Resolving a challenging supersymmetric low-scale seesaw scenario at the ILC[1]

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Scenarios of Interest

We extend the content of the MSSM with 3 singlet superfields $\hat{\nu}_R$

$$\mathcal{W}_{\text{eff}} = \mathcal{W}_{\text{MSSM}} + \frac{1}{2}(M_R)_{ij}\,\hat{\nu}_{Ri}\,\hat{\nu}_{Rj} + (Y_\nu)_{ij}\,\widehat{L}_i \cdot \widehat{H}_u\,\hat{\nu}_{Rj}$$

This superpotential allows for soft SUSY-breaking terms:

$$\mathcal{V}^{soft} = \mathcal{V}^{soft}_{\text{MSSM}} + (m^2_{\tilde{\nu}_R})_{ij}\tilde{\nu}^*_{Ri}\tilde{\nu}_{Rj}$$

$$+ \left(\frac{1}{2}(B_{\tilde{\nu}})_{ij}\tilde{\nu}_{Ri}\tilde{\nu}_{Rj} + (T_\nu)_{ij}\,\tilde{L}_i \cdot H_u\,\tilde{\nu}_{Rj} + \text{h.c.} \right)$$

We assume $\mu < M_{1,2,3}$ such that the lightest neutralinos and charginos are higgsino-like.
$$B_{\tilde{\nu}} = T_\nu = 0$$

Scenarios of Interest

We fix $\mu = 500 \text{ GeV}$, $\tan\beta = 6$, $m_{\tilde{\nu}_R} \in [0, 350] \text{ GeV}$ and assume $m_{\tilde{L}} = m_{\tilde{E}} \in [100, 500] \text{ GeV}$, such that $m_{\tilde{\nu}_R} < m_{\tilde{L}} < \mu$.
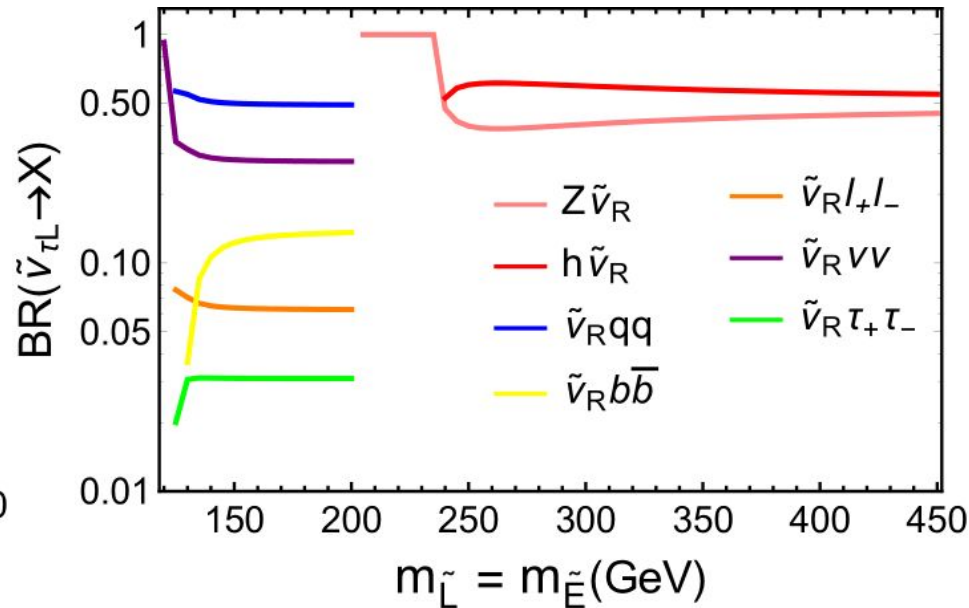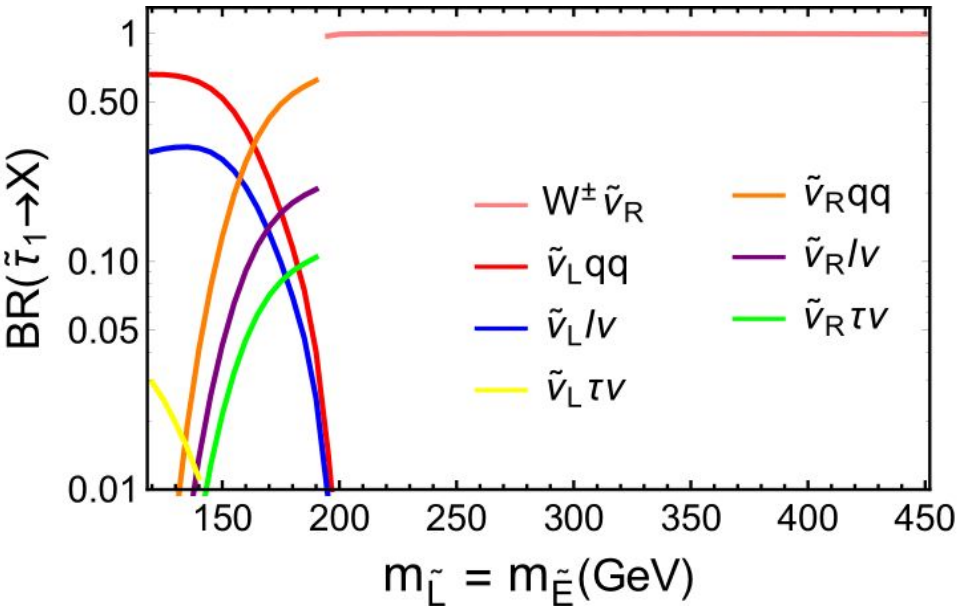
Decay modes for leptons of first and second generations:

$$\tilde{\ell} \rightarrow \tilde{\nu}_L \, W^* \sim 90\%$$

$$\tilde{\ell} \rightarrow \tilde{\nu}_R \, W \sim 10\%$$

Scenarios of Interest

Branching Ratios for the lightest Stau and L-Sneutrinos

Scenarios of Interest

In the following we consider 3 scenarios:

- Scenario SE, the only light MSSM sleptons are $\tilde{e}_L$, $\tilde{e}_R$ and $\tilde{\nu}_{eL}$.

- Scenario ST, $\tilde{\tau}_1$, $\tilde{\tau}_2$ and $\tilde{\nu}_{\tau L}$ are the light MSSM sleptons.

- Scenario DEG, we consider the situation where all MSSM sleptons share the same soft masses

ILC $\sqrt{s} = 1$ TeV run, with electron(positron) polarization set to 80%(20%).

