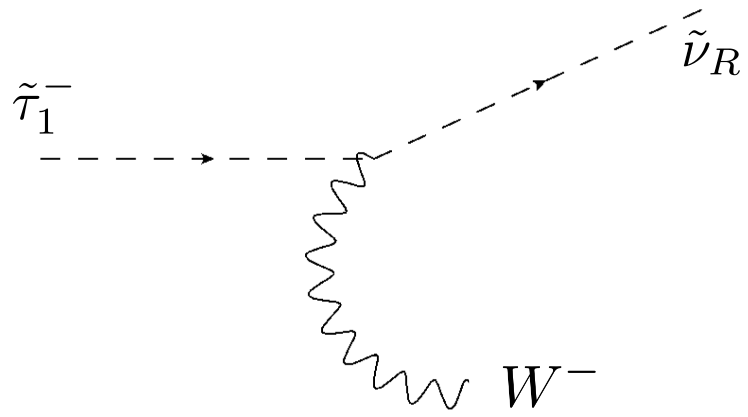
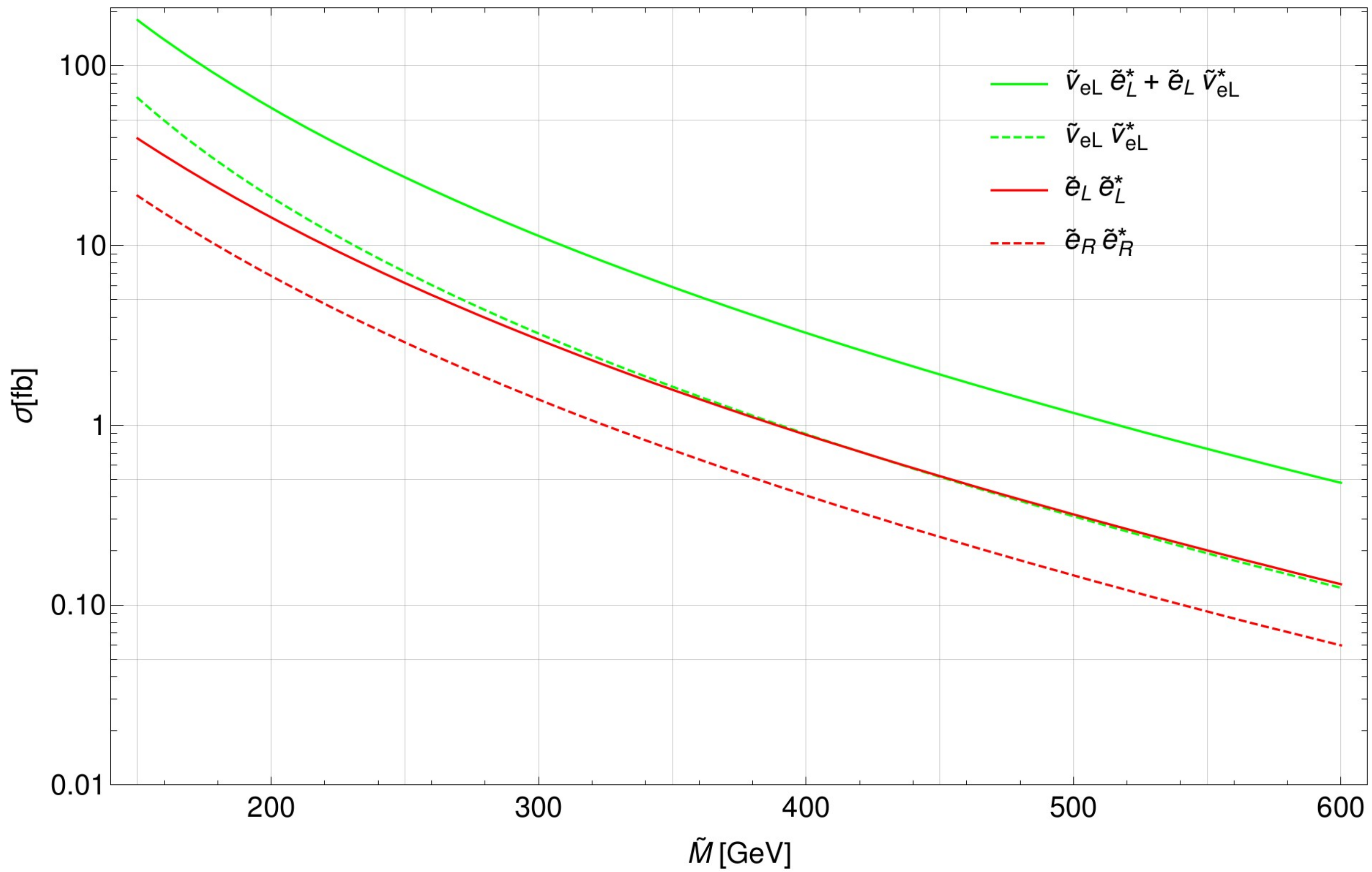
Different decay mode for $\tilde{\tau}_1$



Slepton Production at the LHC

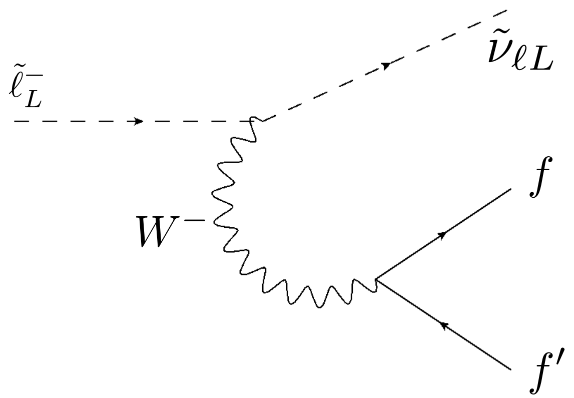
Drell-Yan production favours $\tilde{\nu}_L \, \tilde{\ell}_L$ initial state

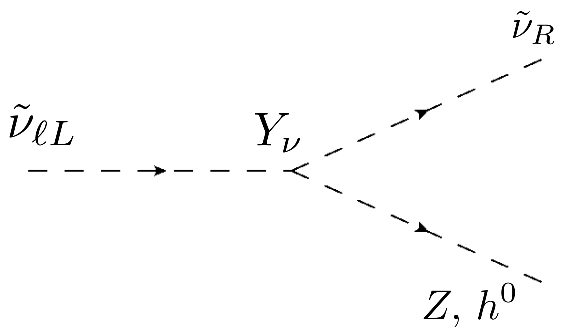
Cross-section at the LHC (13 TeV), according to MadGraph.



Slepton Decay modes:

Selectrons, smuons:



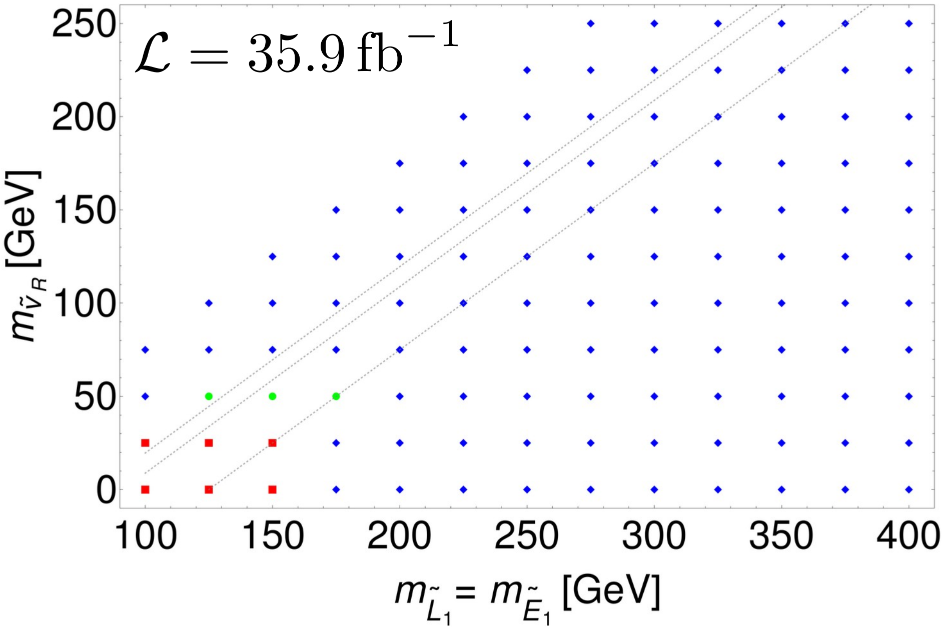


Charged slepton starts a small cascade, involving L-sneutrino and very soft fermions

Final states have Z / h pairs, and missing energy due to R-sneutrino.

Evaluated in CheckMATE.

