A low-scale supersymmetric neutrino seesaw and its resolution at the ILC

Werner Porod

(Uni. Würzburg)

in coll. with J. Masias, N. Cerna-Velazco, J. Jones-Perez
(PRD **103** (2021) no.11, 115028)

16 Sept. 2021

Overview

Model and scenario selection

Discovery potential at ILC with $\sqrt{s} = 1$ TeV

Slepton mass reconstruction

Conclusions & outlook

Model

MSSM + 3 $\hat{\nu}_R$ at electroweak scale

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

$$\mathcal{V}^{soft} = \mathcal{V}^{soft}_{\text{MSSM}} + (m^2_{\tilde{\nu}_R})_{ij}\tilde{\nu}^*_{Ri}\tilde{\nu}_{Rj} + \left(\frac{1}{2}(B_{\tilde{\nu}})_{ij}\tilde{\nu}_{Ri}\tilde{\nu}_{Rj} + (T_\nu)_{ij}\,\tilde{L}_i \cdot H_u\,\tilde{\nu}_{Rj} + \text{h.c.}\right)$$

Assumptions

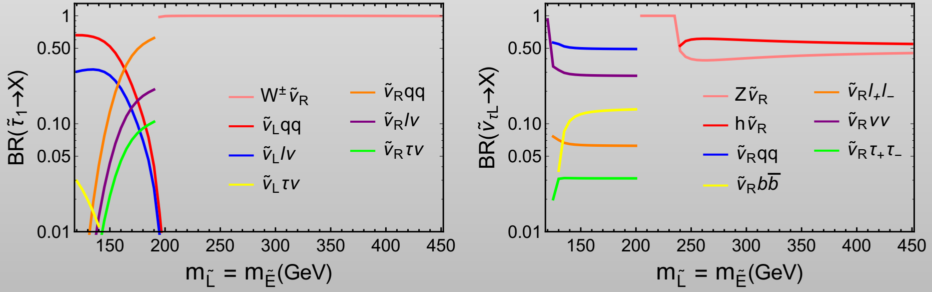
- $|\mu| \ll |M_i| \Rightarrow$ higgsino-like $\tilde{\chi}^0_{1,2}$ and $\tilde{\chi}^+_1$
- $B_{\tilde{\nu}} = T_\nu = 0$
- flavour diagonal slepton mass matrices and $m^2_{\tilde{L}} = m^2_{\tilde{E}}$
- $m_{\nu_{R,1}} \sim$ O(keV), $m_{\nu_{R,2}} = m_{\nu_{R,3}} = 20$ GeV

Scenarios

Parameter region: $\mu = 500$ GeV, $\tan\beta = 6$, $m_{\tilde{\nu}_R} \in [0, 200]$ GeV, $m_{\tilde{L}} = m_{\tilde{E}} \in [100, 450]$ GeV

$\Rightarrow$ decay modes for 1st and 2nd generation sleptons

$$BR(\tilde{l} \to \tilde{\nu}_L W^*) \sim 0.9 \quad \text{and} \quad BR(\tilde{l} \to \tilde{\nu}_R W) \sim 0.1$$
$$BR(\tilde{\tau}_2 \to \tilde{\nu}_L W^*) \gtrsim 0.95 \quad \text{and} \quad BR(\tilde{\tau}_2 \to \tilde{\tau}_1 Z^*) \lesssim 0.05$$



$m_{\tilde{n}u_R} = 100$ GeV

Scenarios

note:

- slepton decays lead here to same signatures as light electroweakinos within MSSM

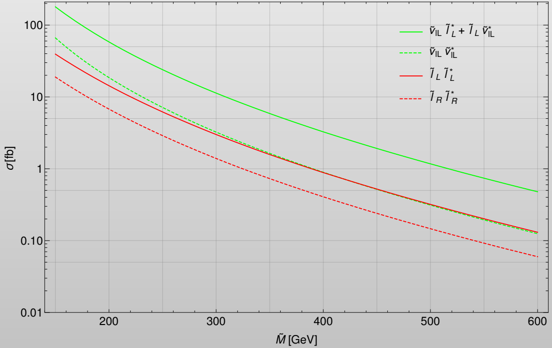
Consider the following 3 cases

- scenario SE: the only light MSSM sleptons are $\tilde{e}_L, \tilde{e}_R, \tilde{\nu}_{e,L}$ (no difference to 2^{nd} generation)
- scenario ST: the only light MSSM sleptons are $\tilde{\tau}_1, \tilde{\tau}_2, \tilde{\nu}_{\tau,L}$
- scenario DEG: all three slepton generations have same soft mass $m_{\tilde{L}} = m_{\tilde{E}}$