Sensitivity at ILC

We use the following cuts[2]:

- $p_T^{\mathrm{miss}} > 50$ GeV

- Exactly 4 jets or b-jets with $p_T > 20$ GeV

- Two reconstructed SM bosons such that their invariant masses satisfy:
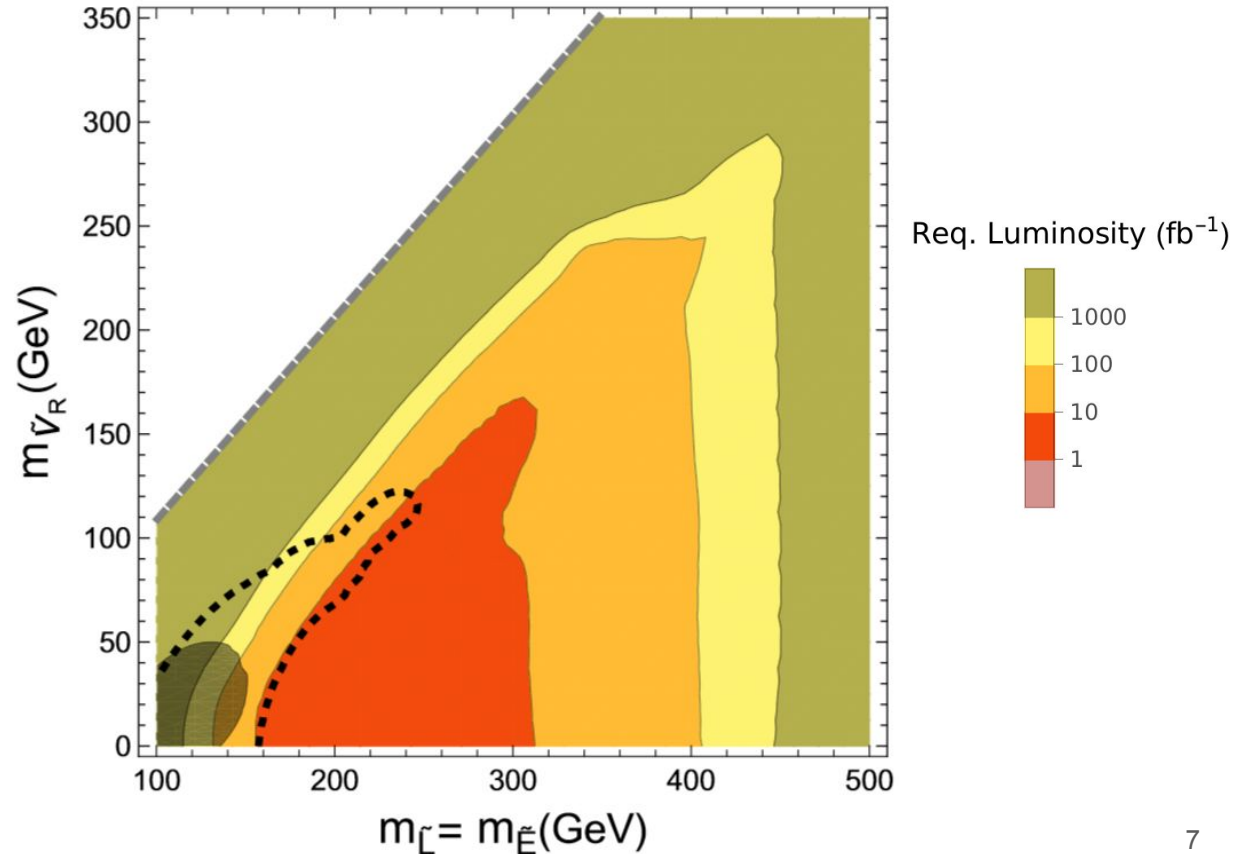
$$\frac{(m_1 - m_{B1})^2 + (m_2 - m_{B2})^2}{\sigma^2} < 4 \qquad \sigma = 5$$

- No leptons with $p_T > 25$ GeV

- The angle between the missing momentum and the beam line must satisfy $\left| \cos(\theta_{\mathrm{miss}}) \right| < 0.99$.
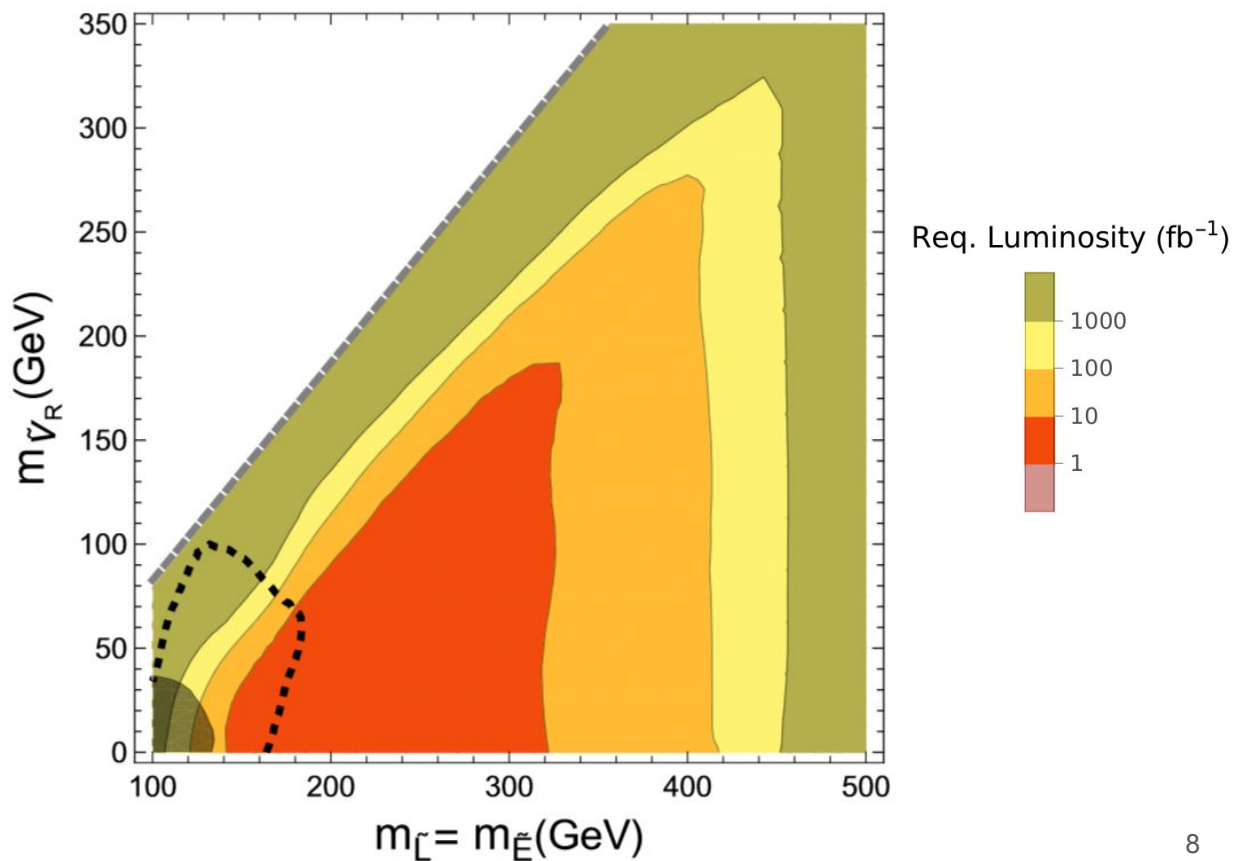
[2] Suehara, List, Chargino and Neutralino Separation with the ILD Experiment