Search for selectrons at LHC:



Constrained mainly by multi-lepton searches (CMS 1709.05406)

Ruled out   Allowed   Ambiguous

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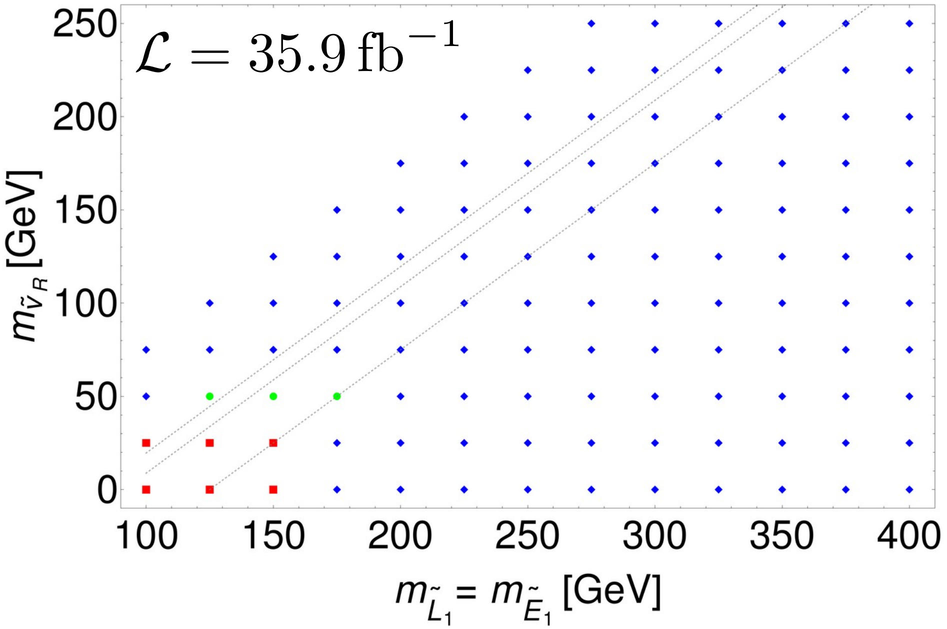

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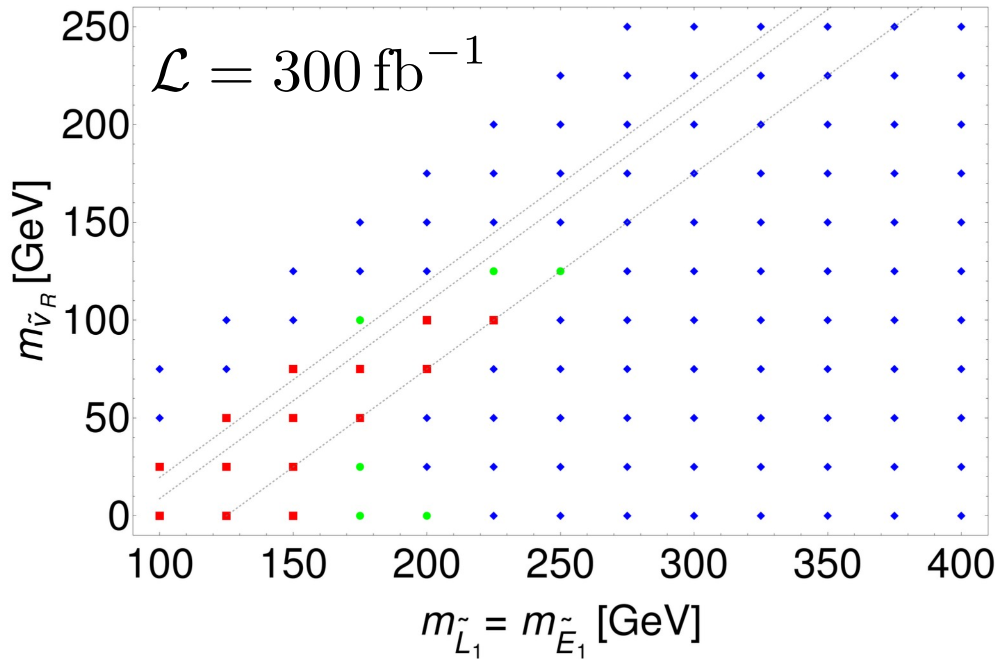

Projection at the end of LHC lifetime has a hard time extending the reach above ~175 GeV.

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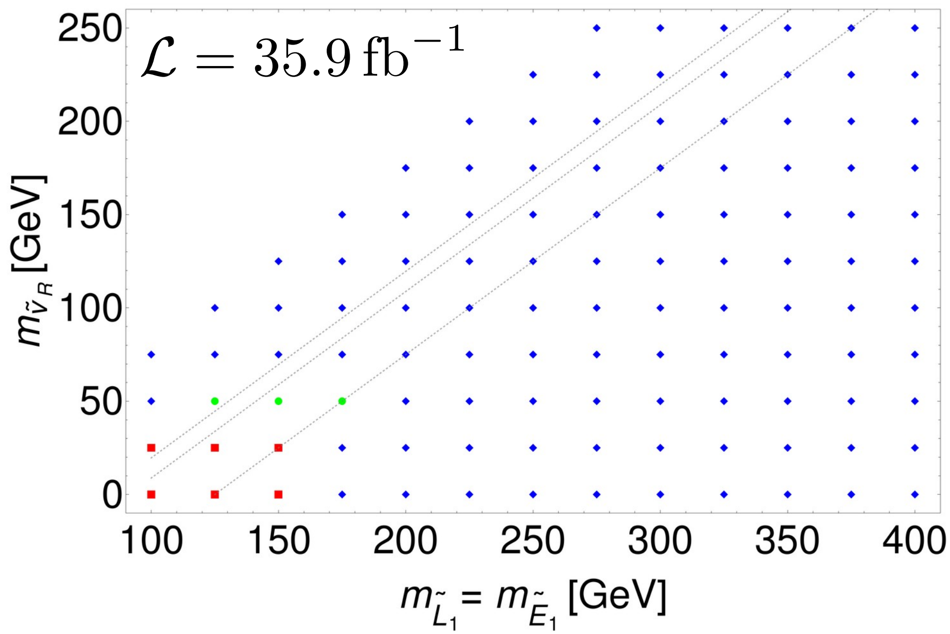

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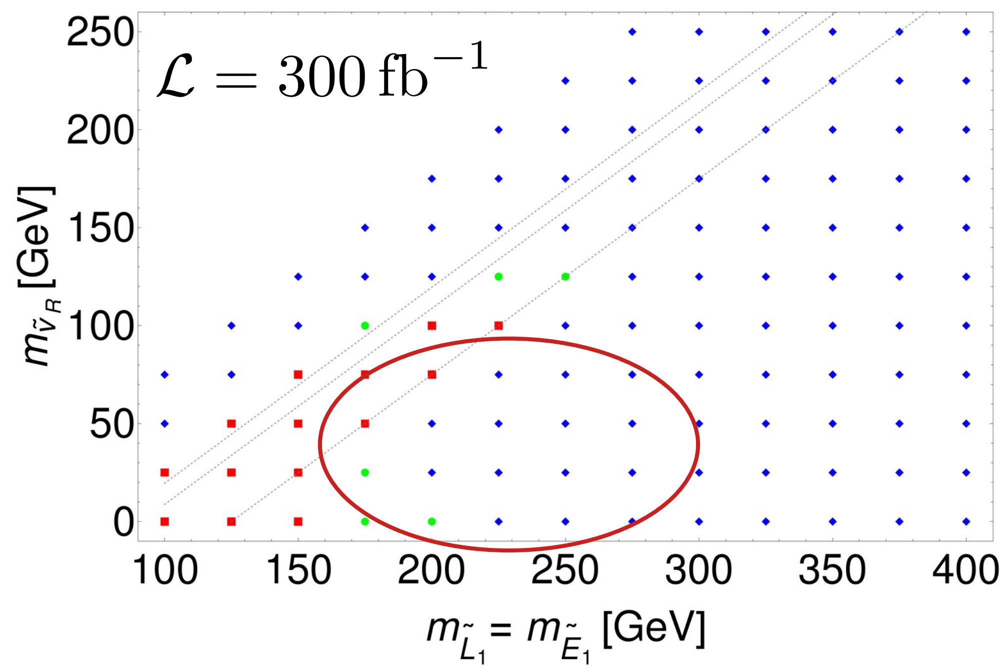

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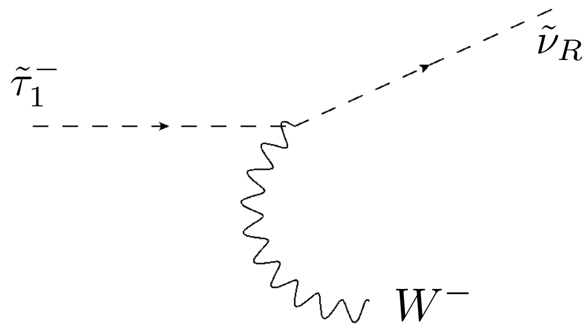
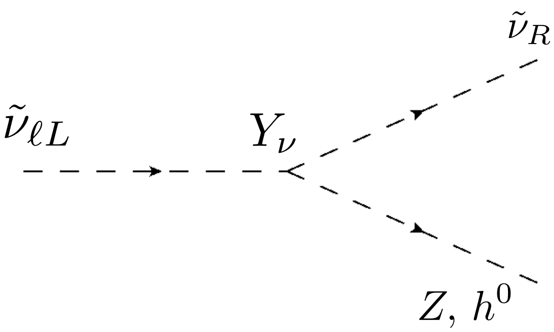
Slepton Decay modes:

Staus:



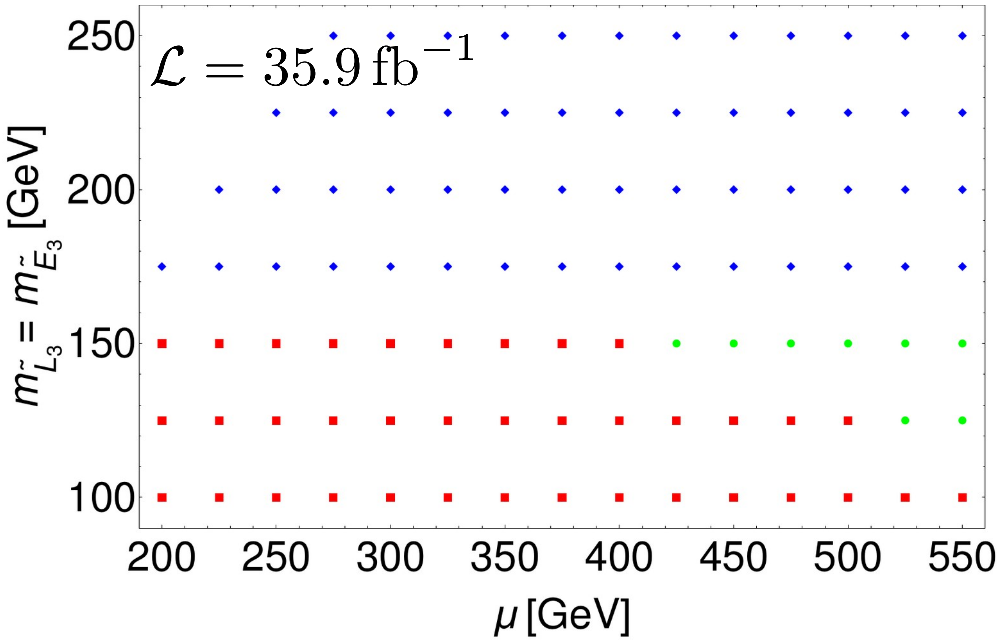


Lightest stau decays directly into R-sneutrino.

Final states have Z / h + W, and missing energy due to R-sneutrino.

Search for staus at LHC:

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



Multi-lepton searches by CMS still most sensitive.

Search for staus at LHC:

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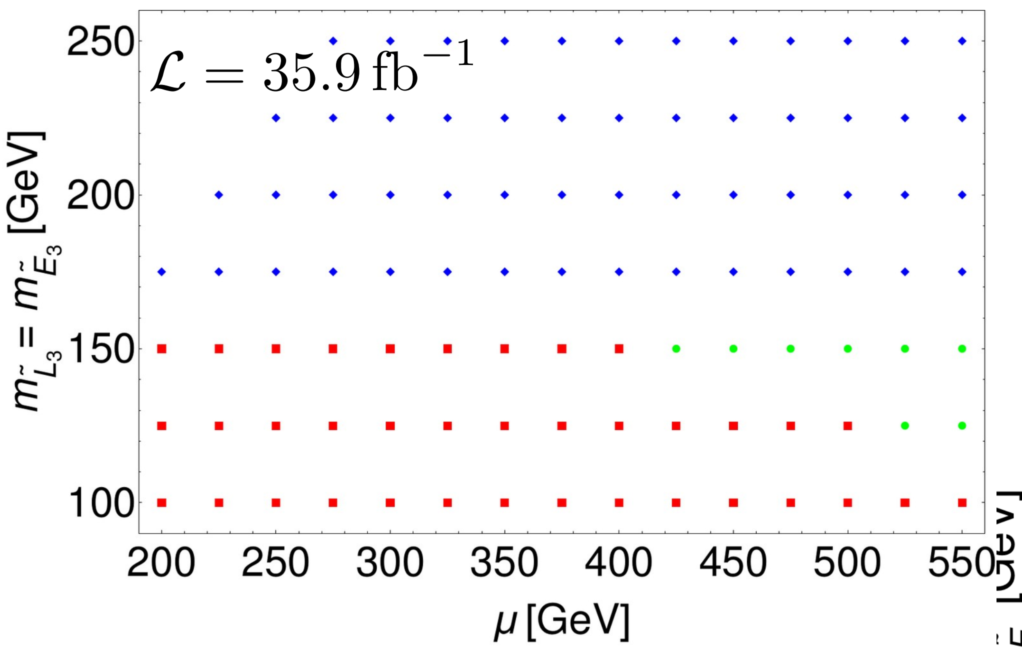
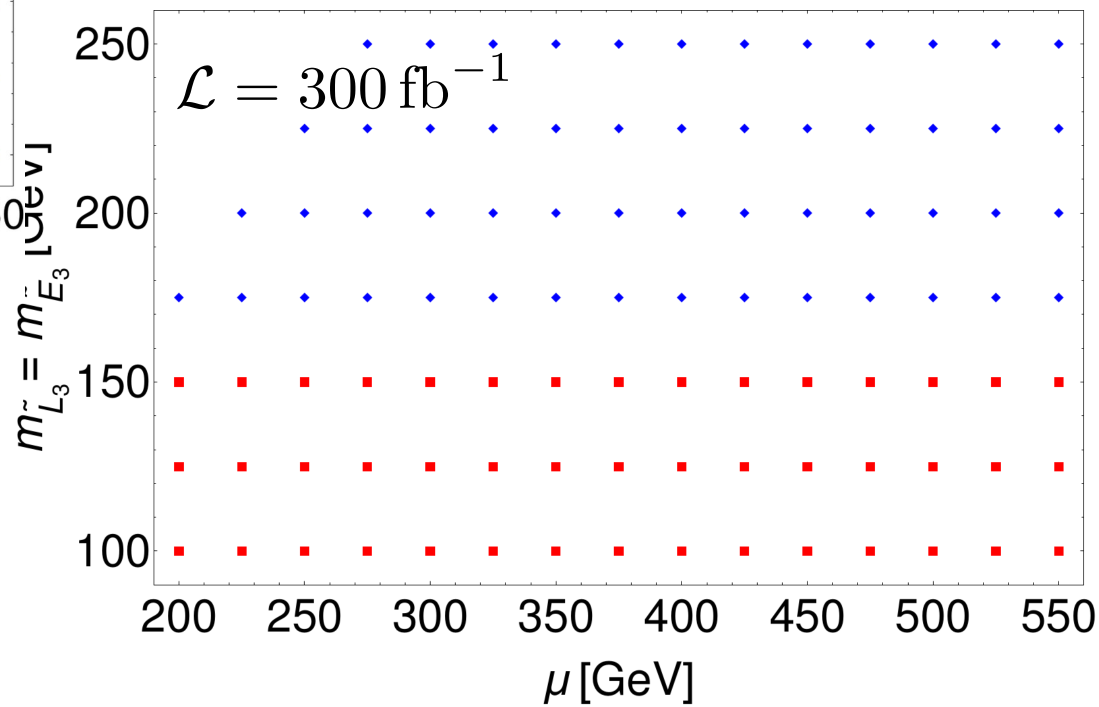


Multi-lepton searches by CMS still most sensitive.

