Measuring neutrino dynamic in NMSSM with a right-handed sneutrino LSP at the ILC [JHEP 01 (2022) 034] [arXiv:2109.06802]

YI LIU

University of Southampton

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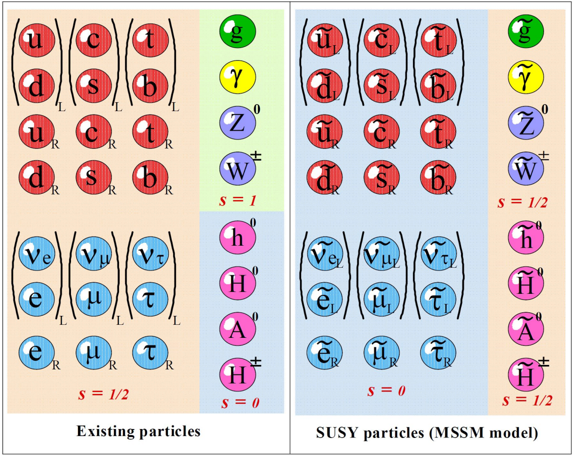
Supervisors: Prof. Stefano Moretti
Dr. Harri Waltari

Outline

Today I shall discuss

- NMSSM with right-hand sneutrino model description
- Signal search and cut application in MC simulation
- Result analysis

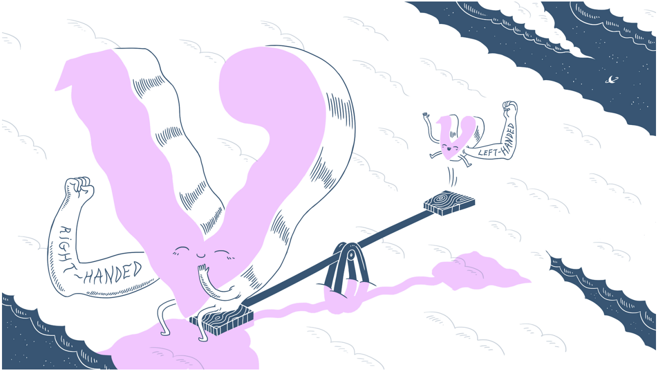
From SM to MSSM



- Supersymmetry(SUSY) with R-parity conservation offers a natural Dark Matter (DM) candidate
- But non-zero neutrino mass
- But μ problem

Why seesaw?

Seesaw mechanism is a natural way to explain neutrino mass.



- B-L breaking effect can be parameterized through an effective dimension-5 Weinberg operator $\lambda LLHH/M$
- Type-I seesaw.

$$m_\nu = Y_N^T \frac{1}{M} Y_N v^2 \tag{1}$$

DM candidate in SUSY

- Lightest supersymmetric particle (LSP) can be DM candidate.

- Mixed with left-hand sneutrino, right-hand sneutrino can be a DM candidate in MSSM.

Solution of μ problem

The μ term should be around the electroweak scale, why?
Extending the MSSM to the Next-to-Minimal Supersymmetric Standard Model (NMSSM) is to promote the μ term to a gauge singlet, chiral superfield S.

- The superpotential for the MSSM is

$$W_{MSSM} = Y_u H_2 \cdot Qu + Y_d H_1 \cdot Qd + Y_e H_1 \cdot Le - \mu H_1 \cdot H_2 \tag{2}$$

- By adding a singlet superfield S, the NMSSM superpotential is

$$W_{NMSSM} = Y_u H_2 \cdot Qu + Y_d H_1 \cdot Qd + Y_e H_1 \cdot Le - \lambda S H_1 \cdot H_2 + \frac{1}{3}\kappa S^3 \tag{3}$$

- $\mu = \lambda \langle \hat{S} \rangle$

Model description

The NMSSM with right-hand neutrino (NMSSMr) model is MSSM extended by adding two singlet superfields.

- One extra singlet superfield S addresses the μ problem and provide extra Higgs and neutralino states.
- The other singlet N account for right-hand neutrino and sneutrino states.