Sensitivity at ILC

Required Luminosity for a sensitivity of $\sigma = 5$

Scenario SE

Required Luminosity for a
sensitivity of $\sigma = 5$

Scenario ST
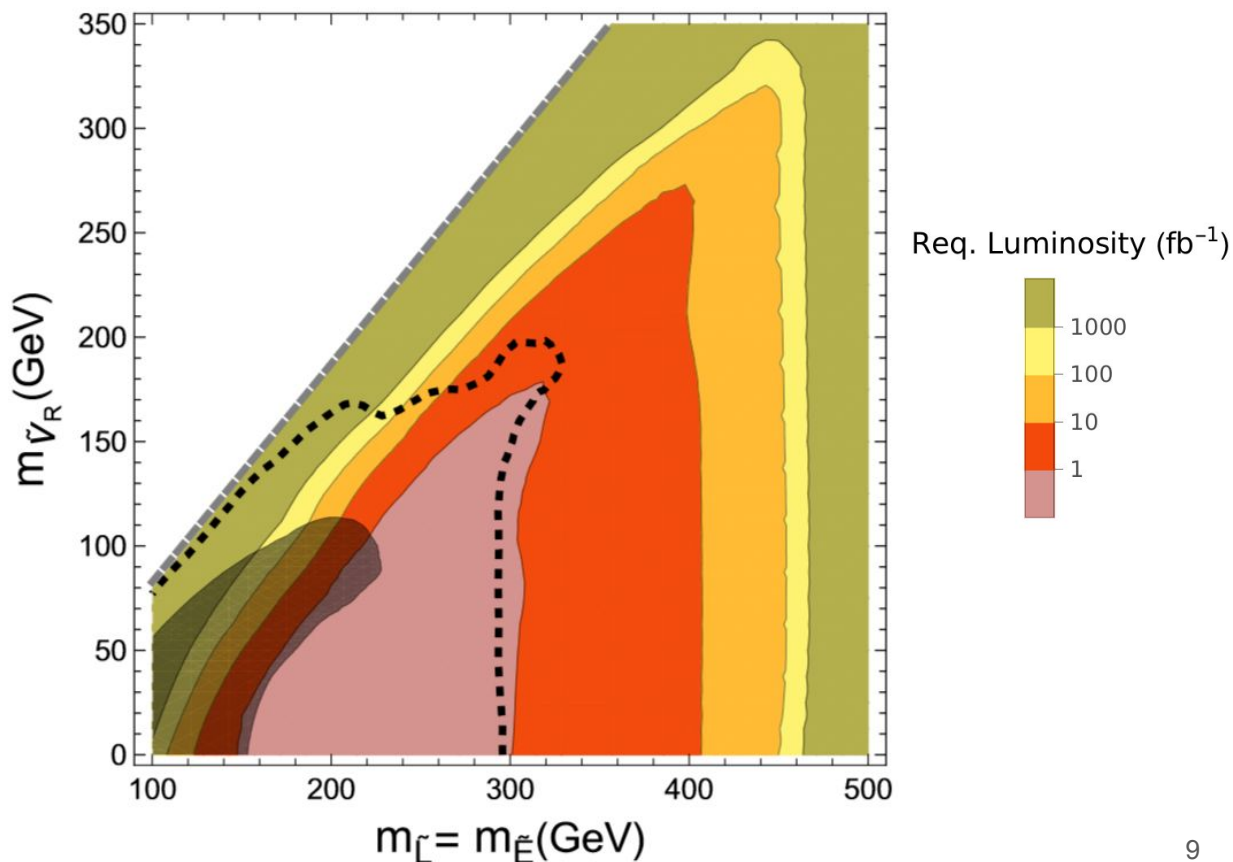

Req. Luminosity (fb^{-1})

Sensitivity at ILC

Required Luminosity for a sensitivity of $\sigma = 5$

Scenario DEG

Mass reconstruction

In case of an observation we would be interested in extracting as much information as possible from the newly observed particles.

We aim to evaluate the mass reconstruction via endpoints for our three scenarios.

We neglect possible effects due to ISR and Beamstrahlung, and assume E_{beam} = 500 GeV for 1000 fb^{-1}.

$$m_{\tilde{\nu}_R} = 100 \text{ GeV} \qquad\qquad m_{\tilde{L}} = 300 \text{ GeV}$$

Mass reconstruction

We can solve for $m_{\tilde{\ell}}$ and $m_{\tilde{\nu}_R}$

$$\tilde{\ell} \to \tilde{\nu}_R \; B$$

$$m_{\tilde{\ell}} = \frac{2E_{\text{beam}}}{E_{B+} + E_{B-}} E'_B \qquad m_{\tilde{\nu}_R} = \sqrt{m_{\tilde{\ell}}^2 + m_B^2 - 2E'_B m_{\tilde{\ell}}}$$

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

We obtain 2 possible values consistent with the measurement, so we need at least 2 datasets in order the fix the correct sign of E'_B .

Mass reconstruction

We apply the same cuts as before with a stricter condition for the SM boson reconstruction, we now require the bosons to be equal (WW, ZZ, hh).

Events fall in three datasets, W-like, Z-like and Higgs-like.

$$\tilde{\tau}_1 \tilde{\tau}_1 \to \text{W-like} \to jjjj \text{ (excluding b-jets)}$$

$$\tilde{\nu}_L \tilde{\nu}_L \to \text{Z/Higgs-like} \to jjjj/bbbb$$

$$\tilde{\ell}\tilde{\ell} \to \tilde{\nu}_L \tilde{\nu}_L \to \text{Z/Higgs-like}$$

Mass reconstruction

1. We take the MC events corresponding to the SM background, and use them to fit the six parameters of the following distribution:

$$f_{SM}(E;\, E_{\text{SM}-},\, a_{0-2},\, \sigma_{\text{SM}},\, \Gamma_{\text{SM}}) = \int_{E_{\text{SM}-}}^{\infty} \left(a_2 E'^2 + a_1 E' + a_0\right) V(E' - E, \sigma_{\text{SM}}, \Gamma_{\text{SM}})\, dE'$$

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2. Using the fitted parameters, we generate one hundred new datasets of SM background following the f_{SM} distribution.

3. For each SM dataset, we fit the sum of the SUSY and SM spectra into a new distribution which allows us to find the desired endpoints:

$$\begin{aligned} f(E;\,E_{B-},\,E_{B+},\,b_{0-2},\,\sigma_1,\,\Gamma_1) \;&=\; f_{SM}(E;\,E_{\text{SM}-},\,a_{0-2},\,\sigma_{\text{SM}},\,\Gamma_{\text{SM}}) \\ &\quad + \int_{E_{B-}}^{E_{B+}} (b_2 E'^2 + b_1 E' + b_0) V(E' - E, \sigma_1, \Gamma_1) dE' \end{aligned}$$
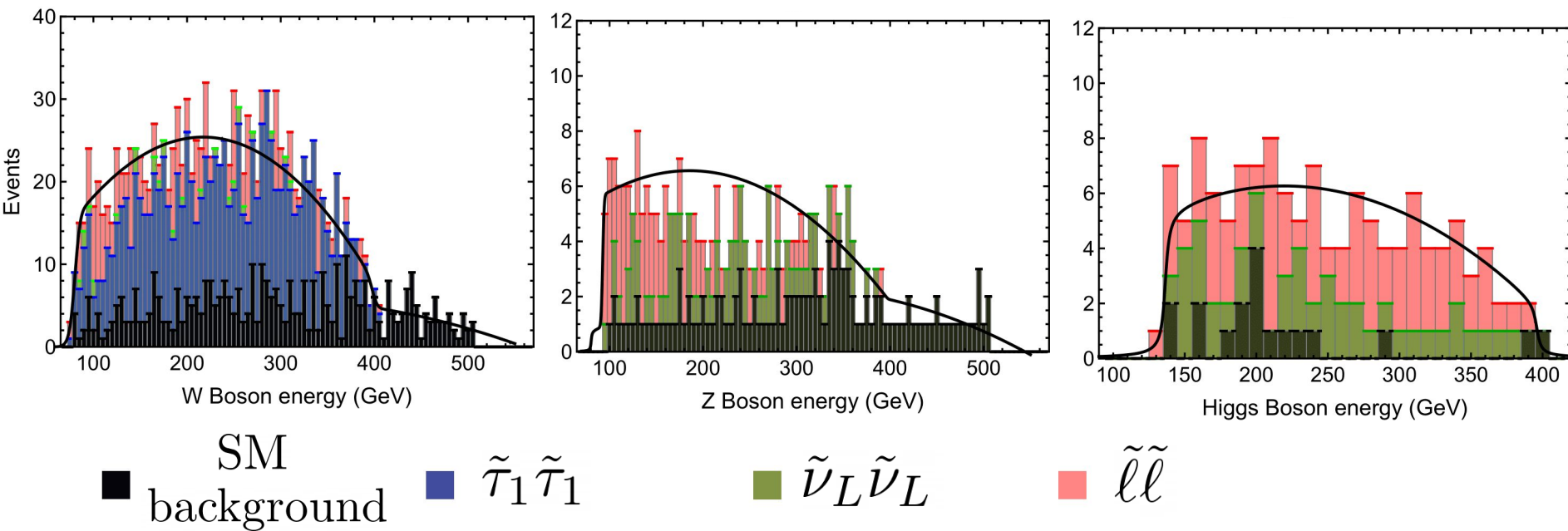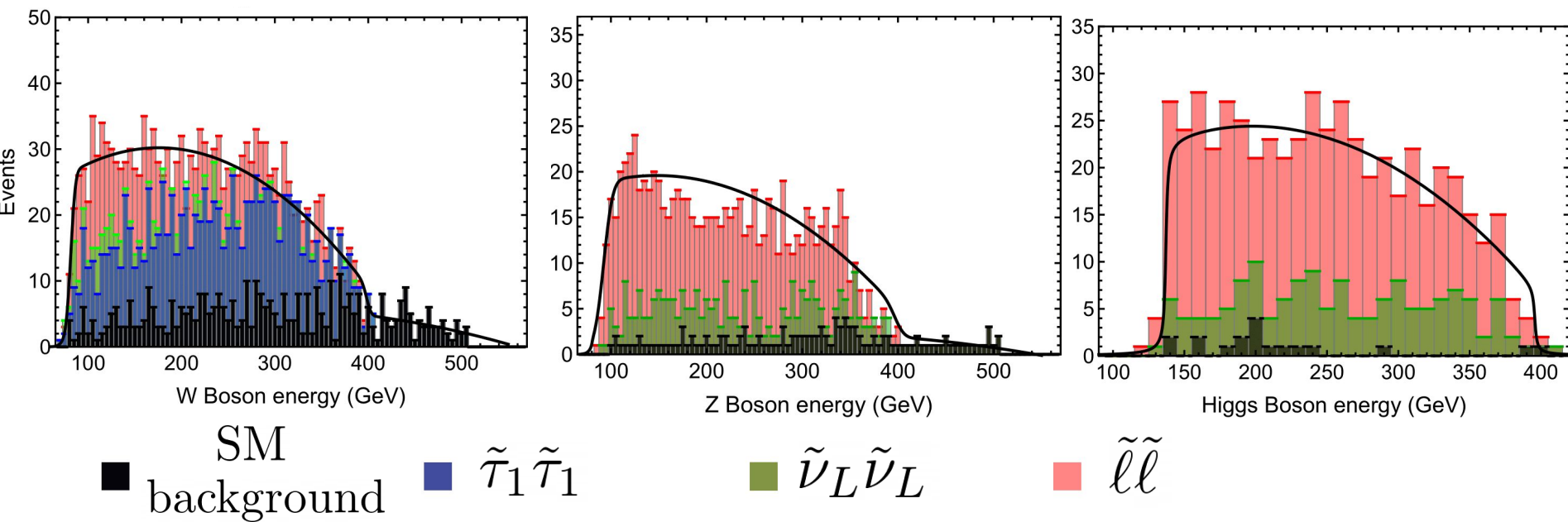
Mass reconstruction

Scenario SE
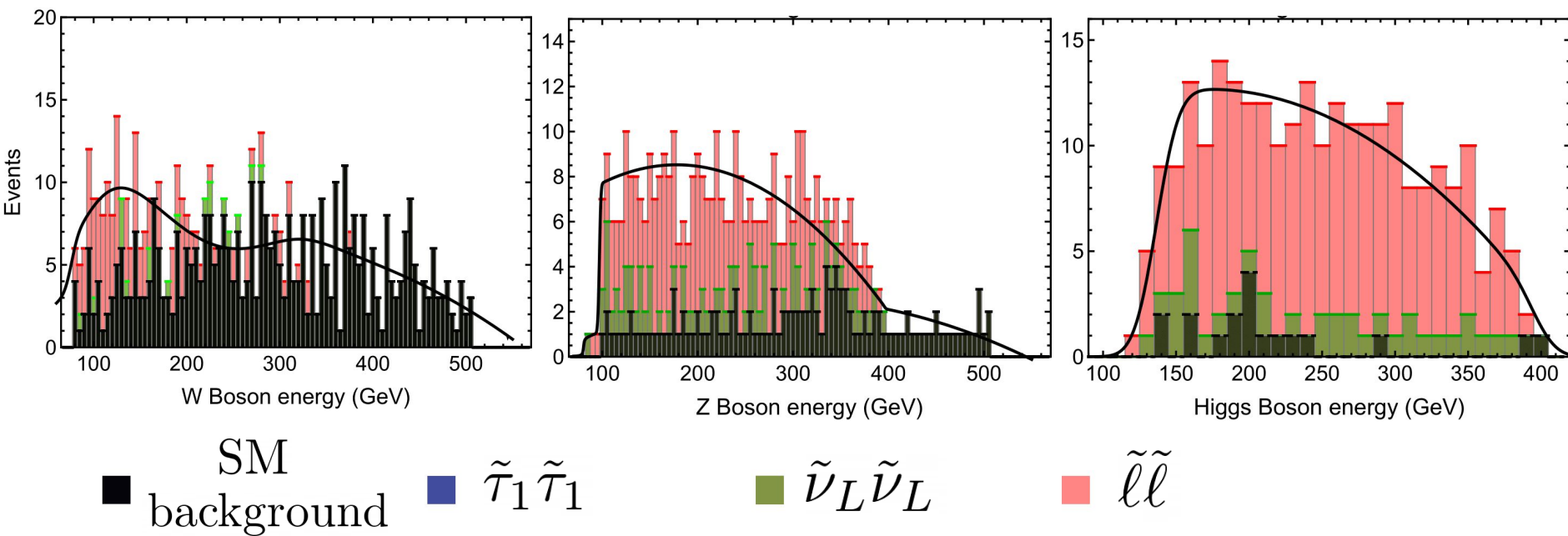
Mass reconstruction

Scenario ST

Mass reconstruction

Scenario DEG

Mass reconstruction

Using this method we find the following endpoints for our scenarios:

Endpoint	SE	ST	DEG	Theory
E_{W-} (GeV)	95.24 ± 3.77	80.49 ± 0.43	81.52 ± 0.64	80.88 / 80.41
E_{W+} (GeV)	347.38 ± 18.35	398.11 ± 1.11	398.59 ± 1.15	399.81 / 399.09
E_{Z-} (GeV)	91.90 ± 0.40	92.66 ± 0.65	92.38 ± 0.84	91.66
E_{Z+} (GeV)	397.52 ± 1.79	397.85 ± 1.82	397.92 ± 1.75	398.53
E_{h-} (GeV)	136.89 ± 1.45	137.05 ± 1.69	137.05 ± 1.01	137.25
E_{h+} (GeV)	396.09 ± 1.18	396.00 ± 1.29	395.70 ± 0.61	395.65

