Displaced Higgs production in Supersymmetric type III seesaw model at the LHC

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Neutrinos

- In 1930 Pauli postulated the neutrino:

$$n \longrightarrow p^{+} + e^{-} + \bar{\nu}^{0}$$

$$\Downarrow$$

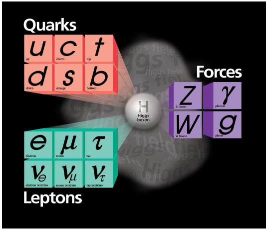
Takes away the remaining part of energy, momentum and angular momentum to balance the initial & final states

- 1956 Reines & Cowan first discovered the neutrinos through:

$$\bar{\nu}_e + p^{+} \longrightarrow n + e^{+}$$

- Reines was awarded the Nobel prize in 1995.

Particle Spectrum



- SM predicted the existence of W, Z, gluon, top and charm quark.
- Predicted properties were experimentally confirmed with good precision.
- Higgs mass is not protected by any symmetry ⇒ Hierarchy problem.
- No cold dark matter candidate.
- Neutrinos are massless in SM.

Hierarchy & Supersymmetry

- Supersymmetry protects the Higgs mass by giving possible cancellation. ⇒ For each particle there is a super partner differing by spin 1/2.
- *R*-parity, $P_R = (-1)^{3(\mathrm{B}-\mathrm{L})+2\mathrm{s}}$⇒ LSP(Lightest supersymmetric particle) can not decay ⇒ a cold dark matter candidate.
- But still can not generate neutrino mass.
- There are some *R*-parity violating model which generates small neutrino masses at loop level.
- But breaking *R*-parity ⇒ no cold dark matter candidate.

Seesaw model

- Seesaw mechanism is one where the smallness of neutrino mass is explained by a large scale.
- There are different versions of this seesaw mechanism but have a basic structure:

$$M_\nu \simeq \frac{< v >^2}{M_{\text{seesaw}}} \simeq \frac{\text{MeV}^2}{\text{TeV}} \approx \text{eV}$$

- Introduces two scales: very high scale and a moderate scale to get the very small scale.
- We supersymmetrize the type III seesaw models.

1. we can generate neutrino mass at the tree-level
2. as well as we have a drak matter candidate

Supersymmetric seesaw model

- We supersymmetrize the type III seesaw models.
- Advantage of doing this is that,
  1. we can generate neutrino mass at the tree-level
  2. as well as we have a drak matter candidate
- Type III seesaw mechanism ⇒ real $SU(2)_L$ triplets with $Y = 0$.

$$\mathbf{\Sigma} = \Sigma_i \cdot \sigma_i = \begin{pmatrix} \Sigma^0 & \sqrt{2}\Sigma^+ \\ \sqrt{2}\Sigma^- & -\Sigma^0 \end{pmatrix}$$

where $\Sigma^{\pm} = \frac{1}{\sqrt{2}}(\Sigma_1 \mp i\Sigma_2)$

- The superpotential is given by,

$$W_{III} = yL^T i\sigma_2 \mathbf{\Sigma} H_2 + \frac{1}{4} M \mathrm{Tr}(\mathbf{\Sigma}^2) \,,$$

Neutrino mass and type III seesaw model

- Integrating heavy triplet fields one gets the neutrino mass as,

$$\tilde{m}_\nu = \frac{|y|^2 v_2^2}{M} \, ,$$

where $v_2 = \langle H_2^0 \rangle$. $V = \sqrt{v_1^2 + v_2^2} = 174$ GeV

- Neutrino mass ~ 0.05 eV
- DM searches $\Rightarrow$ $m_{\tilde{\Sigma}_1^{0,\pm}} \geq 550$ GeV E. J. Chun
- There are mass splitting among the scalar triplets and the mass eigenstates are

$$\tilde{\Sigma}_1^0 = \frac{1}{\sqrt{2}i}(\tilde{\Sigma}^0 - \tilde{\Sigma}^{0*}), \quad \tilde{\Sigma}_2^0 = \frac{1}{\sqrt{2}}(\tilde{\Sigma}^0 + \tilde{\Sigma}^{0*}),$$
$$\tilde{\Sigma}_{1,2}^+ = \frac{1}{\sqrt{2}}(\tilde{\Sigma}^+ \mp \tilde{\Sigma}^{-*}).$$