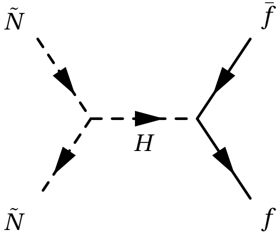
The superpotential is

$$W = W_{NMSSM} + \lambda_N SNN + y_N L \cdot H_2 N \tag{4}$$

$$W_{NMSSM} = Y_u H_2 \cdot Qu + Y_d H_1 \cdot Qd + Y_e H_1 \cdot Le - \lambda S H_1 \cdot H_2 + \frac{1}{3}\kappa S^3 \tag{5}$$

Right-handed sneutrino as a dark matter candidate

- In MSSMr, it is not easy to satisfy the constrain from the relic density with a right-handed sneutrino LSP.
- The NMSSMr offers an additional method to enhance the annihilation cross section. The scalar potential has a term $\lambda\lambda_N H_u H_d \tilde{N}\tilde{N}$ which, after EW Symmetry Breaking (EWSB), creates a three-point coupling between the right-handed sneutrinos and Higgs bosons.



Neutrino mass and sneutrino mass

- The superpotential term $\lambda_N SNN$ in eq 4 leads to a Majorana mass term $M_N = 2\lambda_N v_s$. The left-handed neutrino masses are $m_\nu = y_N^2 v_2^2 / M_N$.
- The left-hand sneutrino $\tilde{\nu}_L$ and right-hand sneutrino $\tilde{N}$ can be decomposed by a pair of CP-even (real component) and CP-odd (imaginary component) basis.

$$\tilde{\nu}_L \equiv \frac{1}{\sqrt{2}}(\tilde{\nu}_{L1} + i\tilde{\nu}_{L2}) \qquad \tilde{N} \equiv \frac{1}{\sqrt{2}}(\tilde{N}_1 + i\tilde{N}_2) \tag{6}$$

The sneutrino quadratic mass term is:

$$\frac{1}{2} \; (\tilde{\nu}_{L1}, \tilde{N}_1, \tilde{\nu}_{L2}, \tilde{N}_2) \; \mathcal{M}^2_{\text{sneutrino}} \begin{pmatrix} \tilde{\nu}_{L1} \\ \tilde{N}_1 \\ \tilde{\nu}_{L2} \\ \tilde{N}_2 \end{pmatrix} \tag{7}$$

Sneutrino mass

The sneutrino mass matrix can be given from the quadratic terms in the scalar potential:

$$\mathcal{M}^2 = \begin{pmatrix} m_{L\bar{L}}^2 & \frac{m_{LR}^2+m_{\bar{L}\bar{R}}^2+c.c}{2} & 0 & i\frac{m_{LR}^2-m_{\bar{L}\bar{R}}^2-c.c}{2} \\ \frac{m_{LR}^2+m_{\bar{L}\bar{R}}^2+c.c}{2} & m_{R\bar{R}}^2+M_{RR}^2+m_{RR}^{2*} & i\frac{m_{LR}^2-m_{\bar{L}\bar{R}}^2-c.c}{2} & i(m_{RR}^2-m_{RR}^{2*}) \\ 0 & i\frac{m_{LR}^2-m_{\bar{L}\bar{R}}^2-c.c}{2} & m_{L\bar{L}}^2 & -\frac{m_{LR}^2+m_{\bar{L}\bar{R}}^2+c.c}{2} \\ i\frac{m_{LR}^2-m_{\bar{L}\bar{R}}^2-c.c}{2} & i(m_{RR}^2-m_{RR}^{2*}) & -\frac{m_{LR}^2+m_{\bar{L}\bar{R}}^2+c.c}{2} & m_{R\bar{R}}^2-M_{RR}^2-m_{RR}^{2*} \end{pmatrix} \tag{8}$$

