PROCEEDINGS OF SCIENCE

Measuring neutrino dynamics in NMSSM with a right-handed sneutrino LSP at the ILC

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In this study, we explore the possibility of using a 'dijet + dilepton + Missing Transverse Energy' (MET) signature to measure the neutrino Yukawa couplings in the Next-to-Minimal Supersymmetric Standard Model with right-handed neutrinos (NMSSM) when the lightest Supersymmetric partner (a right-handed sneutrino) is the Dark Matter (DM) candidate. We demonstrate that, unlike the minimal realization of Supersymmetry (MSSM) in which the DM candidate is a much heavier neutralino, the NMSSM model allows for a much lighter sneutrino to be the DM candidate, which can be produced at future e^+e^- colliders with energies up to around 500 GeV. The resulting signal from chargino pair production and subsequent decay is very pure, providing the potential to extract the Yukawa parameters of the (s)neutrino sector. These findings may motivate searches for light DM signals at such accelerators, where the mass of DM candidate is around the Electro-Weak (EW) scale.

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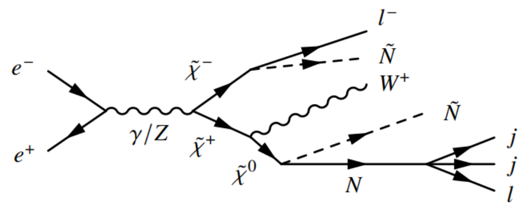

Figure 1: An example of a full process leading to the 'dijet + dilepton + $\not{E}_T$' signature.

1. Introduction

The Large Hadron Collider (LHC) experiments have so far shown good agreement with the predictions of the Standard Model (SM). Some experiments instead shows that the SM needs to be extended. Neutrino oscillations require neutrinos has non-zero mass [1]. Seesaw mechanism is a natural way to explain neutrino masses [2]. From the observation of Cosmic Microwave Background (CMB) [3] and galactic rotation curves [4], it strongly support the existence of Dark matter. Supersymmetry, as one of the most studied frameworks to beyond the SM (BSM) theories, offers a natural DM candidate. The combination of SUSY and seesaw mechanism gives an option of non-standard DM candidates. Specifically, the right-handed sneutrino, when is the Lightest Supersymmetric Particle (LSP), has been of considerable interest over the years [5–7]. Adding a singlet to the MSSM with right-hand sneutrino, the NMSSMr, allows a coupling between the heavy Higgses and sneutrinos, which can assist in the DM annihilation and lead to the correct relic abundance without the need for any left-right mixing in the sneutrino sector [9].

2. 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 given by [9]

$$W = W_{\text{NMSSM}} + \lambda_N SNN + y_N H_2 \cdot LN, \tag{1}$$

$$W_{\text{NMSSM}} = y_u H_2 \cdot Qu + y_d H_1 \cdot Qd + y_e H_1 \cdot Le - \lambda S H_1 \cdot H_2 + \frac{1}{3}\kappa S^3. \tag{2}$$

The process $e^+e^- \rightarrow \gamma/Z \rightarrow \tilde{\chi}^+\tilde{\chi}^-$ is considered. One of the chargino decaying to a lepton and a sneutrino and the other chargino decaying into a neutralino and a virtual W. The decay $\tilde{\chi} \rightarrow \ell\tilde{N}$ arises from the neutrino Yukawa coupling and such a tiny Yukawa couplings makes the decay rare even with favourable kinematics. The Feynman diagram is:

From the Feynman diagram, we can find the signature is 'dijet + dilepton + MET'. The dilepton component should emerge in both same-sign and opposite-sign dileptons due to the Majorana nature of the right-handed neutrino. The latter will have a smaller background from SM processes. The major SM background to this final state comes from the following processes.

- W^+W^-Z production in the case where one $W^\pm$ boson decays into two jets and the other to a lepton and neutrino while the Z boson gives two leptons, one of which is missed by the detector.

- ZZZ production, where the first Z boson decays leptonically, the second Z decay to neutrinos and the third one produce the two jets.