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Mass reconstruction

Final results

Scenario	SE	ST	DEG	Theory
$m_{\tilde{\ell}_1}$ (GeV)	-	296.91 ± 10.69	290.51 ± 10.01	294.47
$m_{\tilde{\nu}_L}$ (GeV)	293.63 ± 3.12	293.32 ± 3.61	293.41 ± 2.15	293.37
$m_{\tilde{\nu}_R}$ (GeV)	100.52 ± 1.65	101.14 ± 1.36	100.05 ± 0.67	100.00

Conclusions

For a $\sqrt{s} = 1\,\mathrm{TeV}$ run at the ILC, provided that $m_{\tilde{l}} - m_B - m_{\tilde{\nu}_R} \sim 60\ \mathrm{GeV}$, a discovery is expected for $m_{\tilde{L}} \in [100, 450]\,\mathrm{GeV}$

Using an endpoint method, the masses of such scenario can be reconstructed, given that they do not lay far from the benchmark used

Backup slides

Motivation

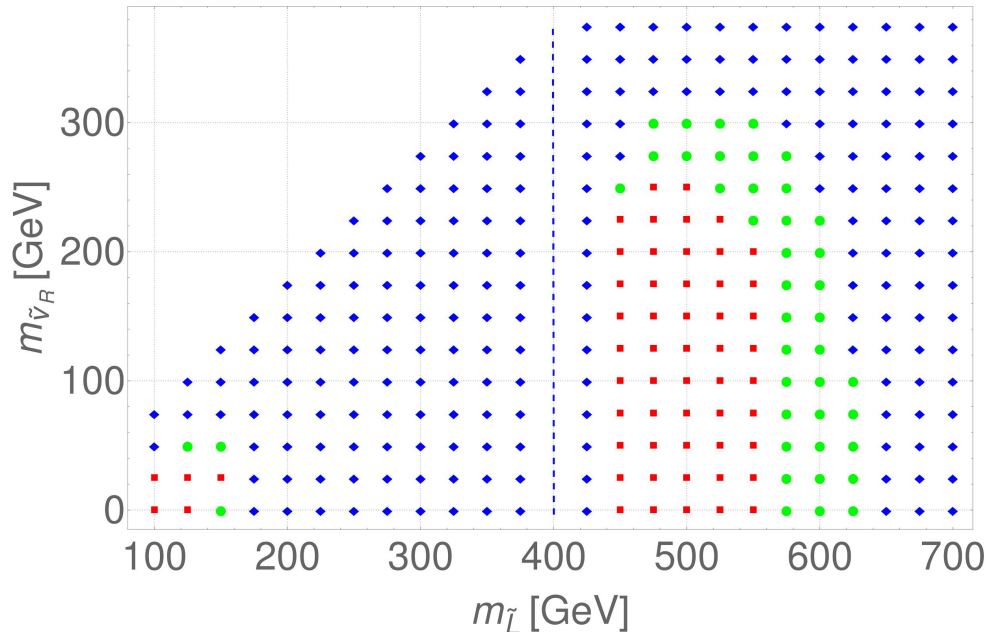Two of the most important unanswered questions faced by the SM, are:
- The generation of neutrino masses

- The hierarchy problem

We present a Super Symmetric Seesaw model capable of tackling both problems

Scenarios of Interest

In a past publication[1], it was shown that for this mass hierarchy one can not exclude SUSY at the LHC

[1] Cerna-Velazco, et al., Constraining sleptons at the LHC in a supersymmetric low-scale seesaw scenario

Update to Slepton Searches at the LHC

At the LHC the most important slepton production processes are:

$$p\,p \to \tilde{\tau}_{1,2}\, \tilde{\nu}_\tau \qquad\qquad p\,p \to \tilde{\ell}_L\, \tilde{\nu}_L$$
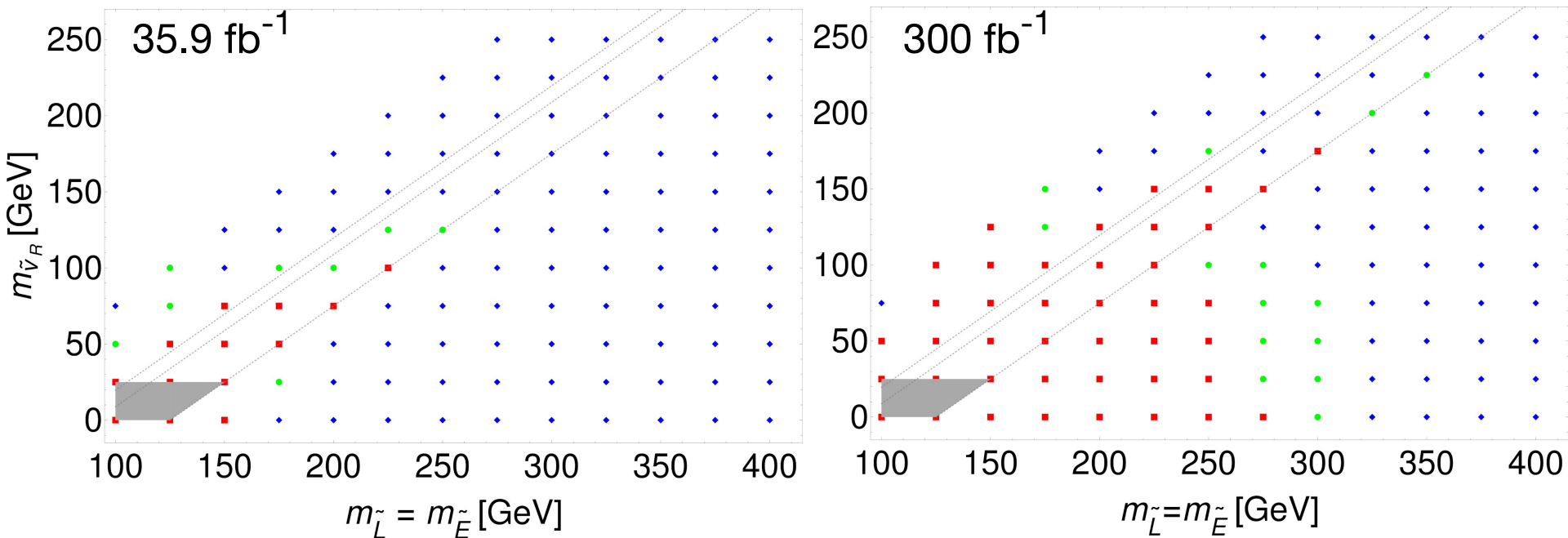
So we are interested in final states:

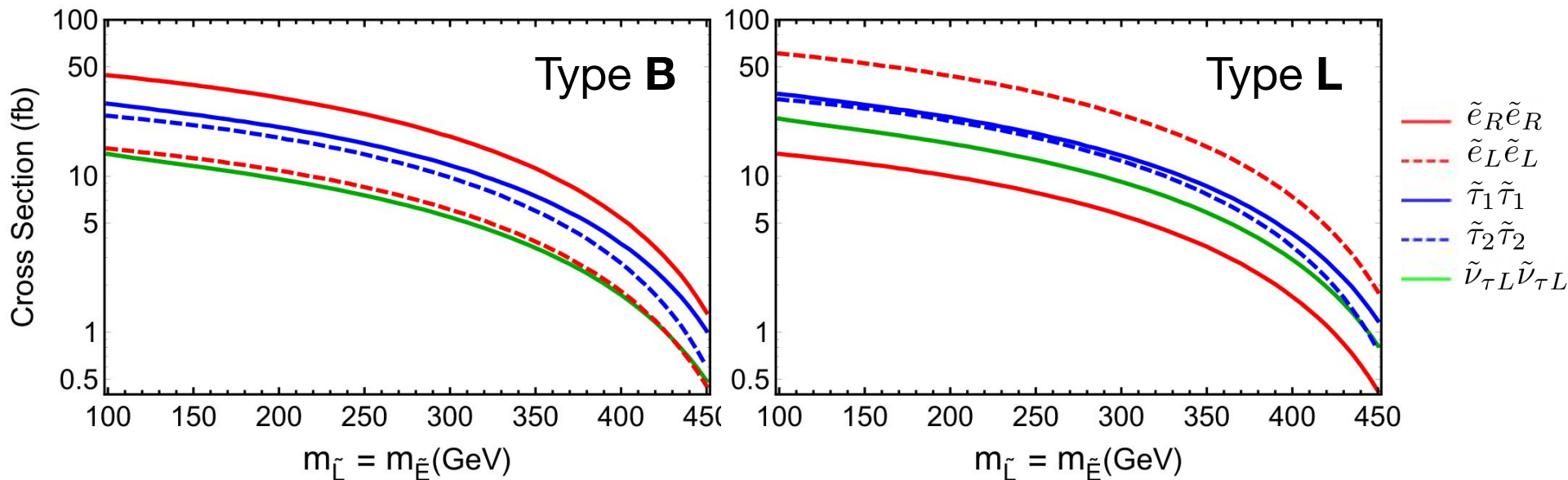$$W^{(*)} + (Z/h)^{(*)} + p_T^{\mathrm{miss}} \qquad 2(Z/h)^{(*)} + p_T^{\mathrm{miss}} + \text{soft fermions}$$

Update to Slepton Searches at the LHC

Currently excluded points and expectations for scenario DEG

We show cross section for our channels of interest in both polarizations:

Scenarios of Interest

We take two heavy neutrinos with masses of 20 GeV, and a much lighter third.

We can enhance the naive Seesaw expectation for the Yukawas:

$$(Y_\nu)_{a4} \;=\; (U_{\mathrm{PMNS}})^*_{a1} \sqrt{\frac{2m_1 M_4}{v_u^2}} \qquad (Y_\nu)_{a5} \;=\; i\, z_{56}\, Z^*_a \sqrt{\frac{2m_3 M_5}{v_u^2}} \cosh\gamma_{56}\, e^{-i\, z_{56}\, \rho_{56}}$$

$$(Y_\nu)_{a6} \;=\; -Z^*_a \sqrt{\frac{2m_3 M_6}{v_u^2}} \cosh\gamma_{56}\, e^{-i\, z_{56}\, \rho_{56}}$$

The parameter γ_{56} is responsible for enhancing the Yukawas, we take $\gamma_{56} = 8$ such that $|Y_{a5}| = |Y_{a6}| \sim \mathcal{O}(10^{-4})$

Scenarios of Interest

We fix $\mu = 500 \text{ GeV}, \ \tan\beta = 6, \ m_{\tilde{\nu}_R} = 100 \text{ GeV}$, and assume $m_{\tilde{L}} = m_{\tilde{E}}$, such that $m_{\tilde{\ell}} > m_{\tilde{\nu}_L} > m_{\tilde{\nu}_R}$.

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

$$(m_{\tilde{\tau}_1} - m_{\tilde{\ell}})_{LR} \sim -\frac{m_\tau \, \mu \tan\beta}{2m_{\tilde{L}}}$$

For our benchmark $m_{\tilde{L}} = m_{\tilde{E}} = 300 \text{ GeV}$, we find
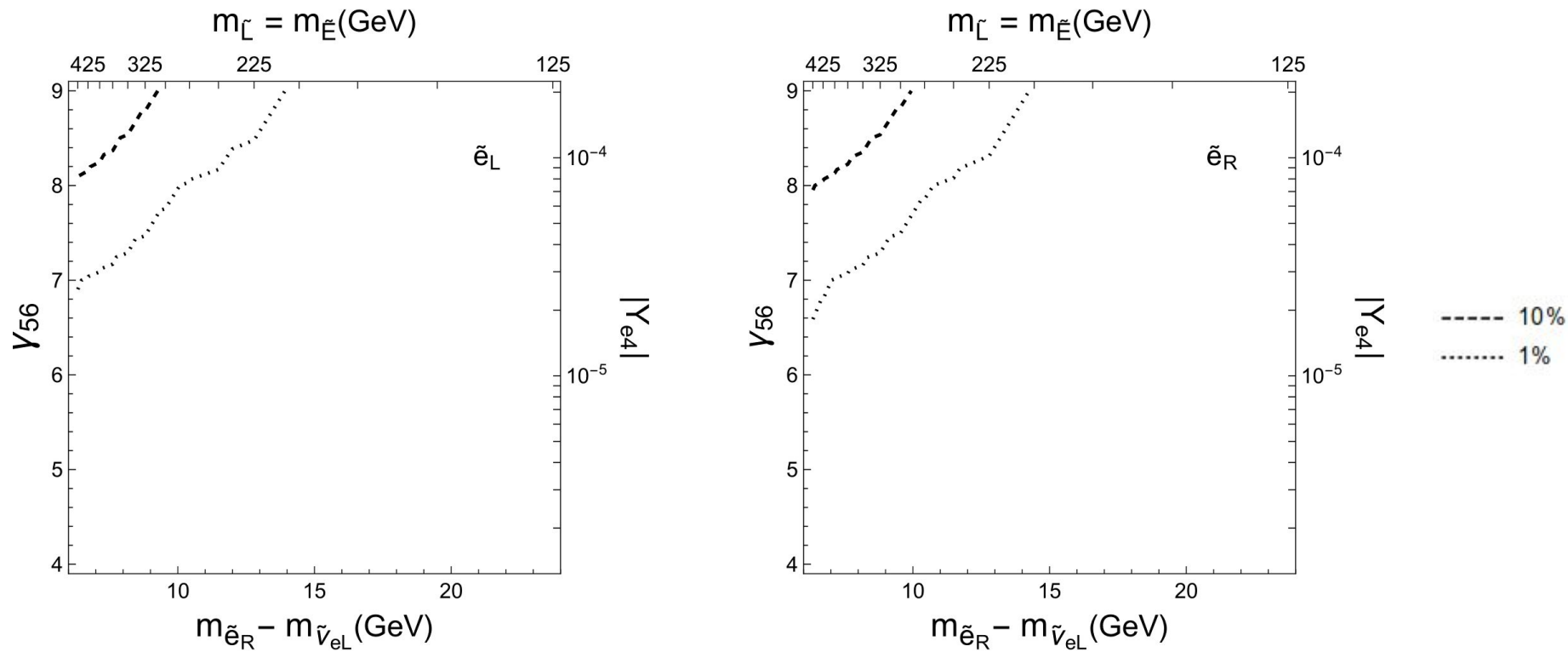
$$(m_{\tilde{\ell}_R} - m_{\tilde{\nu}_L}) \approx 9 \text{ GeV}$$