The parameter are defined as follow:

$$\begin{aligned} m_{L\bar{L}}^2 &\equiv m_{\tilde{L}}^2+|y_N v_2|^2+\text{D-term} \\ m_{LR}^2 &\equiv y_N(-\lambda v_s v_1)^\dagger + y_N A_N v_2 \\ m_{\bar{L}\bar{R}}^2 &\equiv y_N v_2(-\lambda v_s)^\dagger \\ m_{R\bar{R}}^2 &\equiv m_{\tilde{N}}^2+|2\lambda_N v_s|^2+|y_N v_2|^2 \\ m_{RR}^2 &\equiv \lambda_N(A_{\lambda_N} v_s+(\kappa v_s^2-\lambda v_1 v_2)^\dagger) \end{aligned} \tag{9}$$

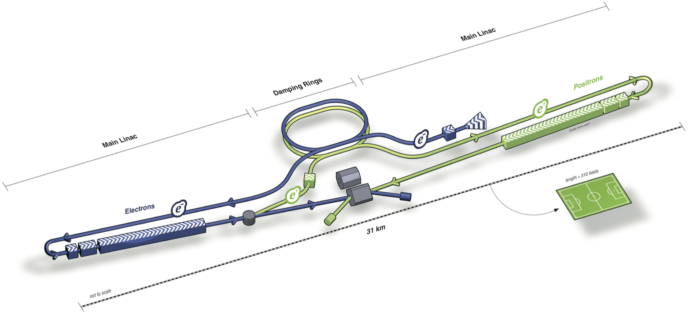
Sneutrino mass

Assuming there is no CP-violation which means the sneutrino real part and imaginary part do not mix. Eq 7 can be simplified as:

$$\begin{aligned}&\frac{1}{2}(\tilde{\nu}_{L1}\tilde{N}_1)\begin{pmatrix} m^2_{L\bar{L}} & m^2_{LR}+m^2_{L\bar{R}} \\ m^2_{LR}+m^2_{L\bar{R}} & m^2_{R\bar{R}}+2m^2_{RR}\end{pmatrix}\begin{pmatrix}\tilde{\nu}_{L1}\\ \tilde{N}_1\end{pmatrix}+\\ &\frac{1}{2}(\tilde{\nu}_{L2}\tilde{N}_2)\begin{pmatrix} m^2_{L\bar{L}} & -m^2_{LR}+m^2_{L\bar{R}} \\ -m^2_{LR}+m^2_{L\bar{R}} & m^2_{R\bar{R}}-2m^2_{RR}\end{pmatrix}\begin{pmatrix}\tilde{\nu}_{L2}\\ \tilde{N}_2\end{pmatrix}\end{aligned} \tag{10}$$

International Linear Collider

The International Linear Collider (ILC) is a proposed linear particle accelerator in Japan, the collision energy ranges from 250 GeV to 1TeV.



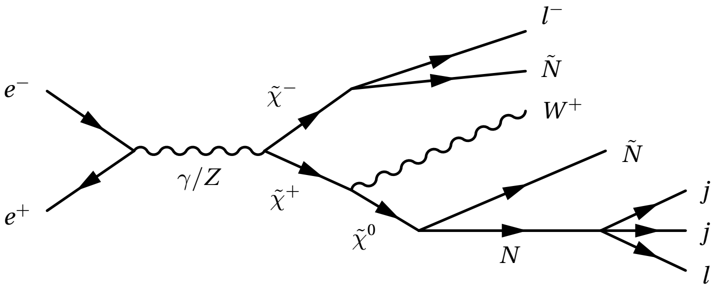
At the ILC physicists hope to be able to:

- Measure the mass, spin, and interaction strengths of the Higgs boson.
- Investigate the lightest supersymmetric particles, possible candidates for DM.

