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

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Motivation

- Seesaw mechanism is a natural way to explain neutrino mass.
- Supersymmetry(SUSY) with R-parity conservation offers a natural dark matter candidate
- Extension of MSSM can solve μ problem and give neutrino mass mechanism.

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.

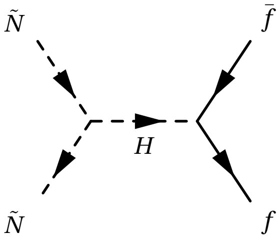
The superpotential is:

$$W = W_{NMSSM} + \lambda_N SNN + y_N L \cdot H_2 N \tag{1}$$

$$W_{NMSSM} = Y_u H_2 \cdot Q_u + Y_d H_1 \cdot Qd + Y_e H_1 \cdot Le - \lambda S H_1 \cdot H_2 + \frac{1}{3}\kappa S^3 \tag{2}$$

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.



Overall process of determining Yukawa coupling

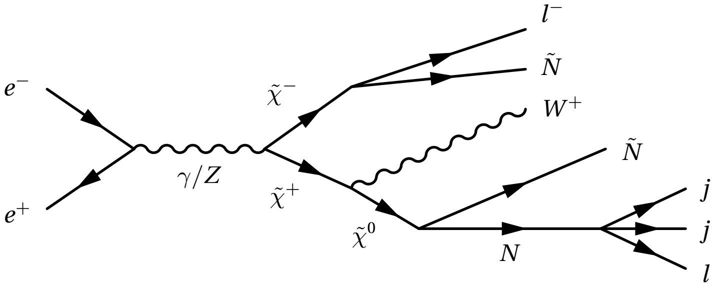
See a signal of the two-body process$\rightarrow$ Determine the branching ratio (initial number of event cuts & chargino production cross section) $\rightarrow$ Use three-body decay width to compute two-body width$\rightarrow$Relate this to Yukawa couplings.

Difficulties:

- finding the signal
- inverting the cuts

The rare chargino decay

We now consider the process $e^+e^- \rightarrow \gamma/Z \rightarrow \tilde{\chi}^+\tilde{\chi}^-$ 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 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
- $t\bar{t}$

The features allow distinguishing the signal from the background.

- The two-body decay has fixed kinematics so E_ℓ is within a narrow range (at LHC not true as lab frame $\neq$ CM frame)
- The RH 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

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 with different Benchmark point:

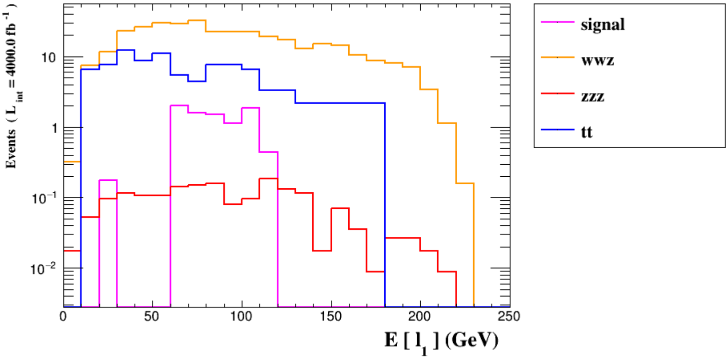
Particle	BP1	BP2	BP3
$\tilde{\chi}_1^{\pm}$	239.3 GeV	234.8 GeV	233.3 GeV
$\tilde{N}_1$	130.6 GeV	127.9 GeV	127.4 GeV
N_1	101.7 GeV	90.5 GeV	88.6 GeV

The requirement for the final state topology:

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

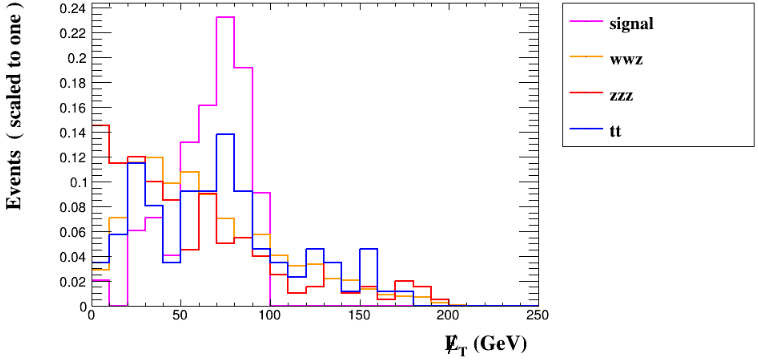
The energy of the leading lepton ℓ_1 for signal and different background components.