- $t\bar{t}$ production, One of the top (anti)quarks decay to a $W^\pm$ boson plus a b-quark, while one lepton produced from the $W^\pm$ boson and the other lepton from a B-meson.

3. Event simulation

We prepared three Benchmark Points (BPs), which can be detected by the International Linear Collider (ILC) with $\sqrt{s}$ = 500 GeV. The integrated luminosity is 4000 fb^{-1} [10].In our BPs, the charginos is slightly lighter than 250 GeV and the right-handed neutrino and sneutrino is light enough in order to make the process $\tilde{\chi}^0 \to \tilde{N}N$ kinematically allowed. Some detail of our BPs is shown in Table 1. We use MadDM v3.0 [11] to check that the BPs satisfy the constraints from the relic density and direct detetion experiments.

	BP1	BP2	BP3
$m(\tilde{\chi}_1^\pm)$ (GeV)	239.3	234.8	233.3
$m(\tilde{\chi}_1^0)$ (GeV)	233.3	228.7	227.3
$m(\tilde{N}_1)$ (GeV)	130.6	127.9	127.4
$m(N_1)$ (GeV)	101.7	90.5	88.6
BR($N \to \ell jj$)	60%	68%	68%
BR($W^* \to$ leptons)	28%	28%	28%
$\tan\beta$	2.3	2.4	2.1
y^ν_{1j}, y^ν_{2j} (10^{-7})	5.3, 3.5	6.1, 4.7	5.3, 4.0

Table 1: Some mass spectrum and parameter in BPs

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We select two same-sign leptons, two jets and veto against b-jets as a handle. The preselection and full cuts are given in Table 2. It also shows the event number changing when cut applied.

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	$N(b) = 0$

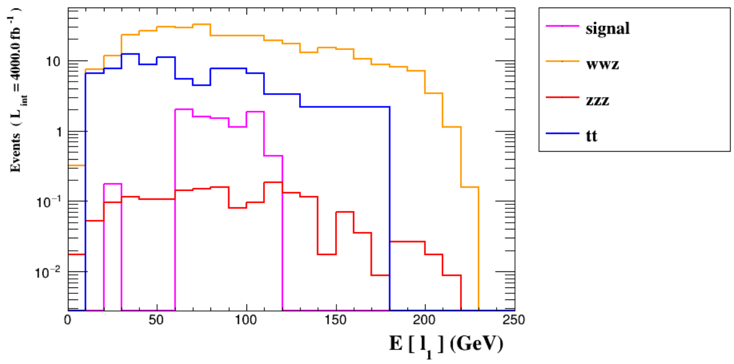

Figure 2: The energy of the leading lepton ℓ_1 for our signal and different background components.

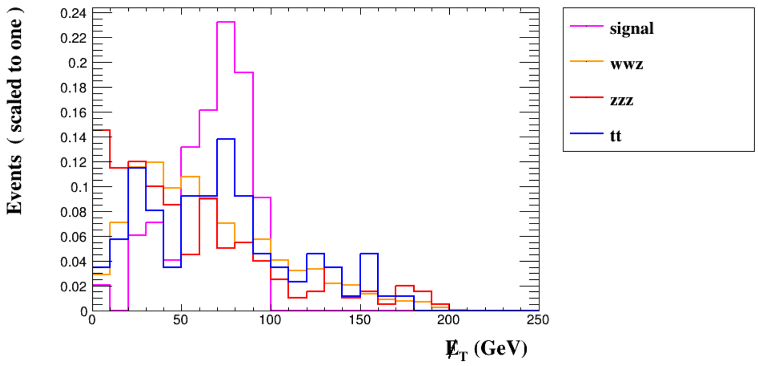

Figure 3: The MET distribution for the signal and background components. Here we have normalised the distributions to unity.