Ruled out   Allowed   Ambiguous



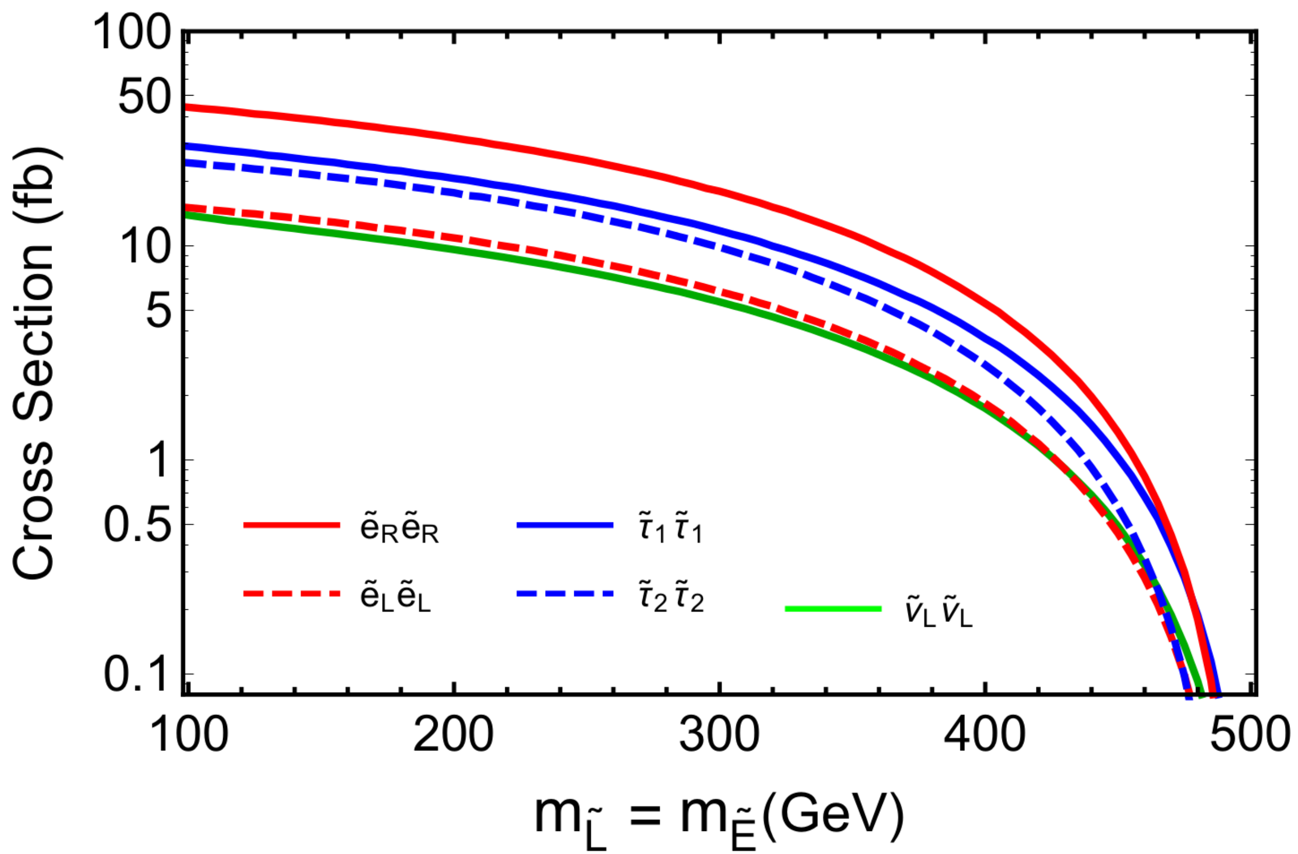
For stau masses above 150 GeV, there are no constaints.

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. $(e^-_R\, e^+_L)$



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:

$$f_{SM}(E;\ E_{\mathrm{SM}-},\ a_{0-2},\ \sigma_{\mathrm{SM}},\ \Gamma_{\mathrm{SM}})$$

Voigt function

$$= \int_{E_{\mathrm{SM}-}}^{\infty} (a_2 E'^2 + a_1 E' + a_0)\, V(E' - E, \sigma_{\mathrm{SM}}, \Gamma_{\mathrm{SM}})\, dE'$$

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:

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

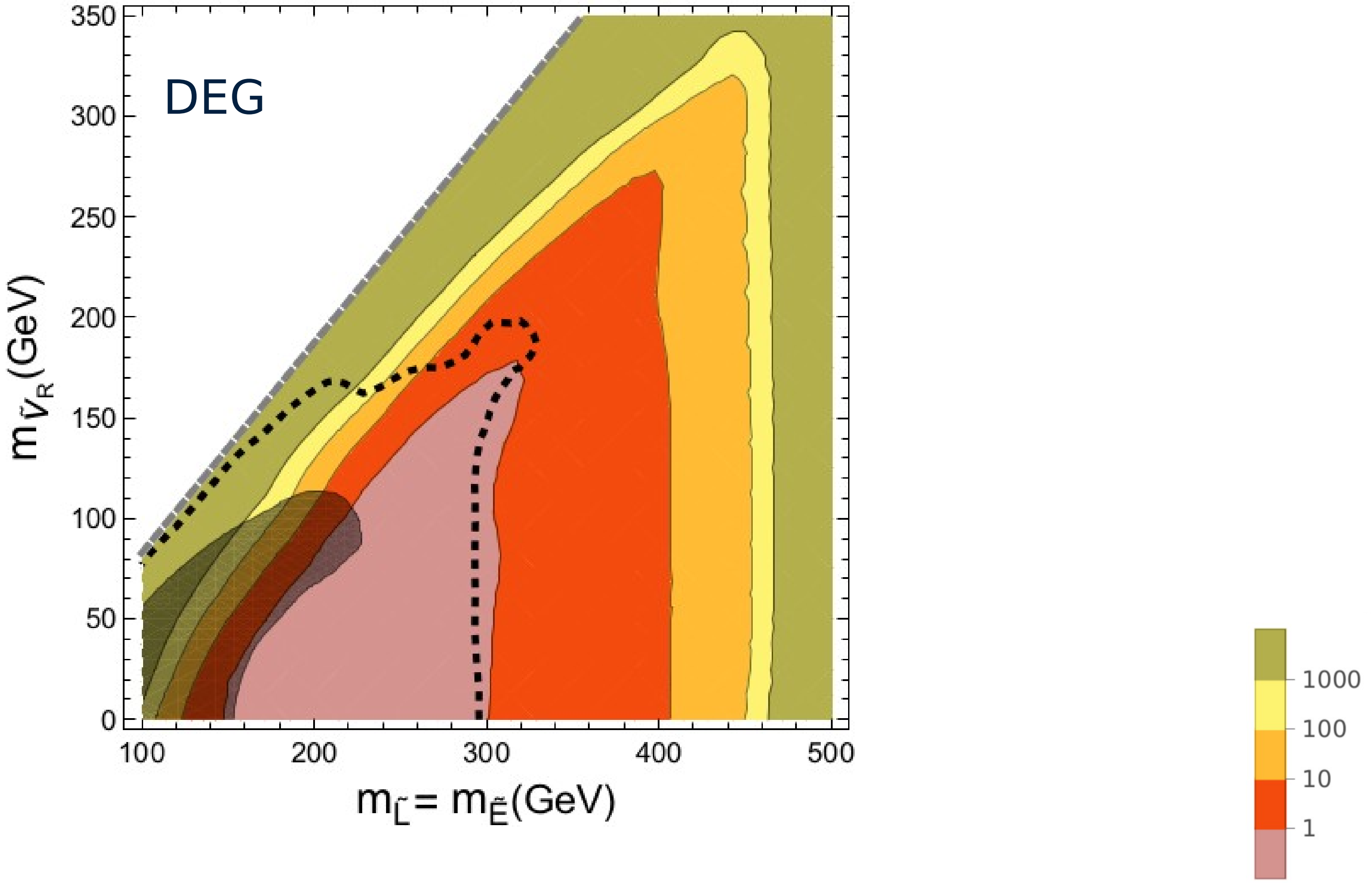
$$= f_{SM}(E;\, E_{\mathrm{SM}-}, a_{0-2}, \sigma_{\mathrm{SM}}, \Gamma_{\mathrm{SM}})$$