Scalar triplet in type III seesaw model

- The neutral scalar components with $T_3 = 0$ take the mass-squareds given by

$$m^2_{\tilde{\Sigma}^0_{2,1}} = M^2 + \tilde{m}^2 \pm BM\,.$$

- The mass-squared eigenvalues of the charged scalar components $\tilde{\Sigma}^{\pm}$ carrying $T_3 = \pm 1$ are

$$m^2_{\tilde{\Sigma}^{\pm}_{2,1}} = M^2 + \tilde{m}^2 \pm \sqrt{B^2 M^2 + c^4_W m^4_Z c^2_{2\beta}}\,.$$

  where c_W is the cosine of the weak mixing angle and the angle β is defined by $t_\beta = v_2/v_1$.

- The lighter states $\tilde{\Sigma}_1$ have the mass splitting $\Delta m \equiv m_{\tilde{\Sigma}^{\pm}_1} - m_{\tilde{\Sigma}^0_1} \leq 167$ MeV
  $\Rightarrow \tilde{\Sigma}^{\pm}_1 \rightarrow \pi^{\pm}\tilde{\Sigma}^0_1 / e^{\pm}\nu_e\tilde{\Sigma}^0_1$
  $\Rightarrow$ highly-ionizing tracks longer than 5.5 cm

E.J. Chun

Couplings of the dark matter triplets

- The light Higgs boson couplings are

$$-\mathcal{L}_{h^0} = \frac{y\cos\alpha}{\sqrt{2}}(M - A - \mu\tan\alpha)\,h^0\left[\tilde{l}^-\tilde{\Sigma}_1^+ + \tilde{l}^+\tilde{\Sigma}_1^- - \tilde{\nu}_l\tilde{\Sigma}_1^0\right]$$

- Higgs field VEV gives rise to the $\tilde{l}^\pm$–$\tilde{\Sigma}_1^\pm$ and $\tilde{\nu}$–$\tilde{\Sigma}_1^0$ mixing.

$$\theta_{\tilde{l}} \approx \frac{yv_2(M - A + \mu/\tan\beta)}{(m_{\tilde{l}}^2 - m_{\tilde{\Sigma}_1^+}^2)}$$

$$\text{and} \quad \theta_{\tilde{\nu}} \approx -\frac{yv_2(M - A + \mu/\tan\beta)}{(m_{\tilde{\nu}}^2 - m_{\tilde{\Sigma}_1^0}^2)}$$

- The fermion couplings give the mixing between l (ν) and Σ^- (Σ^0):

$$\theta_l \approx \frac{\sqrt{2}yv_2}{M} \quad \text{and} \quad \theta_\nu \approx \frac{yv_2}{M}\,.$$

Cascade decays

- The SUSY cascades of strongly interacting particles (squarks & gluinos):⇒ Large production cross-section

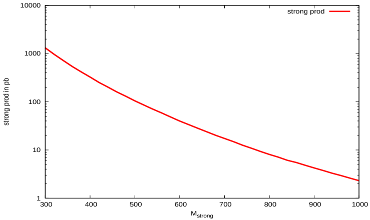


Figure: Strong Supersymmetric production cross-section in pb in y-axis and $M_{\tilde{q}} = M_{\tilde{g}} = M_{\rm strong}$ in GeV in x-axis

- If the dark matter triplets are LSPs then can be copiously produce in the cascade decays.
- NLSP decaying to these triplet(s) will be interesting.