The rare chargino decay

- We now consider the process $e^+e^- \to \gamma/Z \to \tilde{\chi}^+\tilde{\chi}^-$ with one of the chargino decaying to a lepton and a sneutrino and the other chargino decaying into a neutralino and a virtual W leading to a soft lepton or hadrons.
- The decay $\tilde{\chi} \to \ell\tilde{N}$ arises from the neutrino Yukawa coupling and such a tiny Yukawa couplings makes the decay rare even with favourable kinematics.

The Feynman diagram is:



Signal and background

The signature is: ‘dijet + dilepton + MET’.
The major SM background to this final state comes from the following processes.

- W^+W^-Z
- ZZZ
- $t\bar{t}$

These features allow distinguishing the signal from the background.

- The two-body decay has fixed kinematics so E_ℓ is within a narrow range.
- The right-handed neutrino leads to a lepton and two jets having an invariant mass near m_N
- The two LSPs give a substantial amount of $\not{p}_T$

Event simulation platform

The simulation tool is below:

- SARAH v4.14
- SPHENO v4.03
- MADGRAPH5 v2.8.2
- PYTHIA v8.2
- MADDM v3.0
- MADANALYSIS5 v1.8

The signal as follows:

- We prepared a number of benchmark points, which could be probed at the $\sqrt{s} = 500$ GeV phase of the ILC.
- We select the charginos to be slightly lighter than 250 GeV and the right-handed neutrino and sneutrino so light that $\tilde{\chi}^0 \to \tilde{N} N$ is kinematically allowed.

Benchmark point and signal topology

The mass spectra for different Benchmark Points (BPs):

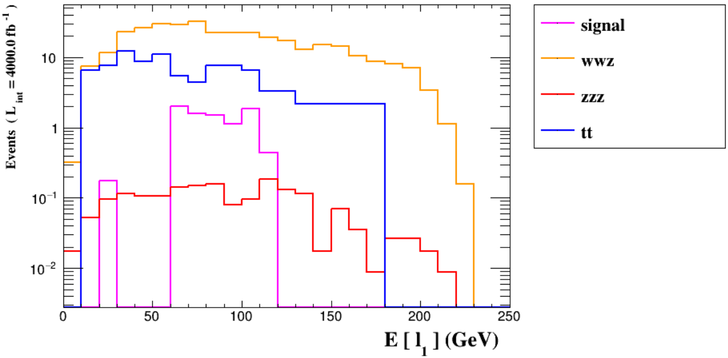
Particle	BP1	BP2	BP3
$\tilde{\chi}_1^{\pm}$	239.3 GeV	234.8 GeV	233.3 GeV
$\tilde{N}_1$	130.6 GeV	127.9 GeV	127.4 GeV
N_1	101.7 GeV	90.5 GeV	88.6 GeV

The requirements for the final state topology (ℓ stands for e , μ):

Number of leptons	$N(\ell) = 2$
Same-sign lepton pair	$N(\ell^+)$ or $N(\ell^-) = 2$
Number of jets	$N(j) = 2$
B-jet veto	$N(b) = 0$

Simulation result

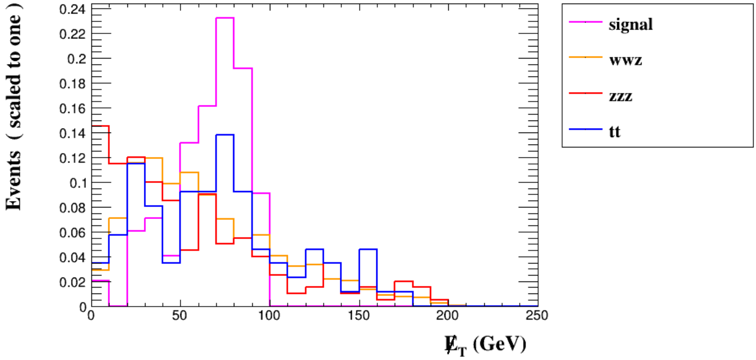
The energy of the leading lepton ℓ_1 for signal and different background components.