LHC constraints

dominant production processes

$$p\,p \to \tilde{l}_L \tilde{\nu}_{lL} \quad \text{and} \quad p\,p \to \tilde{\tau}_{1,2} \tilde{\nu}_{\tau L}$$



LHC, 13 TeV, tree-level
for searches: $\times$ K-factor 1.17
(B. Fuks et al., arXiv:1304.0790)

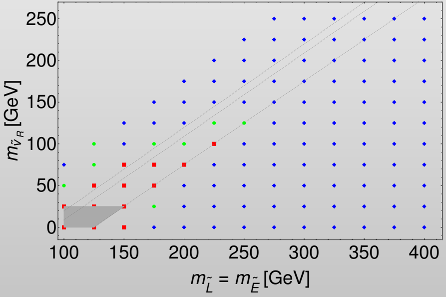
resulting final states

$$W^{(*)} + (Z/h)^{(*)} + p_T^{miss} \quad \text{or} \quad 2\,(Z/h)^{(*)} + p_T^{miss}$$

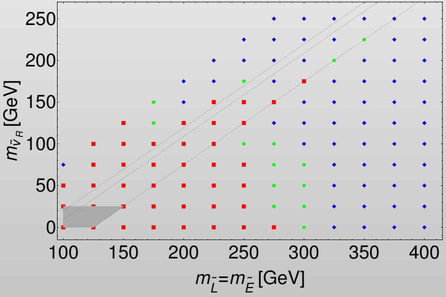
LHC constraints

scenario DEG

current exclusion



expected for $L = 300$ fb^{-1}



using `CheckMATE 2.0`, based on $L = 35.9$ fb^{-1} ■ excluded, ● ambigous, ◇ allowed

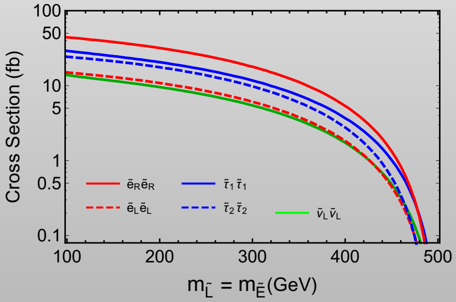
Reach at ILC, $\sqrt{s} = 1$ TeV

- We are mainly interested in the following channels:

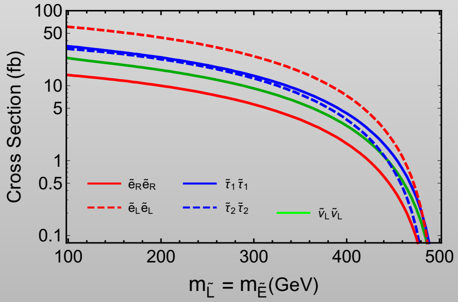
$$e^-e^+ \to \tilde{l}^-\tilde{l}^+ , \qquad \tilde{l}^- \to \tilde{\nu}_L\, f\, f'$$
$$e^-e^+ \to \tilde{\nu}_L\bar{\tilde{\nu}}_L , \qquad \tilde{\nu}_L \to \tilde{\nu}_R\, Z/h$$
$$e^-e^+ \to \tilde{\tau}_1^-\tilde{\tau}_1^+ , \qquad \tilde{\tau}_1 \to \tilde{\nu}_R\, W$$

- Consider the following beam polarisation:

type **B** polarization ($e_R^- e_L^+$)



type **L** polarization ($e_L^- e_R^+$)



with electron (positron) polarization of 80% (20%)