NLSP decay to dark matter triplets

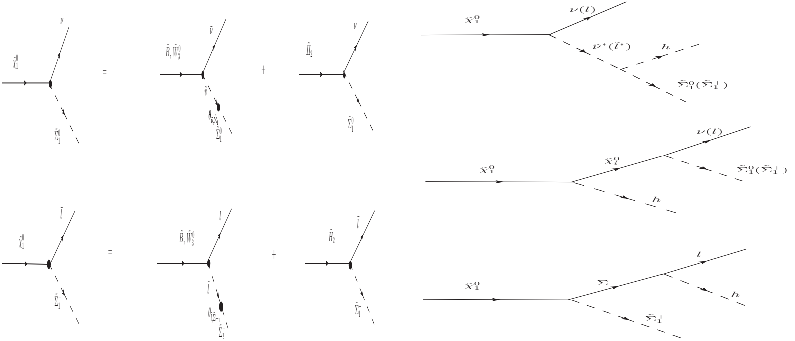


Figure: Feynman diagrams for the NLSP two-body decay (left) $\chi_1^0 \to \nu\tilde{\Sigma}_1^0$ and $l^\pm\tilde{\Sigma}_1^\mp$ and three-body decay (right) $\chi_1^0 \to \nu h^0\tilde{\Sigma}_1^0$ and $l^\pm h^0\tilde{\Sigma}_1^\mp$.

Input parameters & Mass spectrum

- The input parameters for our example are given below.

  $$m_{\tilde{\Sigma}} = 550\mathrm{GeV}, \quad \mathrm{M} = 1\mathrm{TeV} \mathrm{m}_{\tilde{\mathrm{q}},\, \tilde{\mathrm{g}}} = \mathrm{m}_{\tilde{\mathrm{l}},\, \tilde{\nu}} = 900\,\mathrm{GeV}$$
  $$m_A = 600\,\mathrm{GeV}, \quad \mu = -2000\,\mathrm{GeV},$$
  $$A_t = -1000\,\mathrm{GeV}, \quad \mathrm{A}_{\mathrm{b},\tau} = 0 \quad \tan\beta = 10$$
  $$M_1 = 750\,\mathrm{GeV}, \quad \mathrm{M}_2 = 800\,\mathrm{GeV}, \quad \mathrm{M}_3 = 900\,\mathrm{GeV}$$

- A is varied from -1 TeV to 2 TeV.
- With this set of input parameters, the corresponding Higgs mass spectum is:

  $$m_h = 119\,\mathrm{GeV}, \quad \mathrm{m}_{\mathrm{H}} = 599\,\mathrm{GeV},$$
  $$m_A = 600\,\mathrm{GeV}, \quad \mathrm{m}_{\mathrm{H}^\pm} = 604\,\mathrm{GeV}$$

- The gaugino mass spectrum is :

  $$m_{\chi_1^0} = 745\,\mathrm{GeV}, \quad \mathrm{m}_{\chi_2^0} = 810\,\mathrm{GeV}$$
  $$m_{\chi_3^0} = 1983\,\mathrm{GeV}, \quad \mathrm{m}_{\chi_4^0} = 1984\,\mathrm{GeV}$$

Decay of the Bino NLSP to dark matter triplets

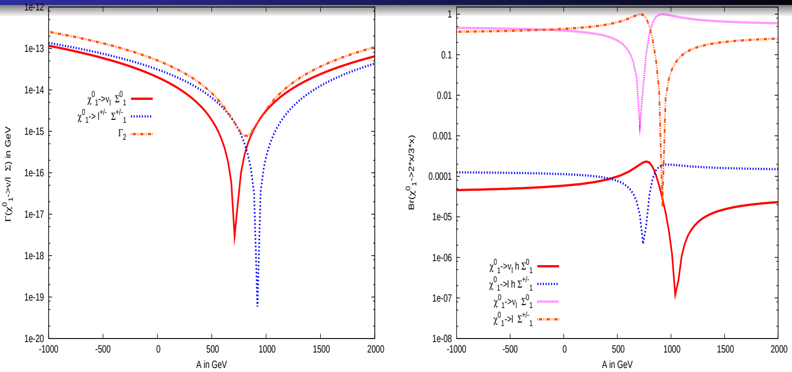


Figure: Partial and total two-body decay width of $\chi_1^0 \to \nu_e(l)\Sigma_1^0(\Sigma_1^+)$ (left)with M=1 TeV and A varied in the x axis. The effective neutrino mass is taken to be $\tilde{m}_\nu = 0.05$ eV.Branching fractions of different modes on of χ_1^0(right)