- The leading lepton arises from $\tilde{\chi}^{\pm} \to \tilde{N}\ell_1^{\pm}$, which is a two-body process. As long as the beam energy is not much larger than $2m_{\tilde{\chi}^{\pm}}$, the lepton energies in the lab frame are in a rather narrow range determined by the event kinematics.

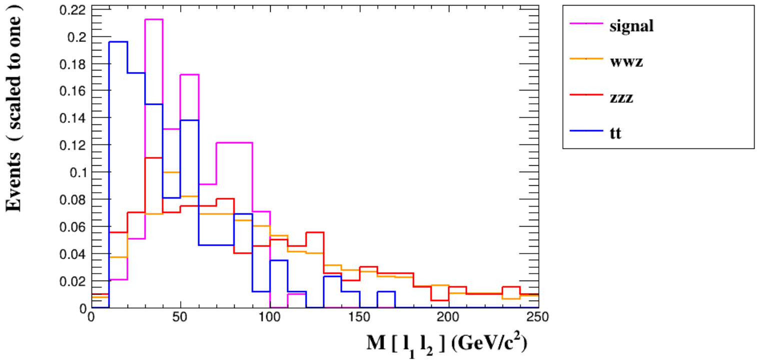
Simulation result

The distribution of missing transverse energy ($\not{E}_T$) for the signal and background components.



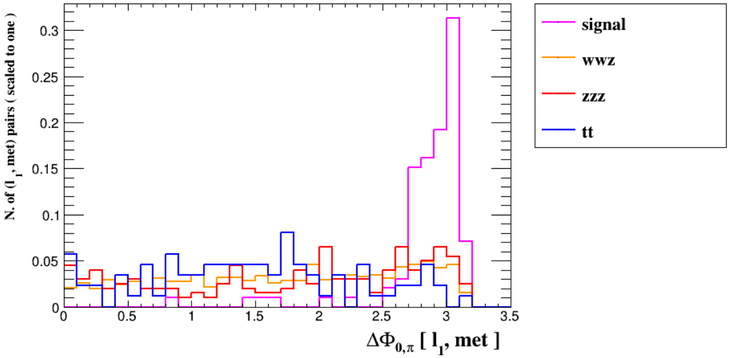
The distribution of $\not{E}_T$ for the signal is mostly in the interval [50, 100] GeV, hence we select that interval.

Simulation result



The distribution of invariant mass of the leading two leptons, the different distributions are normalised to unity.

Simulation result



The distribution of the azimuthal angle between the leading lepton and missing transverse energy, the different distributions are normalised to unity.

Cut table

The full set of cuts used in MC analysis

Transverse momentum of leading lepton	30 GeV $< p_t(\ell_1) <$ 100 GeV
Energy of leading lepton	60 GeV $< E(\ell_1) <$ 120 GeV
Transverse momentum of sub-leading lepton	$p_t(\ell_2) <$ 40 GeV
Transverse momentum of leading jet	$p_t(j_1) <$ 70 GeV
Total hadronic energy	$H_T <$ 100 GeV
Missing transverse energy	50 GeV $< \not{E}_T <$ 100 GeV
Invariant mass of ℓ_1 ℓ_2	$M(\ell_1\ell_2) <$ 80 GeV
Angle of leading lepton with MET	$\Delta\Phi_{0,\pi} > 2.5$
Invariant mass of two jets and sub-leading lepton	90 GeV $< M(j_1 j_2 \ell_2) <$ 110 GeV