Reach at ILC, $\sqrt{s} = 1$ TeV

Cuts†

- $p_T^{\text{miss}} > 50$ GeV (note, that $m_{\tilde{\nu}_R}$ can be of the order of a few GeV)
- exactly four jets or b-jets with $p_T^j > 20$ GeV
- Two reconstructed SM bosons with two pairs of dijets with invariant masses m_1, m_2 minimizing

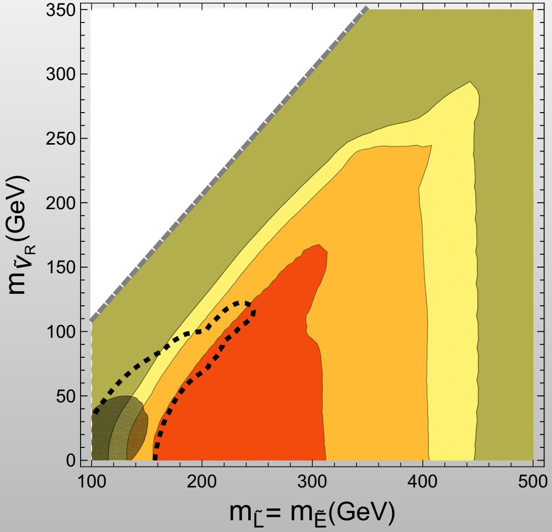
$$f(m_1, m_2) = \frac{(m_1 - m_{B1})^2 + (m_2 - m_{B2})^2}{\sigma^2} < 4 \quad \text{with } \sigma = 5$$

- no leptons with $p_T^l > 25$ GeV
- angle between the beam direction and $\vec{p}^{\text{miss}}$ is constrained such that

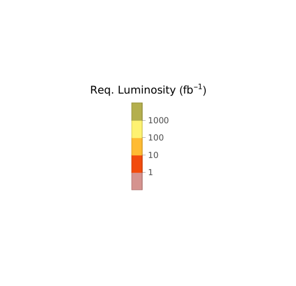
$$|\cos(\theta_{\text{miss}})| < 0.99$$

† based on T. Suehara and J. List, Chargino and Neutralino Separation with the ILD Experiment, (arXiv:0906.5508 (hep-ex)).

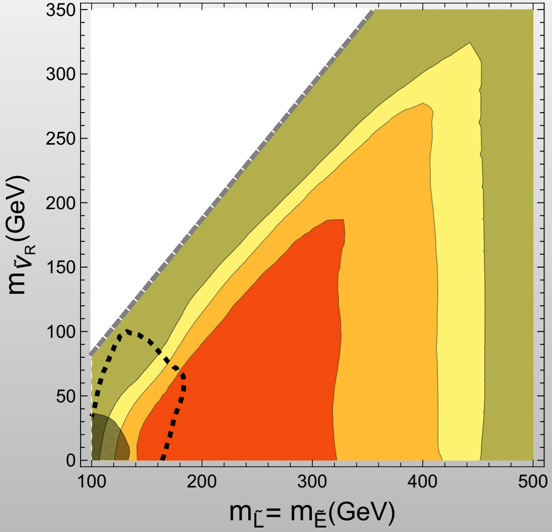
Reach at ILC, $\sqrt{s} = 1$ TeV



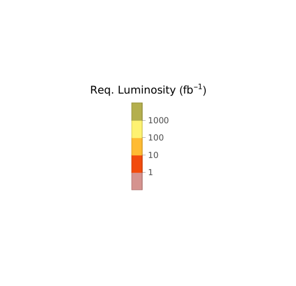
scenario SE ($\tilde{e}_{L,R}, \tilde{\nu}_L$), type **B** pol.
required luminosity for discovery at 5σ CL