- Because of the $(M - A + \mu/\tan\beta)$ nature of the mixing angle we have the suppression in the decay widths at some

$\tilde{\tau}_1$ NLSP

- For $\tilde{\tau}_1$ NLSP we changed the following two parameters:

$$m_{\tilde{l}_3} = 700\mathrm{GeV} \quad \text{and} \quad \mathrm{m}_{\tilde{\mathrm{r}}_3} = 800\mathrm{GeV} \Rightarrow \quad m_{\tilde{\tau}} = 696.3 \text{ GeV}$$

- The decay mode $\tilde{\tau}_1 \longrightarrow h\tilde{\Sigma}_1^0$

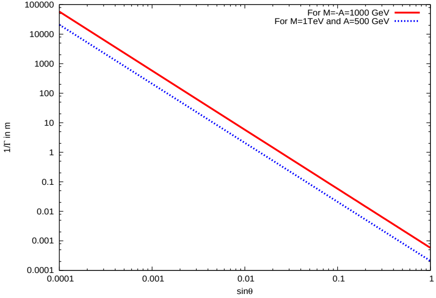


Figure: Decay length in meter of $\tilde{\tau}_1 \longrightarrow h\tilde{\Sigma}_1^0$ (in y-axis) vs $\sin\theta$(x-axis). Wher θ is the mixing angle between $\tilde{\tau}_L$ and $\tilde{\tau}_1$.

Decay lengths & Signals at LHC

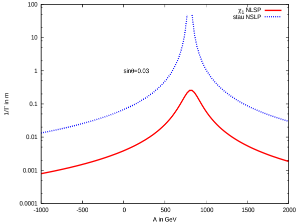


Figure: Decay length in meter for the bino and stau NLSP with M=1 TeV and $\tilde{m}_\nu = 0.05$ eV. Both decay lengths scale with $\tilde{m}_\nu$ and the stau decay length scales with $\sin^2\theta$.

- The two NLSP decay to the charged lepton with displaced vertex could be a signature of this model.
- The three-body decay branching fraction is as low as 0.04% $\Rightarrow$ Have a chance to Higgs production with displaced vertex at higher luminosity.

Signal at the LHC

- Main source of this could be the cascade decays of the $\tilde{q}$ and $\tilde{g}$.
- Production cross-section of which drops to a low value for Higher values of $m_{\tilde{q},\tilde{g}}$.
- Wino like NLSP:
  The decay length is a bit shorter as $(g > g')$.
- Higgsino like NLSP:
  Here the decay length is much shorter as the coupling is propotional to y_ν.

References:
[1] E.J. Chun, *Minimal dark matter in type III seesaw, JHEP 0912:055,2009[arXiv:0909.3408 [hep-ph]]*
[2]Priyotosh Bandyopadhyay, Eung Jin Chun,*Displaced Higgs production in type III seesaw*, [arXiv:1007.2281 [hep-ph]]

Conclusions

- Supersymmetric type III seesaw is capable of generating neutrino masses and new dark matter candidate.
- With the DM constraint this dark matter triplets are relatively heavy ($\geq$ 550 GeV)
- The new dark matter triplet gets mixed with the $\tilde{l}, \tilde{\nu}$.
- Similar is the case for Σ fermion and leptons.
- Due to the cancellation in the vertices, the mixing angles as well the decay widths go down.
- For some parameters space this lead to displaced production of the leptons in case of two body decays.
- For Higher luminosity one can expect to have Higgs production with displaced vertex
- The production of these mainly depends on the cascade decay of the strongly interacting SUSY particles.

Thank you