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

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

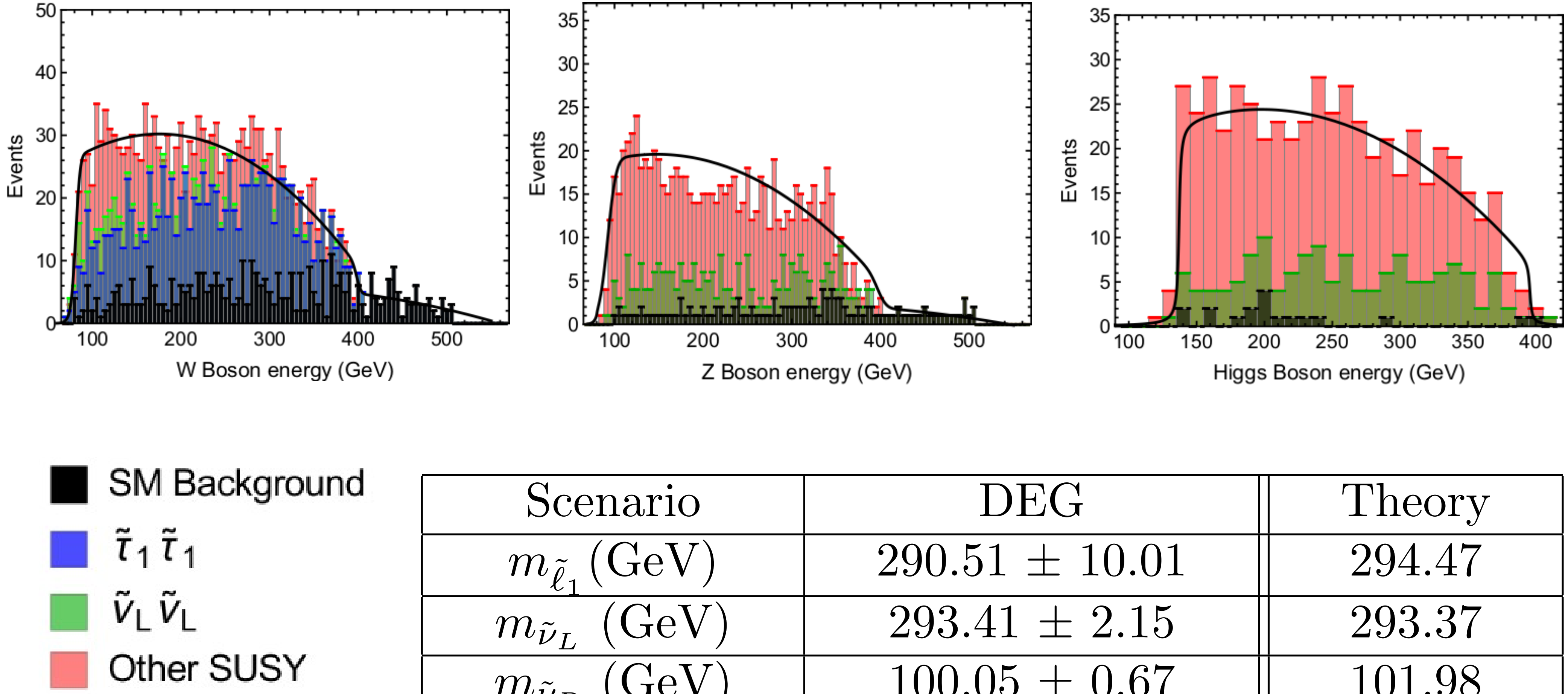
6. For h-like events, background is negligible. Divide into subsets.

Required luminosity (fb^{-1}) at ILC to get 5σ



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

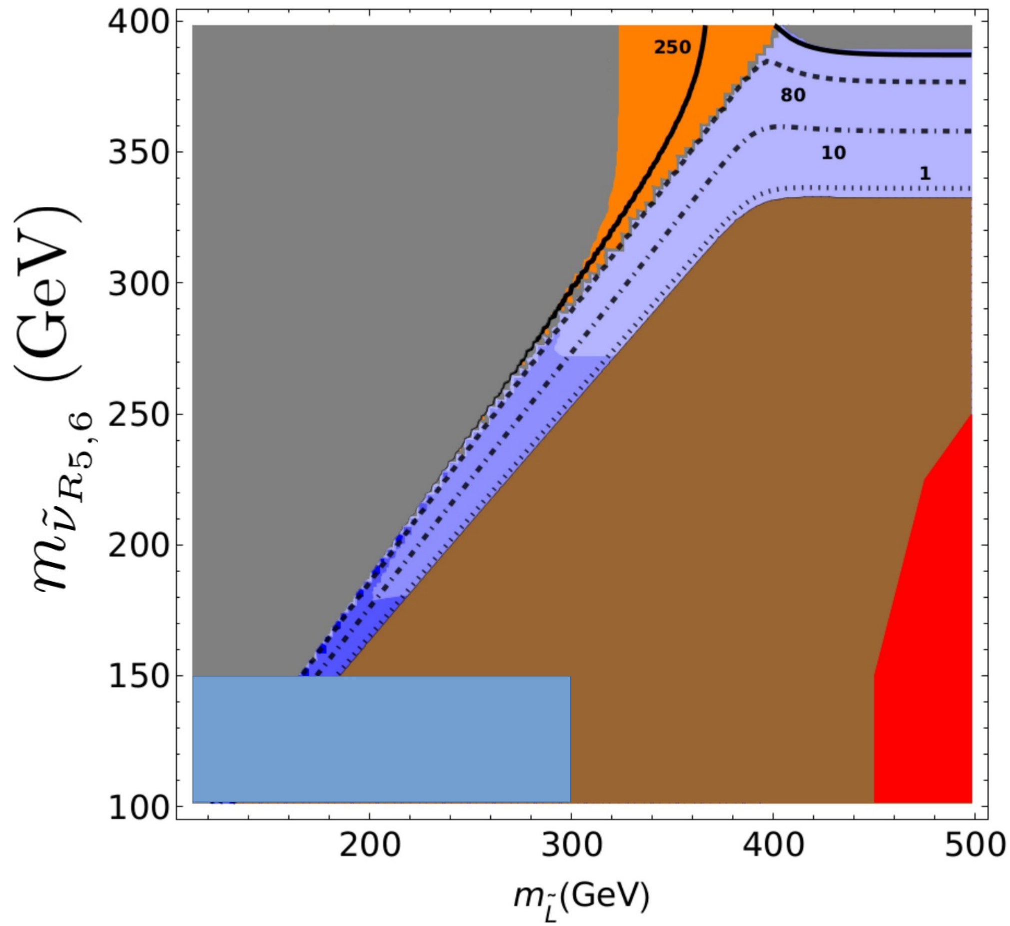
Adding **B** and **L** polarization for h-like



Scenario	DEG	Theory
$m_{\tilde{\ell}_1}$ (GeV)	290.51 ± 10.01	294.47
$m_{\tilde{\nu}_L}$ (GeV)	293.41 ± 2.15	293.37
$m_{\tilde{\nu}_R}$ (GeV)	100.05 ± 0.67	101.98

Non-thermal R-Sneutrino Dark Matter

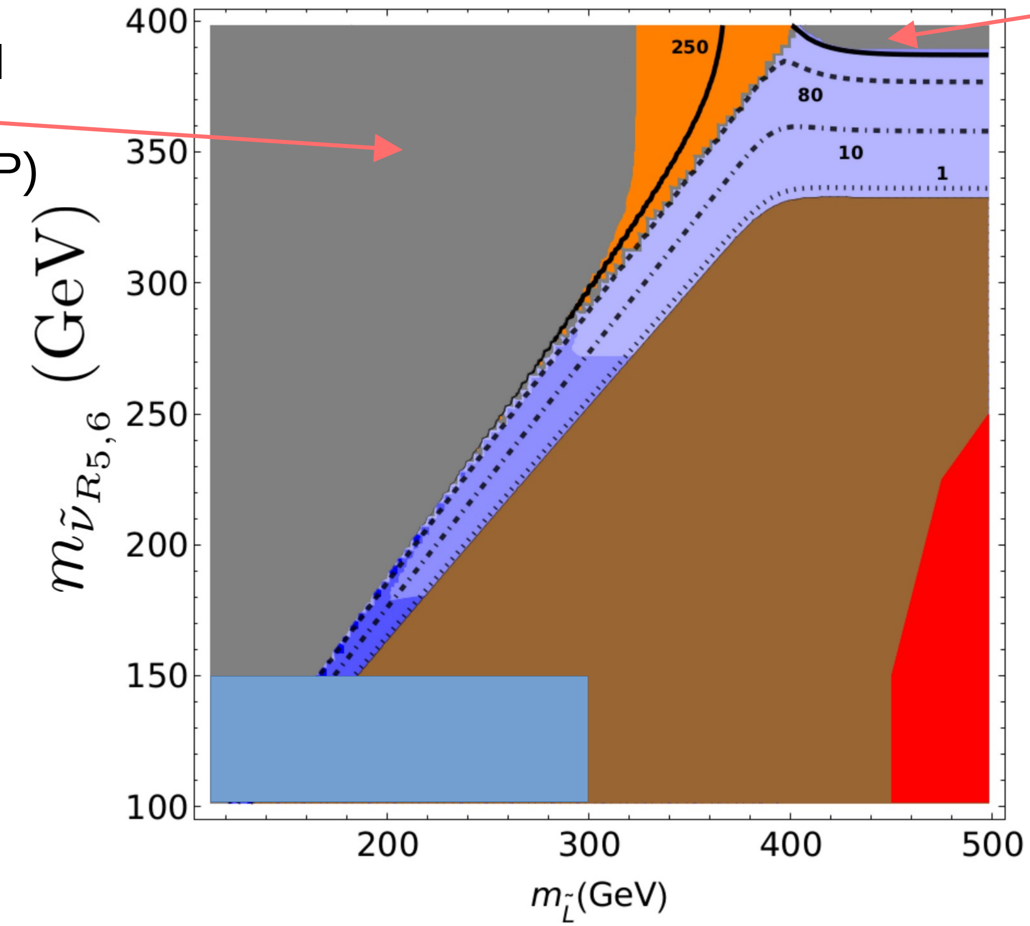
Maximum dark matter mass: 0.7 – 250 GeV



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)