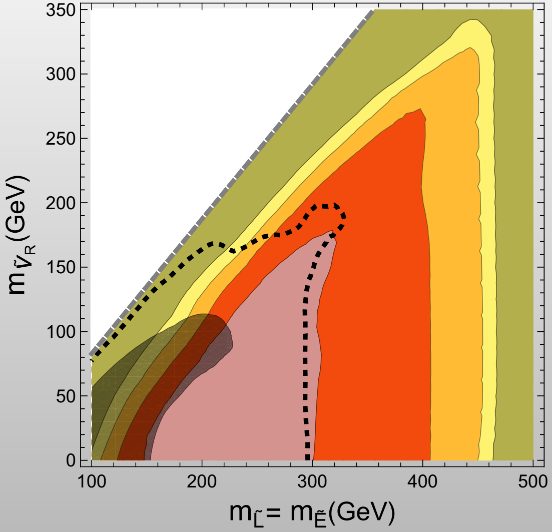
Reach at ILC, $\sqrt{s} = 1$ TeV



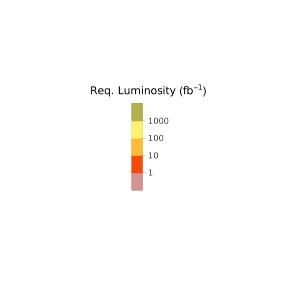
scenario ST ($\tilde{\tau}_{1,2}, \tilde{\nu}_L$), type **B** pol.
required luminosity for discovery at 5σ CL



Reach at ILC, $\sqrt{s} = 1$ TeV



scenario DEG (all $\tilde{l}$, $\tilde{\nu}_L$), type **B** pol.
required luminosity for discovery at 5σ CL



Scenarios & assumptions

- Assume, we have observed some new signal 
- $\Rightarrow$ want to get least information on the mass
possibility: mass reconstruction via endpoints
- assume $E_{beam} = 500$ GeV and $L = 1000$ fb^{-1}
- neglect possible effects due to ISR and beamstrahlung
(for mass reconstruction formula only, not in the simulation)
- $m_{\tilde{\nu}_R} = 100$ GeV, $m_{\tilde{L}} = 300$ GeV

Method

Consider energy spectrum of produced boson B from slepton 2-body decays

$$m_{\tilde{\ell},\tilde{\nu}_L} = \frac{2E_{\rm beam}}{E_{B+}+E_{B-}} E'_B\,, \qquad m_{\tilde{\nu}_R} = \sqrt{m^2_{\tilde{\ell}} + m^2_B - 2E'_B m_{\tilde{\ell}}}$$

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

We obtain 2 possible values consistent with the measurement
$\Rightarrow$ we need at least 2 datasets in order the fix the correct sign of E'_B

Same cuts as before, but require now that both bosons in the final state are the same ($WW\,, ZZ\,, hh$)

$\Rightarrow$ Events fall in three datasets, W-like, Z-like and h-like:

- $\tilde{\tau}_1^+\tilde{\tau}_1^- \to W$-like $\to 4j$ (excluding b-jets)
- $\tilde{\nu}_L\bar{\tilde{\nu}}_L \to Z/h$-like $\to 4j/4b$
- $\tilde{l}^+\tilde{l}^- \to \tilde{\nu}_L\bar{\tilde{\nu}}_L \to Z/h$-like $\to 4j/4b$

Method

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

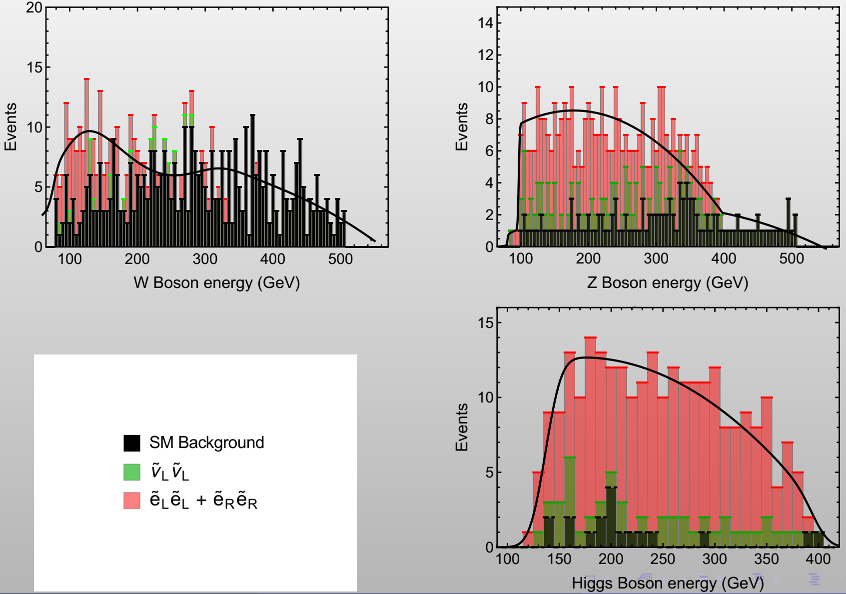
$$f_{SM}(E;\, E_{\mathrm{SM}-},\, a_{0-2},\, \sigma_{\mathrm{SM}},\, \Gamma_{\mathrm{SM}}) = \int_{E_{\mathrm{SM}-}}^{\infty} (a_2 E'^2 + a_1 E' + a_0)\, V(E' - E, \sigma_{\mathrm{SM}}, \Gamma_{\mathrm{SM}})\, dE'$$