4. Estimating neutrino Yukawa couplings

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

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

where a, b refer to neutrino flavours and $|V_{12}| \simeq 1$ in our BPs which represent the higgsino component of the lightest chargino. 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 majority of charginos decay via $\tilde{\chi}^\pm \to \tilde{\chi}^0 \ell^\pm \nu, \tilde{\chi}^0 q\bar{q}'$. This decay is mediated by several heavy particles ($W^\pm$, $\tilde{\ell}^\pm$, $\tilde{\nu}$, $H^\pm$, $\tilde{q}$) and their contributions can interfere. The measurement of the Branching Ratio (BR) of this rare chargino decay would give us an estimate of the neutrino Yukawa couplings through the computed full width. The calculation details are shown in [12].

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
$p_T(j_1) < 70$ GeV	8.66	12.0	8.35	154.5	0.625	26.3	181.4
$p_T(\ell_1) > 30$ GeV	7.87	10.2	8.11	134.5	0.519	17.6	152.6
$p_T(\ell_2) < 40$ GeV	7.87	10.2	8.11	95.7	0.36	17.6	113.7
$H_T < 100$ GeV	7.87	10.2	8.00	76.5	0.24	11.0	87.7
$E(\ell_1) < 120$ GeV	7.87	10.2	8.00	55.5	0.176	7.68	63.4
$E(\ell_1) > 60$ 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
MET > 50 GeV	6.82	7.38	4.98	9.70	0.026	2.19	11.9
MET < 100 GeV	6.82	5.99	4.06	8.27	0.026	2.19	10.5
$M(\ell_1\ell_2) < 80$ GeV	5.60	5.71	3.94	4.77	0.018	1.10	5.89
$M(j_1j_2\ell_2) < 110(100)$ GeV	5.51	5.71	3.94	2.23(1.40)	0.0088(0)	1.10(1.10)	3.34(2.50)
$M(j_1j_2\ell_2) > 90(80)$ GeV	3.67	3.48	2.43	1.11(0.636)	0.0088(0)	0(0)	1.1(0.64)

Table 2: The cutflow for the signal BPs and all background. The luminosity is 4000 fb^{-1} and the energy is $\sqrt{s}$ = 500 GeV.

5. Conclusions

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.

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References

[1] C. Athanassopoulos *et al.* [LSND Collaboration], Phys. Rev. Lett. **81** (1998) 1774 [nucl-ex/9709006].

[2] P. Minkowski, Phys. Lett. B **67** (1977) 421.

[3] P. A. R. Ade *et al.* [Planck Collaboration], Astron. Astrophys. **571** (2014) A16 [arXiv:1303.5076 [astro-ph.CO]].

[4] F. Zwicky, Helv. Phys. Acta **6** (1933) 110.

[5] S. Khalil and S. Moretti, "Supersymmetry Beyond Minimality: From Theory to Experiment",' (CRC Press, December 2017).

[6] T. Asaka, K. Ishiwata and T. Moroi, Phys. Rev. D **73** (2006) 051301 [arXiv:hep-ph/0512118 [hep-ph]].

[7] A. Chakraborty, S. Moretti, C. H. Shepherd-Themistocleous and H. Waltari, JHEP **06** (2021) 027 [arXiv:2012.14034 [hep-ph]].

[8] N. Arkani-Hamed, L. J. Hall, H. Murayama, D. Tucker-Smith and N. Weiner, Phys. Rev. D **64** (2001) 115011 [arXiv:hep-ph/0006312 [hep-ph]].

[9] D. G. Cerdeño, C. Muñoz and O. Seto, Phys. Rev. D **79** (2009) 023510 [arXiv:0807.3029 [hep-ph]].

[10] T. Barklow, J. Brau, K. Fujii, J. Gao, J. List, N. Walker and K. Yokoya, arXiv:1506.07830 [hep-ex].

[11] F. Ambrogi, C. Arina, M. Backovic, J. Heisig, F. Maltoni, L. Mantani, O. Mattelaer and G. Mohlabeng, Phys. Dark Univ. **24** (2019) 100249 [arXiv:1804.00044 [hep-ph]].

[12] Y. Liu, S. Moretti, and H. Waltari J. High Energ. Phys. 2022, 34 (2022). [arXiv:2109.06802 [hep-ph]]