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.

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
$p_T(j_1)<70\,\mathrm{GeV}$	8.66	12.0	8.35	154.5	0.625	26.3	181.4
$p_T(\ell_1)>30\,\mathrm{GeV}$	7.87	10.2	8.11	134.5	0.519	17.6	152.6
$p_T(\ell_2)<40\,\mathrm{GeV}$	7.87	10.2	8.11	95.7	0.36	17.6	113.7
$H_T<100\,\mathrm{GeV}$	7.87	10.2	8.00	76.5	0.24	11.0	87.7
$E(\ell_1)<120\,\mathrm{GeV}$	7.87	10.2	8.00	55.5	0.176	7.68	63.4
$E(\ell_1)>60\,\mathrm{GeV}$	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
$\not{E}_T>50\,\mathrm{GeV}$	6.82	7.38	4.98	9.70	0.026	2.19	11.9
$\not{E}_T<100\,\mathrm{GeV}$	6.82	5.99	4.06	8.27	0.026	2.19	10.5
$M(\ell_1\ell_2)<80\,\mathrm{GeV}$	5.60	5.71	3.94	4.77	0.018	1.10	5.89
$M(j_1j_2\ell_2)<110(100)\,\mathrm{GeV}$	5.51	5.71	3.94	2.23(1.40)	0.0088(0)	1.10(1.10)	3.34(2.50)
$M(j_1j_2\ell_2)>90(80)\,\mathrm{GeV}$	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 under 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

$$\lambda_{\tilde{N}\ell^+\tilde{\chi}^-} = \frac{i}{\sqrt{2}} y^{\nu}_{ab} V_{12} \frac{1+\gamma_5}{2}, \tag{3}$$

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

$$\Gamma(\tilde{\chi}^{\pm} \to \ell^{\pm}_a \tilde{N}_b) = \frac{(m^2_{\tilde{\chi}} - m^2_{\tilde{N}})^2}{64\pi m^3_{\tilde{\chi}}} |y^{\nu}_{ab}|^2 |V_{12}|^2. \tag{4}$$

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.

Estimating neutrino Yukawa couplings

The problem in estimating BR is that the observed number of sneutrino event after the full set of cuts does not represent the number of sneutrinos originally produced.

For example the probability of detecting two lepton that leads to a same-sign dilepton signature is:

$$\begin{aligned}
P(N(\ell)=2) = {} & \epsilon(\ell_1)\epsilon(\ell_2) \times \mathrm{BR}(N \to \ell jj) \times \mathrm{BR}(W^* \to \mathrm{hadrons}) \\
& + \epsilon(\ell_1)\epsilon(\ell_2)(1-\epsilon(\ell_3)) \times \mathrm{BR}(N \to \ell jj) \times \mathrm{BR}(W^* \to \mathrm{leptons}) \\
& + \epsilon(\ell_2)\epsilon(\ell_3)(1-\epsilon(\ell_1)) \times \mathrm{BR}(N \to \ell jj) \times \mathrm{BR}(W^* \to \mathrm{leptons}),
\end{aligned}$$

Summary

- NMSSMr gives a neutrino mass machnism and make right-hand sneutrino as a Dark-matter candidate.
- The rare chargino decay is detectable in the future e^+e^- collider.
- If the right-handed sneutrino is the LSP in the NMSSM with right-handed neutrinos, the Yukawa couplings is smaller than 10^{-6}.

Thank you!