SARAH, SPheno, micrOMEGAs

Non-thermal R-Sneutrino Dark Matter

Maximum dark matter mass: 0.7 – 250 GeV

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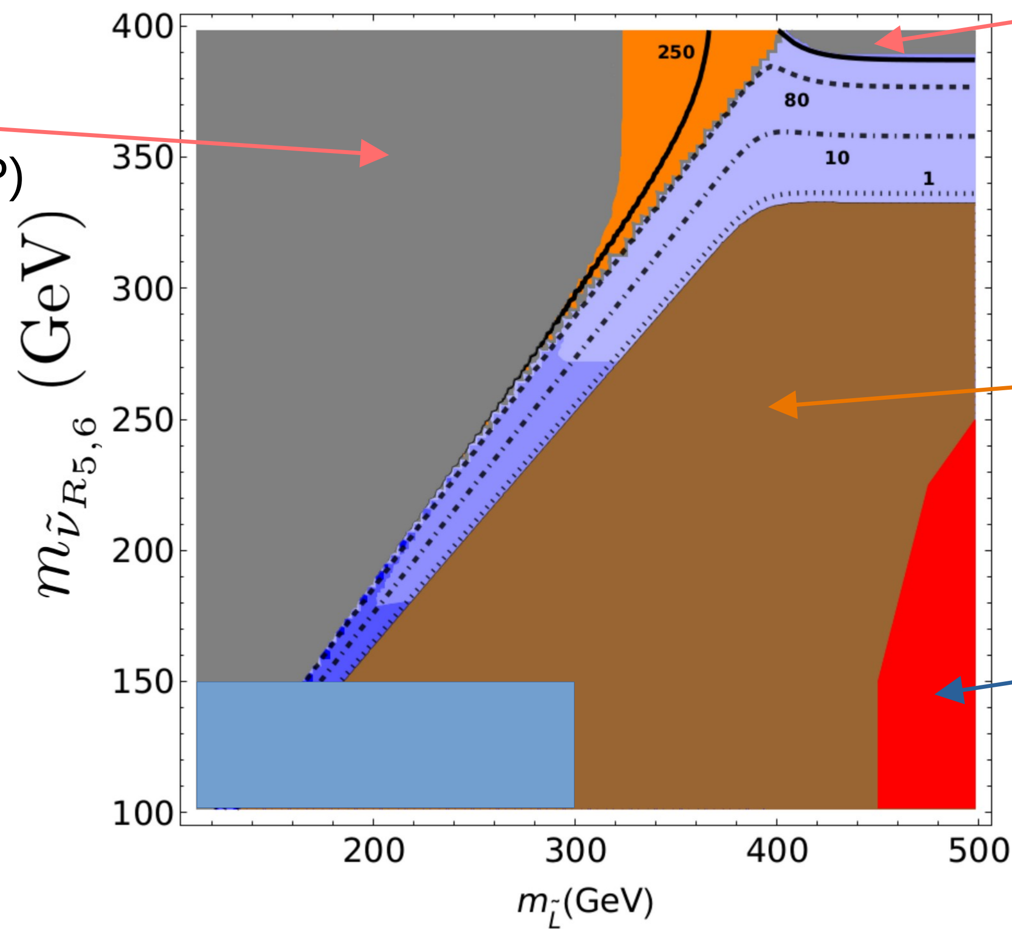

Too small thermal relic density (Higgsino NLSP)

Would require a negative soft mass

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

SARAH, SPheno, micrOMEGAs

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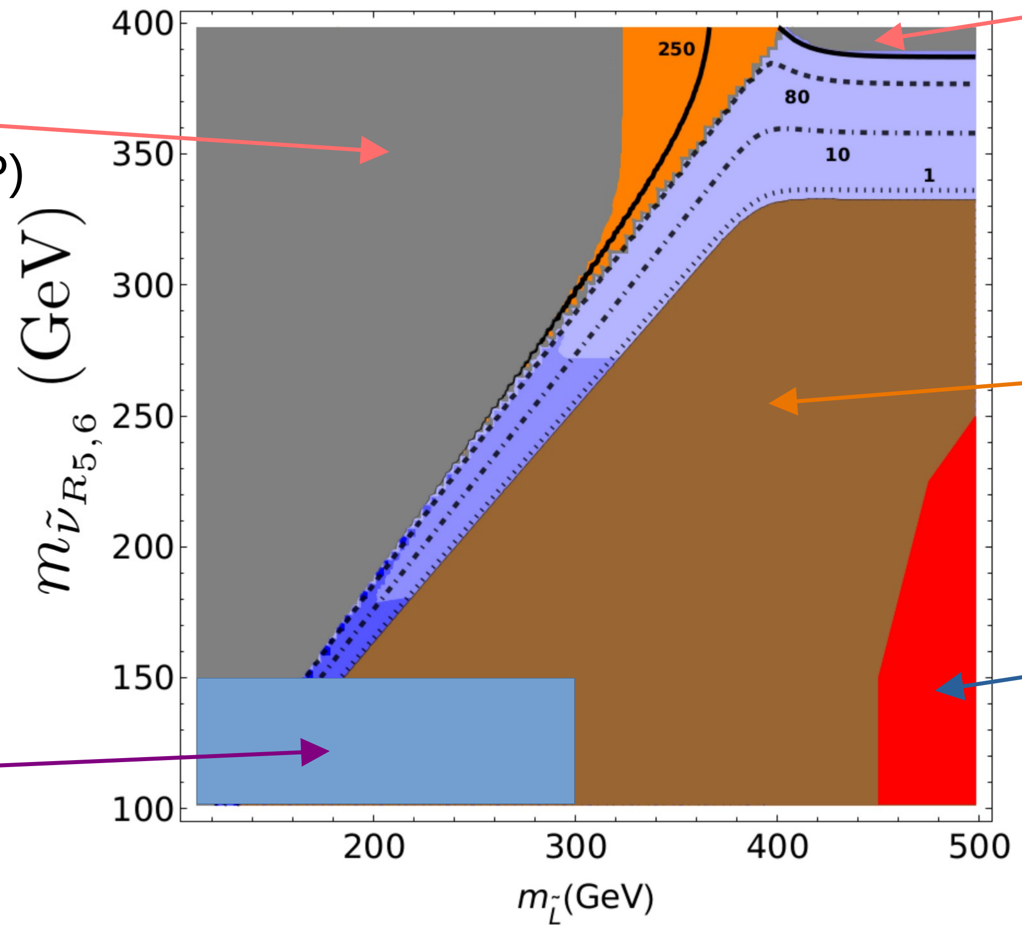


Would require a negative soft mass

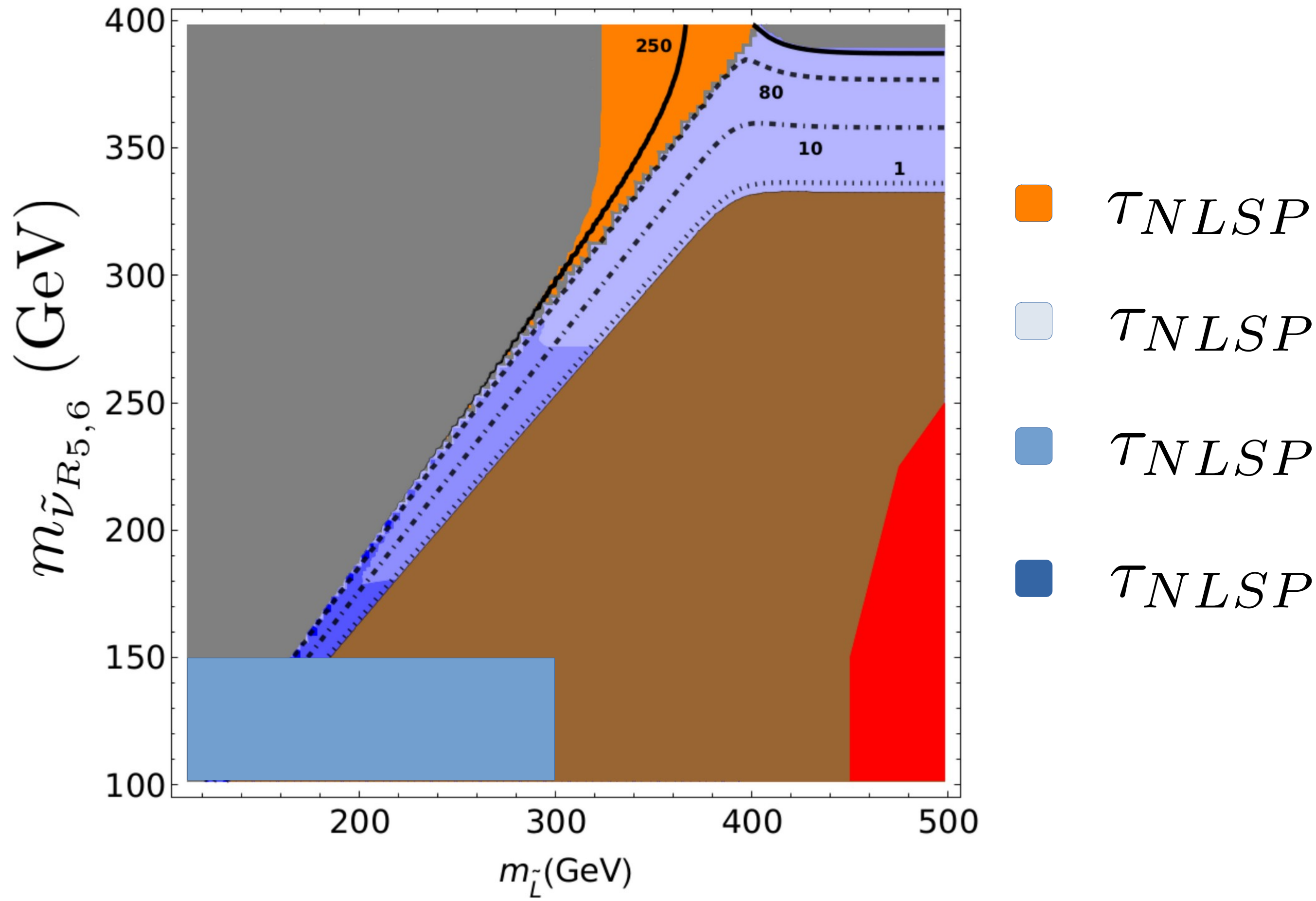
Ruled out by LHC (Higgsino lighter than L-slepton)