$$(m_{\tilde{\ell}_L} - m_{\tilde{\nu}_L}) \approx 10 \text{ GeV}$$

$$(m_{\tilde{\tau}_1} - m_{\tilde{\ell}}) \approx 1 \text{ GeV}$$
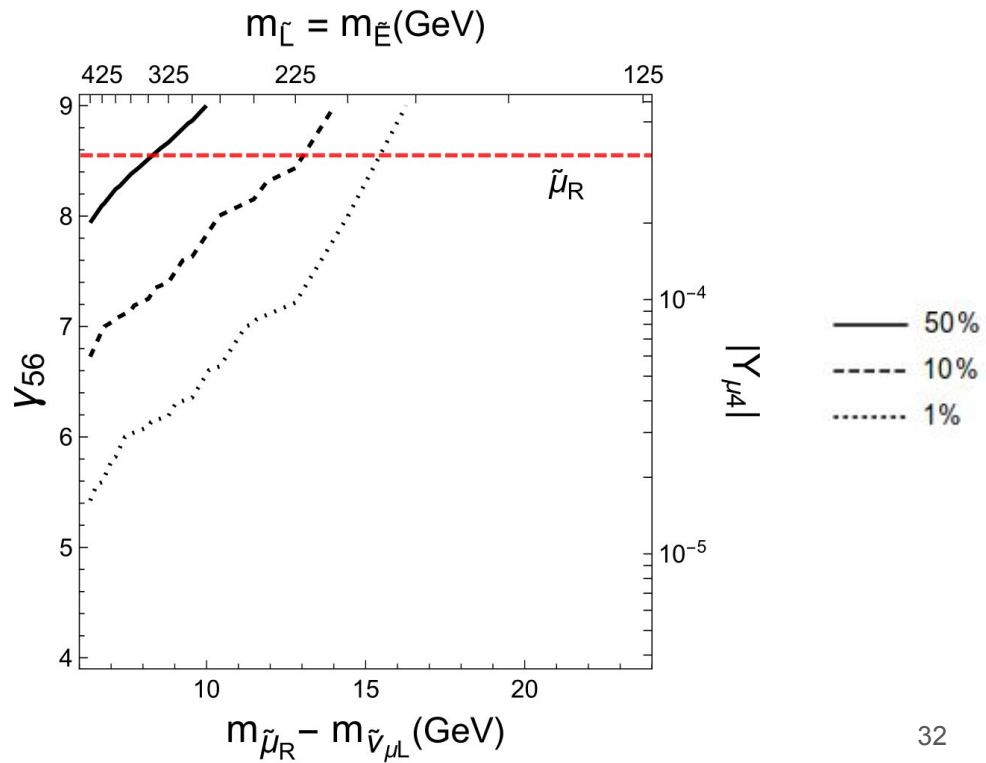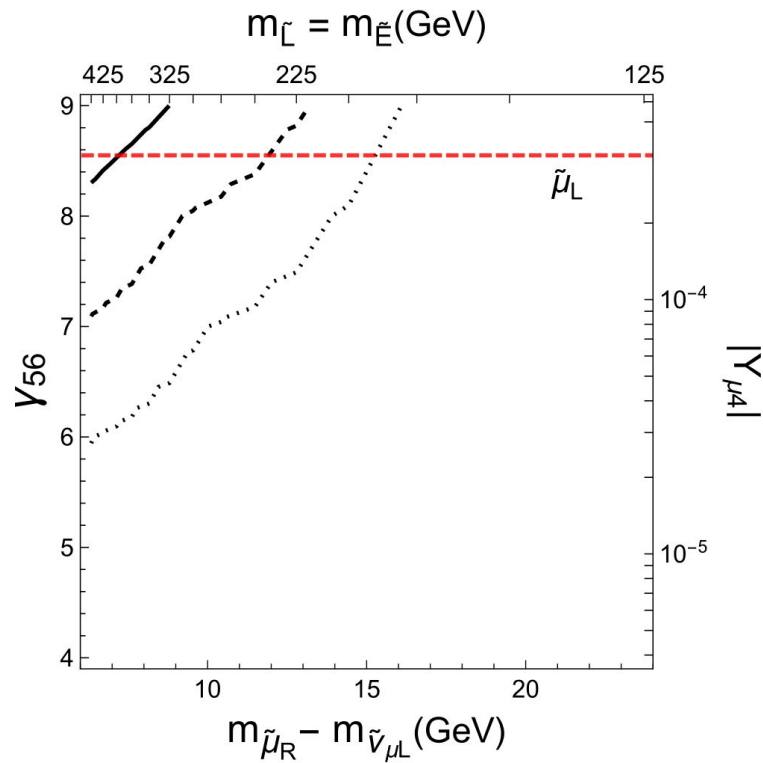
Scenarios of Interest

On-shell Branching Ratio for Selectrons.

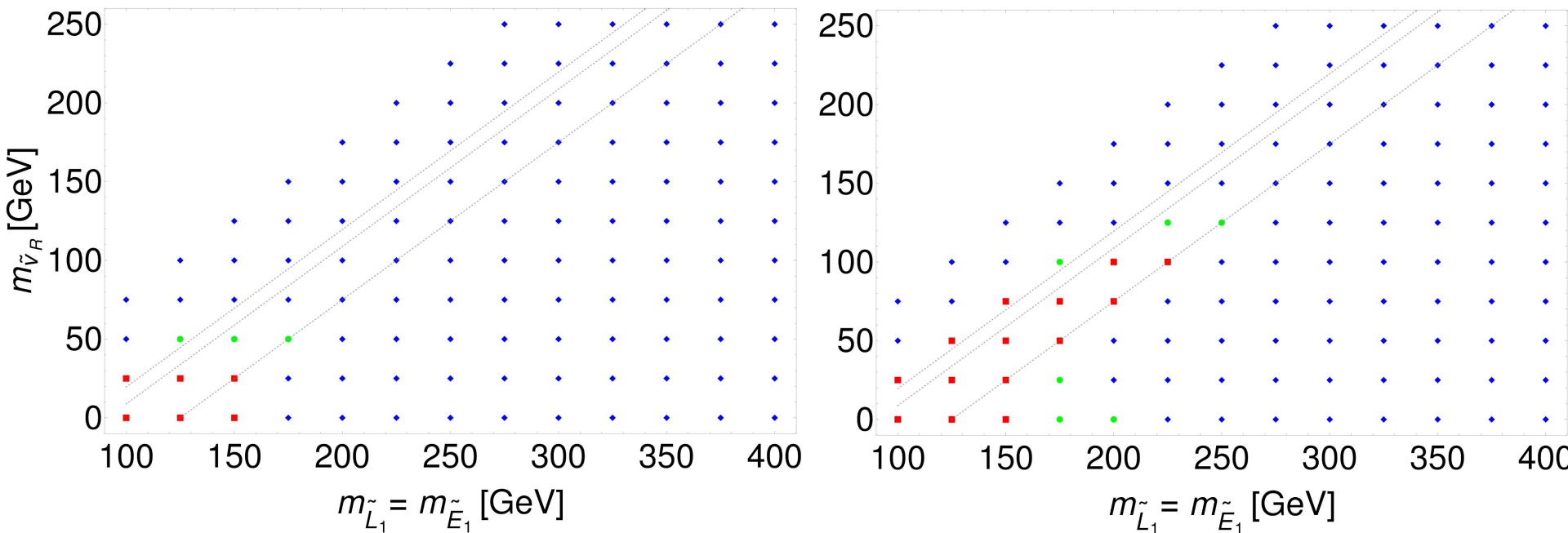# Scenarios of Interest

On-shell Branching Ratio for Smuons.