2. Using the fitted parameters, we generate 100 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:

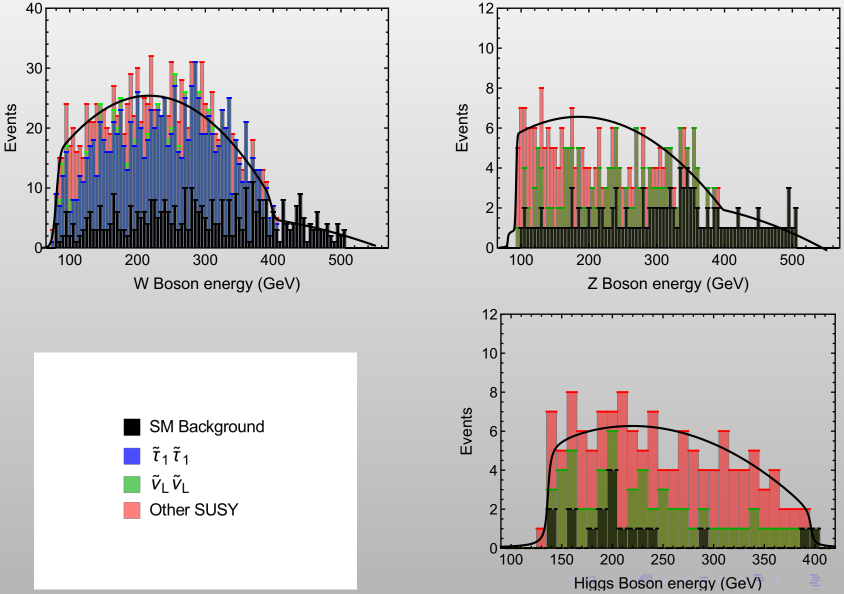
$$f(E;\, E_{B-},\, E_{B+},\, b_{0-2}, \sigma_1, \Gamma_1) = f_{SM}(E;\, E_{\mathrm{SM}-}, a_{0-2}, \sigma_{\mathrm{SM}}, \Gamma_{\mathrm{SM}}) + \int_{E_{B-}}^{E_{B+}} (b_2 E'^2 + b_1 E' + b_0) V(E' - E, \sigma_1, \Gamma_1) dE'$$

† based on T. Suehara and J. List, Chargino and Neutralino Separation with the ILD Experiment, (arXiv:0906.5508 (hep-ex)).

Scenario SE

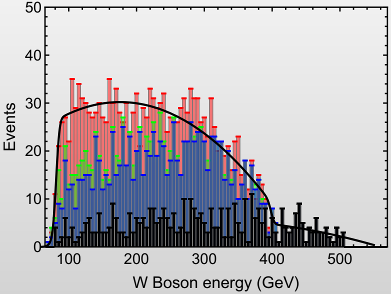

Events
W Boson energy (GeV)
20
15
10
5
0
100
200
300
400
500
Events
Z Boson energy (GeV)
14
12
10
8
6
4
2
0
100
200
300
400
500
SM Background
$\tilde{\nu}_L \tilde{\nu}_L$
$\tilde{e}_L \tilde{e}_L + \tilde{e}_R \tilde{e}_R$
Events
Higgs Boson energy (GeV)
15
10
5
0
100
150
200
250
300
350
400