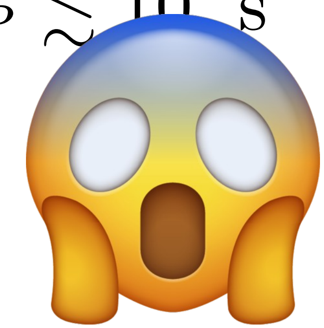
LHC @ 300 fb^{-1}

SARAH, SPheno, micrOMEGAs

Non-thermal R-Sneutrino Dark Matter

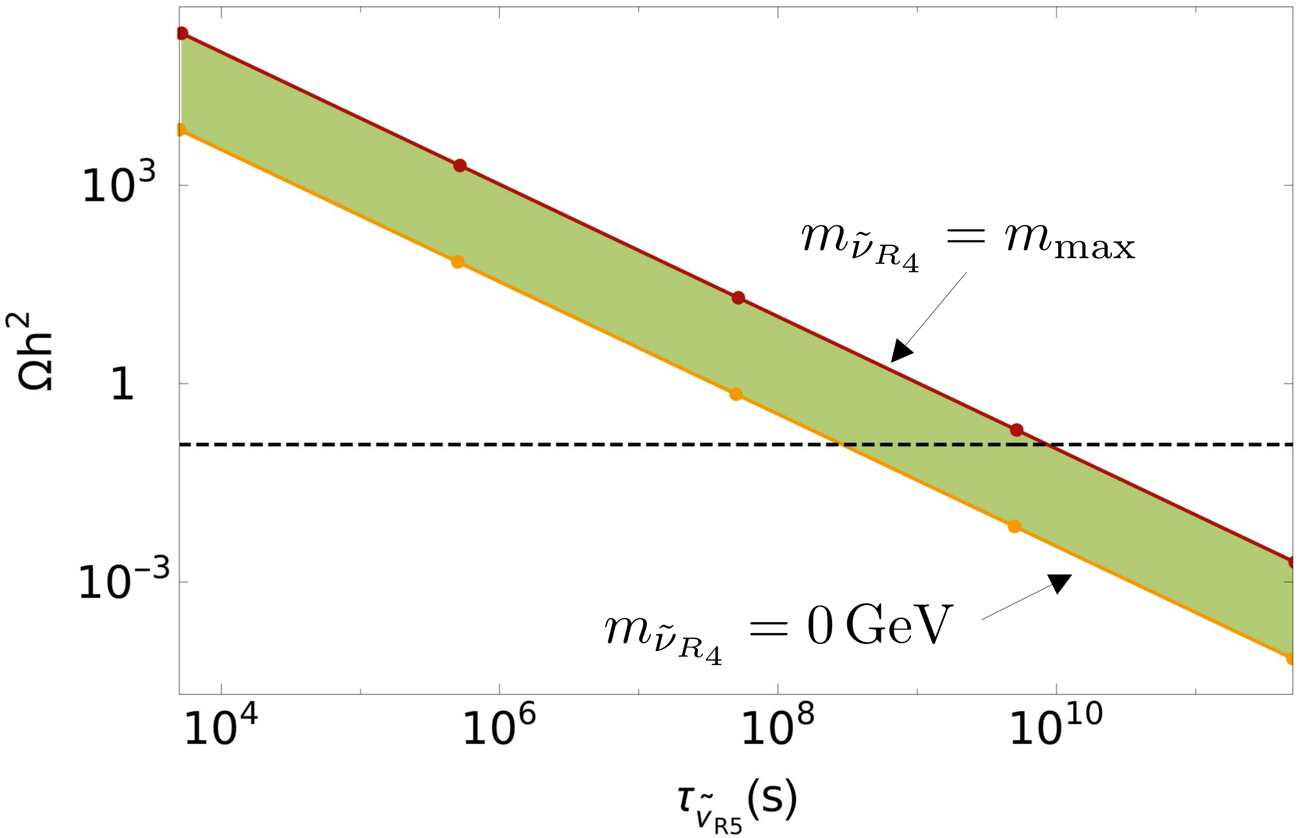
Maximum dark matter mass: 0.7 – 250 GeV





Non-thermal R-Sneutrino Dark Matter

Gets worse when adding annihilation in plasma:



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

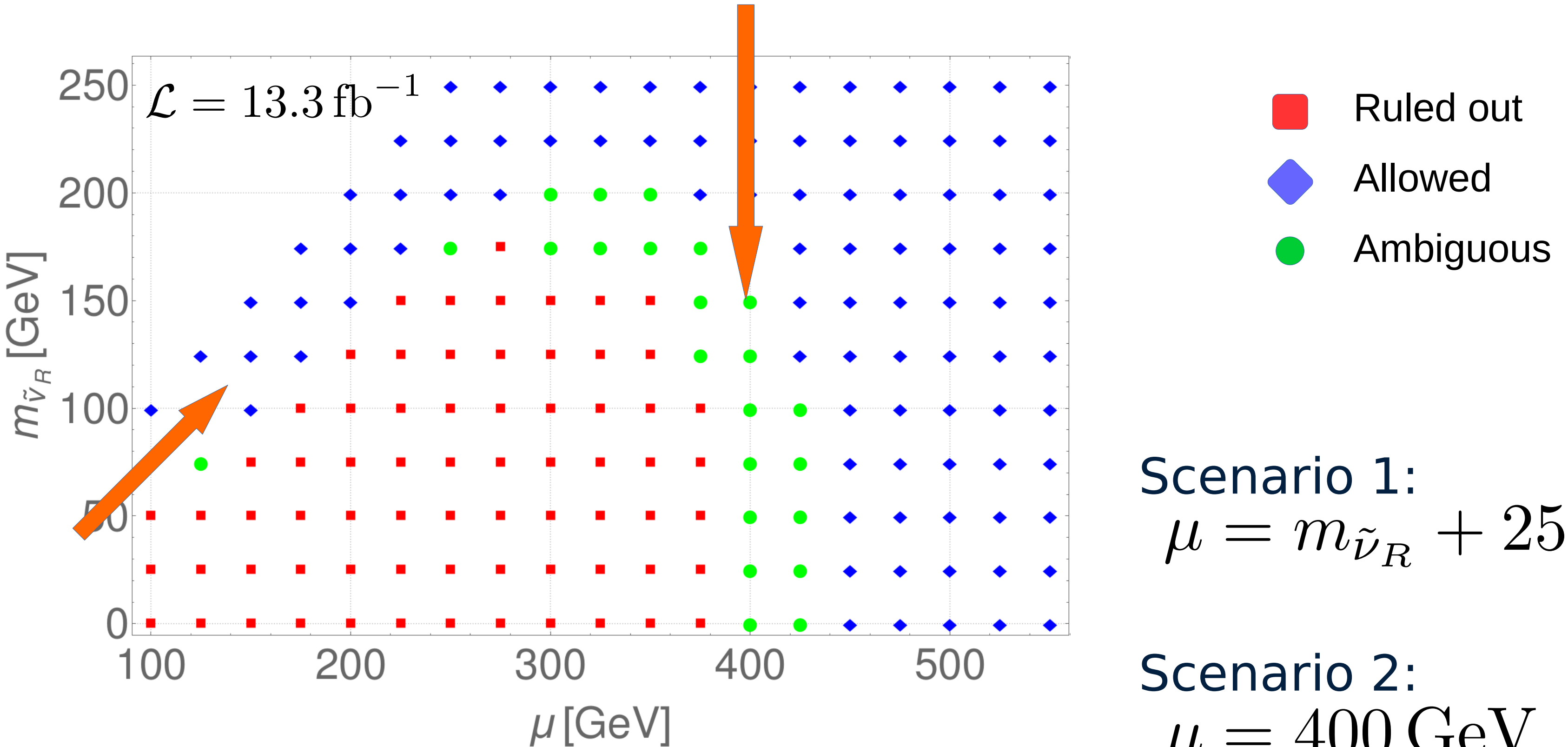
$$m_{\tilde{L}} = 323\,\mathrm{GeV}$$

$$m_{\tilde{\nu}_{R_{5,6}}} = 302\,\mathrm{GeV}$$

SARAH, SPheno, micrOMEGAs

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

Chargino production: $pp \to \tilde{\chi}^+\tilde{\chi}^- \to \ell^+\ell^-\tilde{\nu}_R\tilde{\nu}^*_R$