Cut table

Cut	BP1	BP2	BP3	W^+W^-Z	ZZZ	$t\bar{t}$	Total background
Initial	87.0	139	116	158999	4400	2193599	2356998
b-jet veto	84.2	137	115	133754	2802	240648	377204
$N(\ell)$=2	38.8	54.9	42.0	11308	387	11454	23149
$N(\ell^+)=2$ or $N(\ell^-)=2$	17.8	26.0	20.6	792	6.07	339	1137
$N(j)=2$	8.66	12.3	8.69	343	1.76	95.4	440
$p_T(j_1) < 70\,\text{GeV}$	8.66	12.0	8.35	154.5	0.625	26.3	181.4
$p_T(\ell_1) > 30\,\text{GeV}$	7.87	10.2	8.11	134.5	0.519	17.6	152.6
$p_T(\ell_2) < 40\,\text{GeV}$	7.87	10.2	8.11	95.7	0.36	17.6	113.7
$H_T < 100\,\text{GeV}$	7.87	10.2	8.00	76.5	0.24	11.0	87.7
$E(\ell_1) < 120\,\text{GeV}$	7.87	10.2	8.00	55.5	0.176	7.68	63.4
$E(\ell_1) > 60\,\text{GeV}$	7.87	9.33	7.65	36.6	0.123	5.48	42.2
$\Delta\Phi_{0,\pi} > 2.5$	7.70	8.08	6.14	16.7	0.035	3.29	20.0
$\not{E}_T > 50\,\text{GeV}$	6.82	7.38	4.98	9.70	0.026	2.19	11.9
$\not{E}_T < 100\,\text{GeV}$	6.82	5.99	4.06	8.27	0.026	2.19	10.5
$M(\ell_1\ell_2) < 80\,\text{GeV}$	5.60	5.71	3.94	4.77	0.018	1.10	5.89
$M(j_1j_2\ell_2) < 110(100)\,\text{GeV}$	5.51	5.71	3.94	2.23(1.40)	0.0088(0)	1.10(1.10)	3.34(2.50)
$M(j_1j_2\ell_2) > 90(80)\,\text{GeV}$	3.67	3.48	2.43	1.11(0.636)	0.0088(0)	0(0)	1.1(0.64)

The cutflow for signal with different benchmarks and backgrounds. The integrated luminosity is 4000 fb^{-1} and collision energy is 500 GeV. The bracket stands for the cut and result for BP2 and BP3. After last cut, the significance for BP1 is 3.5σ, BP2 is 4.4σ , BP3 is 3.0σ.

Estimating neutrino Yukawa couplings

The coupling between the right-handed sneutrino, charged lepton and lightest chargino is

$$\lambda_{\tilde{N}\ell^+\tilde{\chi}^-} = \frac{i}{\sqrt{2}} y^{\nu}_{ab} V_{12} \frac{1+\gamma_5}{2}, \tag{11}$$

For our BPs, we have $|V_{12}| \simeq 1$. This leads to the following decay width (neglecting the lepton mass):

$$\Gamma(\tilde{\chi}^{\pm} \to \ell^{\pm}_a \tilde{N}_b) = \frac{(m^2_{\tilde{\chi}} - m^2_{\tilde{N}})^2}{64\pi m^3_{\tilde{\chi}}} |y^{\nu}_{ab}|^2 |V_{12}|^2. \tag{12}$$

The measurement of the Branching Ratio of the rare chargino decay would give us an estimate of the neutrino Yukawa couplings through the computed full width.

Cut efficiencies estimation

- In order to estimate Yukawa couplings, it is necessary to know how many initial events.
- Selection efficiencies can be estimated by other types of events, such as b-tagging efficiency.
- Some cut efficiencies can be calculated by the main decay mode of the chargino, H_T or jet momenta.
- Some cuts need to be simulated, but it can be expected that the statistical uncertainty dominates due to the small event rate.
- As the two-body decay width is proportional to $|y^{\nu}_{ab}|^2|$, so the relative error of the Yukawa coupling is smaller than for the decay rate.

Summary

- In NMSSM with RH neutrinos, sneutrino pairs can be produced and this can give a same-sign dilepton signature
- If the right-handed sneutrino is the LSP, there are some chances of measuring the Yukawa couplings through the rare two-body decay and at future e^+e^- collider.
- ILC could possibly probe neutrino mass generation mechanism through sneutrinos.

And future...