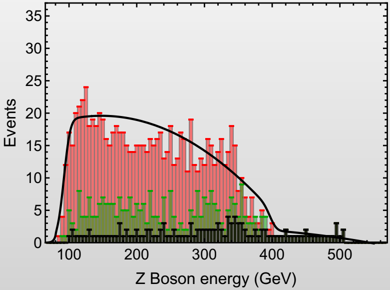
Scenario ST

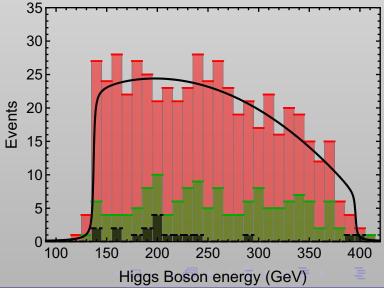


Events
W Boson energy (GeV)
Events
Z Boson energy (GeV)
Events
Higgs Boson energy (GeV)
SM Background
$\tilde{\tau}_1 \tilde{\tau}_1$
$\tilde{\nu}_L \tilde{\nu}_L$
Other SUSY

Scenario DEG







Mass reconstruction

Endpoints

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

Resulting masses

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

- Scenarios with $\tilde{\nu}_R$ LSP can be quite challenging at the LHC
- ILC with $\sqrt{s} = 1$ TeV: discovery expected for $m_{\tilde{L}} \in [100, 450]$ GeV if $m_{\tilde{l}} - m_{\tilde{\nu}_R} - m_B \gtrsim 60$ GeV
- Using an endpoint method, the slepton masses of such scenario can be reconstructed

Open tasks & questions

- how to get the remaining masses
- how to extend method in case of

$$e^+e^- \to \tilde{\nu}_L \bar{\tilde{\nu}}_L \to \tilde{\nu}_R \bar{\tilde{\nu}}_R \, h \, Z$$

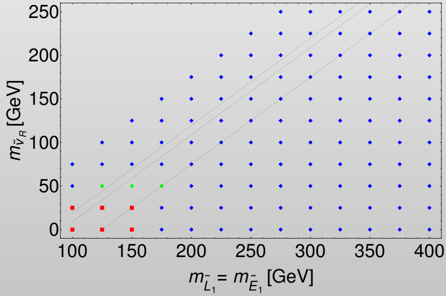
- explore mass reconstruction in case of 3-body decays, becomes in particular important in case of smaller Y_ν couplings and/or if $\tilde{l}_R$ are significantly lighter thant $\tilde{l}_L$.

Backup slides

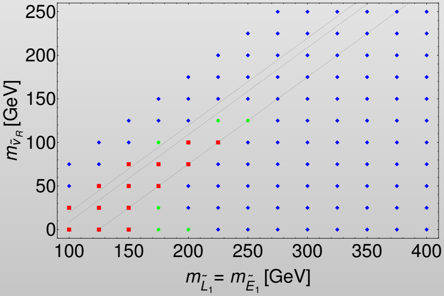
LHC constraints

scenario SE

current exclusion



expected for $L = 300$ fb^{-1}



using `CheckMATE 2.0`, based on $L = 35.9$ fb^{-1} ■ excluded, ● ambigous, ◇ allowed

Background / Signal rates

	Type **B**		Type **L**	
$e^+e^- \to$	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
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

L 500 fb^{-1}. The last rows includes the sum of events from all signal processes, including cascades, for comparison. The efficiency columns refer to the ratio between the number of events after the cuts over those initially generated.

Numerical Tools

Throughout this paper we have used SARAH 4.14.0 to implement the model in SPheno 4.0.4, which calculates the mass spectrum and branching ratios. We used SSP 1.2.5 to carry out the parameter variation. The SARAH output also includes UFO files that enter LHC and ILC event generators.

For LHC studies we use MadGraph5_aMC@NLO 2.7.0 followed by PYTHIA 8.244, which generates the showering and hadronization. Events are generated with the CTEQ6L1 PDF set. The detector simulation and event reconstruction is carried out by DELPHES 3.4.2 , using the built-in ATLAS and CMS cards. To generate the exclusion regions we processed these events by by CheckMATE 2.0.26, which determines if a specific point has been excluded or not by the considered searches.

For our ILC analysis we use WHIZARD 2.6.2. This simulation includes ISR and beamstrahlung implemented with CIRCE1-2.2.0. 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, using the built-in ILD card.