Scenario 1:
$$\mu = m_{\tilde{\nu}_R} + 25\,\mathrm{GeV}$$

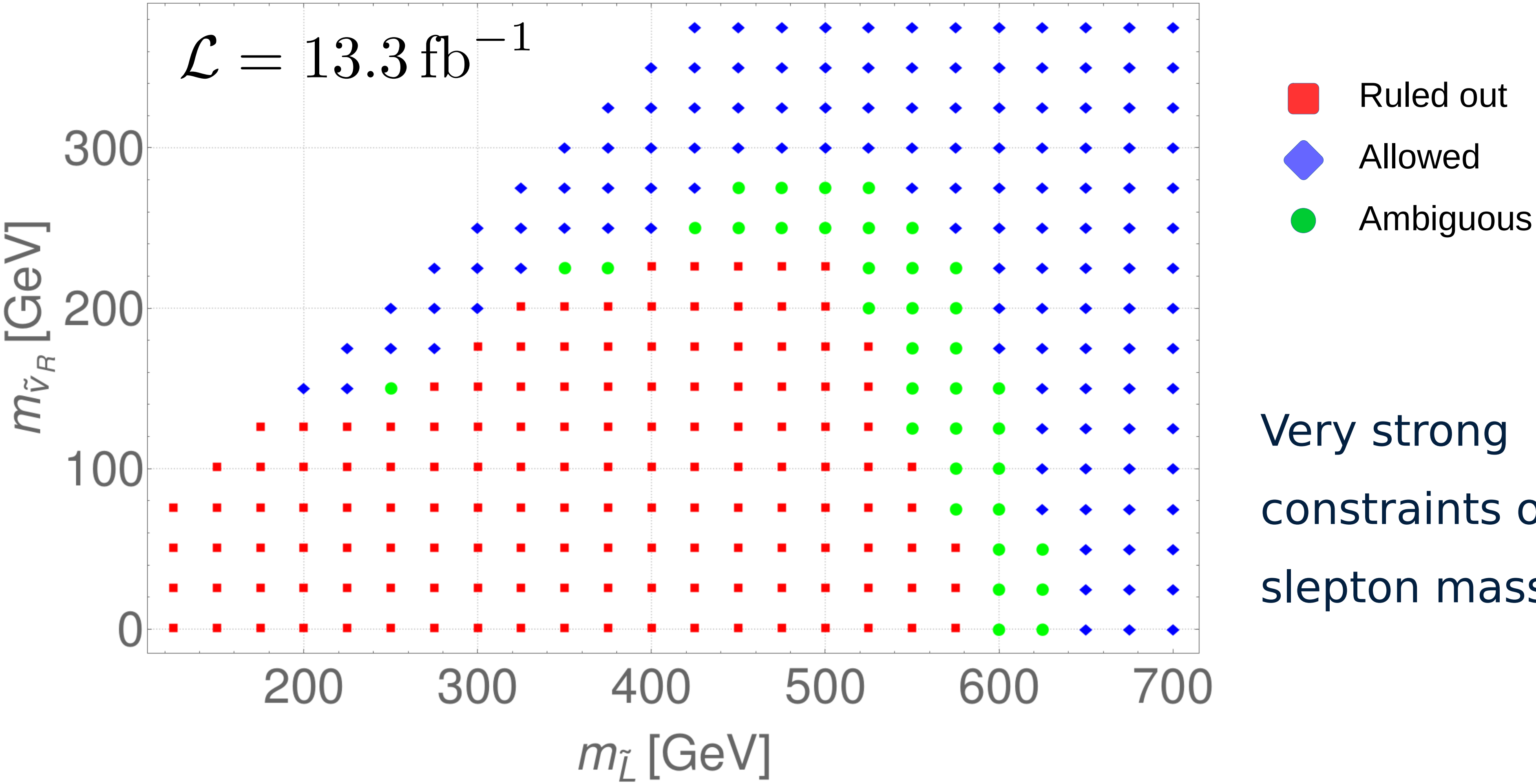
Scenario 2:
$$\mu = 400\,\mathrm{GeV}$$

ATLAS Collaboration (ATLAS-CONF-2016-096)
CheckMATE (1611.09856 [hep-ph])

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

Scenario 1

$$\mu = m_{\tilde{\nu}_R} + 25\,\mathrm{GeV}$$



Very strong constraints on slepton mass!

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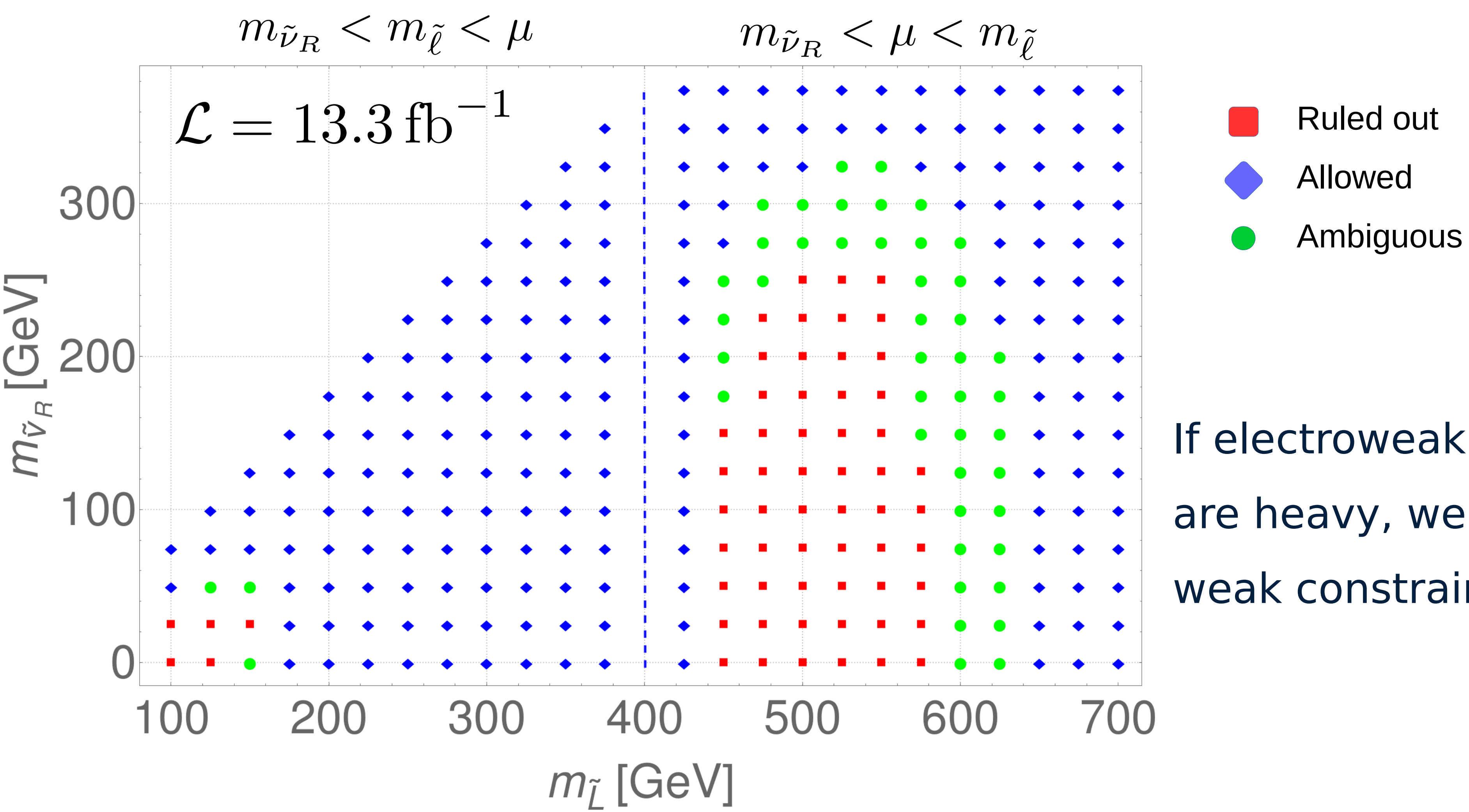
$\mu = 400\,\mathrm{GeV}$



If electroweakinos are heavy, we have weak constraint!

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