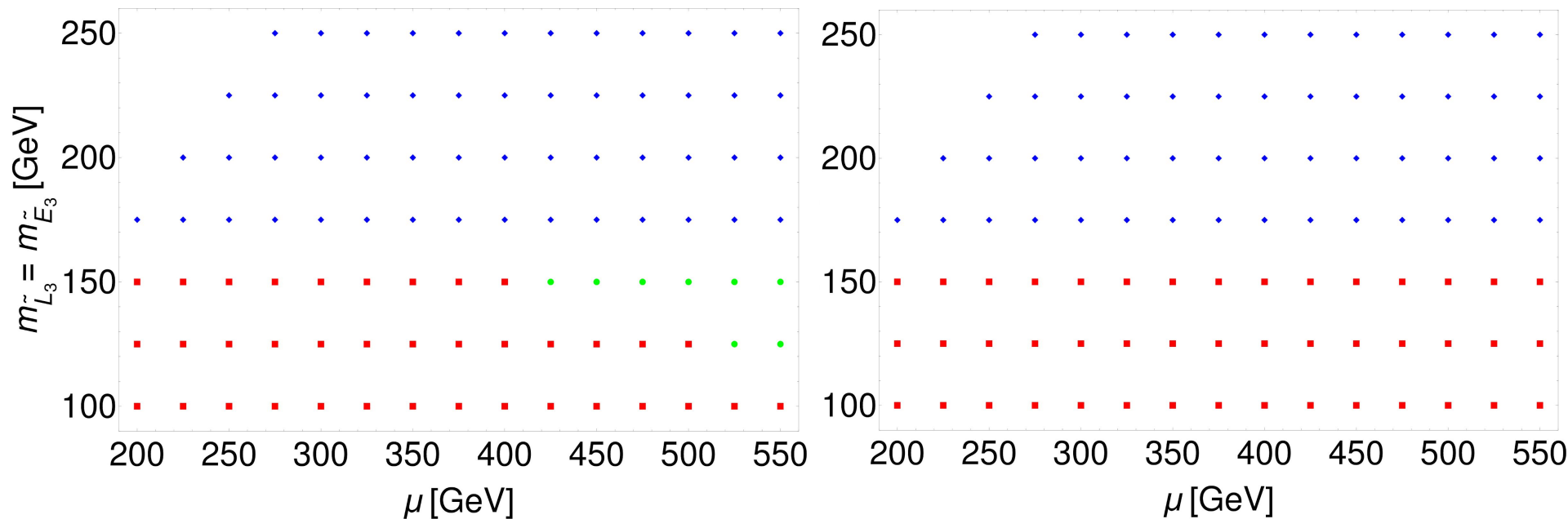# Update to Slepton Searches at the LHC

Currently excluded points and expectations for 300 fb^{-1} for scenario SE

Currently excluded points and expectations for 300 fb^{-1} for scenario ST

Sensitivity at ILC

We consider the most relevant SM background processes for both polarizations:

$e^+e^- \rightarrow$	Type **B**		Type **L**	
	Events	Efficiency (%)	Events	Efficiency (%)
W^+W^-	13	0.005	90	0.003
$\nu\nu Z$	2	0.003	23	0.003
$t\bar{t}$	101	0.1	256	0.2
ZZ	36	0.06	75	0.05
$\nu\nu h$	1	0.003	11	0.005
Zh	52	0.7	81	0.6
ZW^+W^-	74	1	902	1
$b\bar{b}b\bar{b}$	2	0.07	6	0.08
$\nu\nu W^+W^-$	88	4	1132	4
$t\bar{t}b\bar{b}$	1	0.08	2	0.08
$\nu\nu ZZ$	34	5	315	5
hW^+W^-	3	0.7	24	0.6
ZZZ	7	3	28	3
hZZ	1	1	5	2
hhZ	1	0.8	1	0.8
$\nu\nu hh$	1	2	2	2

Sensitivity at ILC

Our total background is an order of magnitude larger for type L polarization.

	Type **B**		Type **L**	
$e^+e^- \rightarrow$	Events	Efficiency (%)	Events	Efficiency (%)
All Background	417	0.08	2950	0.06
All Signal, Scenario SE	758	5	1019	5
All Signal, Scenario ST	922	6	1245	6
All Signal, Scenario DEG	2413	6	3232	6

We only use Type B polarization unless otherwise noted.

Mass reconstruction

From 2 body decay dynamics
$$ee \to \tilde{\ell}\tilde{\ell}, \tilde{\ell} \to \tilde{\nu}_R \, B$$

The energy of the outgoing SM boson in the slepton rest frame is given by:

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

By energy of the slepton is equal to E_{beam} , and we can boost along its direction to find the minimum and maximum energies (endpoints) of the SM boson, which are the measured quantities in this case:

$$E_{B-} = E'_B \frac{E_{\text{beam}}}{m_{\tilde{\ell}}} - \sqrt{E'^2_B - m_B^2} \frac{\sqrt{E_{\text{beam}}^2 - m_{\tilde{\ell}}^2}}{m_{\tilde{\ell}}} \qquad E_{B+} = E'_B \frac{E_{\text{beam}}}{m_{\tilde{\ell}}} + \sqrt{E'^2_B - m_B^2} \frac{\sqrt{E_{\text{beam}}^2 - m_{\tilde{\ell}}^2}}{m_{\tilde{\ell}}}$$

Mass reconstruction

For light jets the discriminating variables are:

$$\chi_W^2(m_1, m_2) = \frac{(m_1 - m_W)^2 + (m_2 - m_W)^2}{\sigma^2}$$

$$\chi_Z^2(m_1, m_2) = \frac{(m_1 - m_Z)^2 + (m_2 - m_Z)^2}{\sigma^2}$$

Where m_1 and m_2 are the dijet masses, and $\sigma = 5$.

An event is considered W-like for $\chi_W^2 < 4, \chi_Z^2 > 5$ or Z-like for $\chi_W^2 > 4, \chi_Z^2 < 2$.

Mass reconstruction

For b-jets the discriminating variables are:

$$\chi_h^2(m_1, m_2) = \frac{(m_1 - m_h)^2 + (m_2 - m_h)^2}{\sigma^2}$$

$$\chi_Z^2(m_1, m_2) = \frac{(m_1 - m_Z)^2 + (m_2 - m_Z)^2}{\sigma^2}$$

Where m_1 and m_2 are the b-jet pair masses, and $\sigma = 5$.

An event is considered Higgs-like for $\chi_h^2 < 4, \chi_Z^2 > 5$ or Z-like for $\chi_h^2 > 4, \chi_Z^2 < 4$.

Mass reconstruction

- SE: Use Z-like and Higgs-like datasets to reconstruct $m_{\tilde{\nu}_L}$ and $m_{\tilde{\nu}_R}$

- ST: Use Higgs-like and W-like datasets to reconstruct $m_{\tilde{\tau}_1}$, $m_{\tilde{\nu}_L}$ and $m_{\tilde{\nu}_R}$

- DEG: Use Z-like and Higgs-like datasets to reconstruct $m_{\tilde{\nu}_L}$ and $m_{\tilde{\nu}_R}$, and the use the upper W-like endpoint to find $m_{\tilde{\tau}_1}$

Appendix

- We used **SARAH 4.14.0** to implement the model in **SPheno 4.0.4**,.and **SSP 1.2.5** to carry out the parameter variation. The **SARAH** output includes the UFO and Whizard model files.

- For the LHC studies we use **MadGraph5_aMC@NLO 2.7.0** followed by **PYTHIA 8.244**, which generates the showering and hadronization. The detector simulation and event reconstruction is carried out by **DELPHES 3.4.2**. To generate the exclusion regions we processed these events by **CheckMATE 2.0.26**

- For our ILC analysis we use **WHIZARD~2.6.2**. The parton shower and hadronization of the jets was carried out with the built-in version of **PYTHIA 6.427**. The detector simulation was again done by **DELPHES**.