High scale Seesaw in SUSY

- Higgs slepton coupling in MSSM
- Difference between Type-I Seesaw and Type-III Seesaw

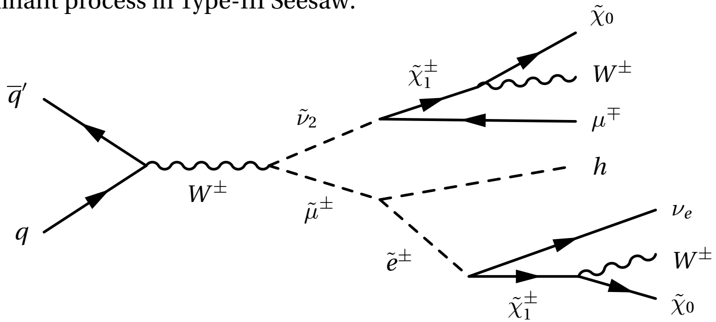
$$\text{Type-I:} \qquad W = W_{\text{MSSM}} + y^{\nu} L \cdot H_u N^c + M_N N^c N^c, \tag{13}$$

$$\text{Type-III:} \qquad W = W_{\text{MSSM}} + y^{\nu} L \Sigma H_u + M_{\Sigma} \text{Tr}(\Sigma^2), \tag{14}$$

- Difference in scalar potential

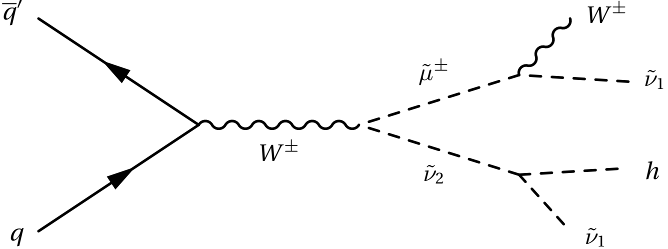
High scale Seesaw in SUSY

The dominant process in Type-III Seesaw:



High scale Seesaw in SUSY

The dominant process in Type-I Seesaw:



Benchmark Points

Mass spectra and BRs of our BPs. BP1 for Type-III seesaw while BP2 for Type-I seesaw.

	BP1	BP2
$m(\tilde{\mu})$ (GeV)	895.3	885.5
$m(\tilde{e})$ (GeV)	701.9	692.9
$m(\tilde{\nu}_2)$ (GeV)	886.8	891.7
$m(\tilde{\nu}_1)$ (GeV)	692.8	697.5
$\mathrm{BR}(\tilde{\mu} \to \tilde{e} + h)$	74.6%	0%
$\mathrm{BR}(\tilde{\nu}_2 \to \tilde{\nu}_1 + h)$	12.2%	30.9%
LSP	410.4($\tilde{\chi}_0$)	410.4($\tilde{\chi}_0$)
NLSP	413.3 ($\tilde{\chi}_1^{\pm}$)	413.3 ($\tilde{\chi}_1^{\pm}$)

The full cut table

The response of the signal BPs and backgrounds to the application of the full cutflow used in the MC analysis in HE-LHC. The luminosity is 10 ab^{-1} and the energy is $\sqrt{s} = 27$ TeV.

Cut	BP1	BP2	$W^{\pm}h$	$t\bar{t}$	Total background
Initial	6150	6220	9249999	2169999	11419998
$N(b) > 1$	1095.3	505.7	1585690	691090	2276780
$N(\ell) = 1$	481.5	238.2	835311	224927	1060238
$\not{E}_T > 500$ GeV	136.5	60.33	422.5	126239	126661.5
$M(b_1 b_2) > 100$ GeV	113.2	52.9	379.7	118569	118948.7
$M(b_1 b_2) < 150$ GeV	46.7	28.0	235.8	10706	10941.8
$p_T(\ell_1) > 400$ GeV	25.8	15.5	15.3	203.1	218.4
$M_T(\ell_1, \not{E}_T) > 100$ GeV	25.8	15.5	3.1	19.9	23.0

More data, flavour hierarchy...

Thank you!