

Displaced Higgs production in type III seesaw

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ABSTRACT: We point out that the type III seesaw mechanism introducing fermion triplets predicts peculiar Higgs boson signatures of displaced vertices with two b jets and one or two charged particles which can be cleanly identified. In a supersymmetric theory, the scalar partner of the fermion triplet contains a neutral dark matter candidate which is almost degenerate with its charged components. A Higgs boson can be produced together with such a dark matter triplet in the cascade decay chain of a strongly produced squark or gluino. When the next lightest supersymmetric particle (NLSP) is bino/wino-like, there appears a Higgs boson associated with two charged tracks of a charged lepton and a heavy charged scalar at a displacement larger than about 1 mm. The corresponding production cross-section is about 0.5 fb for the squark/gluino mass of 1 TeV. In the case of the stau NLSP, it decays mainly to a Higgs boson and a heavy charged scalar whose decay length is larger than 0.1 mm for the stau NLSP mixing with the left-handed stau smaller than 0.3. As this process can have a large cascade production ~ 2 pb for the squark/gluino mass ~ 1 TeV, one may be able to probe it at the early stage of the LHC experiment.

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1. Introduction

The observed neutrino masses and mixing may arise from a TeV scale seesaw mechanism. This implies that new particles responsible for the seesaw mechanism have TeV-scale masses and their Yukawa couplings to neutrinos, denoted by y_ν , are as small as the electron Yukawa coupling. This comes from the fact that the seesaw mass of neutrinos are given by $m_\nu \sim y_\nu^2 v^2 / M$ where $v = 174$ GeV is the Higgs vacuum expectation value and M is the new particle mass. One has $y_\nu \sim 10^{-6}$ for $m_\nu \sim 0.01$ eV and $M = 1$ TeV. As a consequence of a small neutrino Yukawa coupling, TeV-scale seesaw particles can leave displaced vertices which are observable in the LHC detectors. Furthermore, neutrino Yukawa couplings usually involve a Higgs boson and thus it can be produced at such displaced vertices. Since this gives a clean signature free from backgrounds, one may be able to probe a light Higgs boson through its main decay channel $h \rightarrow b\bar{b}$.

A typical example realizing such a feature is the type III seesaw mechanism [1] where a massive $SU(2)_L$ triplet fermion $\Sigma = (\Sigma^+, \Sigma^0, \Sigma^-)$ carrying no hypercharge under $U(1)_Y$ is introduced to provide the neutrino Yukawa coupling; $y_\nu LH_2\Sigma$. Rich phenomenology of the type III seesaw has been studied in Refs. [2, 3, 4, 5, 6]. In this model, the seesaw particles $\Sigma^{\pm,0}$ are produced through electroweak interactions and their main decay modes are $\Sigma^\pm(\Sigma^0) \rightarrow l^\pm(\nu)h$ through the Yukawa coupling y_ν . The corresponding decay length τ_Σ of $\Sigma^{\pm,0}$ can be long enough to be measured at the LHC if y_ν is small enough. For instance, $\tau_\Sigma = 0.6$ mm for $y_\nu^2 v^2 / M = \text{meV}$ and $M = 500$ GeV. The production cross-section of the process $\Sigma^\pm(\Sigma^0) \rightarrow l^\pm(\nu)b\bar{b}$ is in the range of 1 pb – 1 fb for the mass range $M = 0.2 - 1$ TeV [2]. This can be compared to the cross-section for an important Higgs

discovery channel $h \rightarrow \gamma\gamma$. This process suffers a huge background and the expected cross-section for the Higgs boson plus two jet analysis goes down to about 1 fb [7]. Thus, one may anticipate the first Higgs discovery through the production of the triplet in the type III seesaw mechanism.

In this work, we consider a cascade production of displaced Higgs bosons in the supersymmetric type III seesaw. Our focus is on the parameter region of large triplet fermion mass $M \sim 1$ TeV and large neutrino Yukawa y_ν corresponding the atmospheric neutrino mass scale $m_\nu \approx 0.05$ eV for which the triplet fermion decays almost promptly and thus leaves no observable displaced vertices. An interesting aspect of the supersymmetric type III seesaw is that the observational evidences for dark matter and neutrino mass can be correlated in a way that the supersymmetric partner $\tilde{\Sigma}$ of the triplet fermion Σ is the dark matter particle. More precisely, the neutral component $\tilde{\Sigma}^0$ of the scalar triplet can be the lightest supersymmetric particle (LSP) and thus can be dark matter if R-parity is conserved. In this case, next lightest supersymmetric particles (NLSPs) are produced by cascade decays of strongly produced squarks or gluinos, and finally decay to a Higgs boson associated with the dark matter $\tilde{\Sigma}^0$ or its charged companion $\tilde{\Sigma}^\pm$. The NLSP decay involves additional suppression other than the neutrino Yukawa coupling, and thus the decay length becomes much longer than the Σ decay discussed above. Then there will be observable displaced vertices with two b jets and one or two charged particles depending on what the NLSP is. For our discussion, we will take a neutralino or a stau as the NLSP. Recall that various astrophysical and cosmological observations put a rather strong bound on the dark matter mass: $m_{\tilde{\Sigma}^0} \gtrsim 520$ GeV [8]. This pushes up all the ordinary supersymmetric particle masses and thus a compact supersymmetric spectrum is needed to increase the cascade Higgs boson production rate.

This paper is organized as follows. In Section 2, we will introduce the type III seesaw mechanism realizing the dark matter triplet and present all the vertices needed for our calculation. Section 3 presents our main results on the cascade production of the Higgs boson at displaced vertices taking the NLSP as a neutralino or a stau. We conclude in Section 4.

2. Type III seesaw and dark matter triplet

2.1 Supersymmetric type III seesaw

The type III seesaw mechanism introduces real $SU(2)_L$ triplets with $Y = 0$. Using the matrix representation, the triplet field can be written as

$$\mathbf{\Sigma} = \Sigma_i \cdot \sigma_i = \begin{pmatrix} \Sigma^0 & \sqrt{2}\Sigma^+ \\ \sqrt{2}\Sigma^- & -\Sigma^0 \end{pmatrix} \quad (2.1)$$

where $\Sigma^\pm = \frac{1}{\sqrt{2}}(\Sigma_1 \mp i\Sigma_2)$. The gauge invariant superpotential is then

$$W_{III} = y_\nu L^T i\sigma_2 \mathbf{\Sigma} H_2 + \frac{1}{4} M \text{Tr}(\mathbf{\Sigma}^2), \quad (2.2)$$

where we suppressed lepton flavor indices and the scalar component of Σ is assumed to form the dark matter triplet. We will assume one flavor dominance for our calculations. Expanding the above superpotential in components, we get

$$W_{III} = -y_\nu \left[\sqrt{2} l \Sigma^+ H_2^0 + \nu \Sigma^0 H_2^0 + \sqrt{2} \nu \Sigma^- H_2^+ + l \Sigma^0 H_2^+ \right] + M \Sigma^+ \Sigma^- + \frac{M}{2} \Sigma^0 \Sigma^0. \quad (2.3)$$

Integrating out the heavy triplet fields one obtains the seesaw neutrino mass matrix. Here we define the effective neutrino mass associated with the dark matter triplet

$$\tilde{m}_\nu = \frac{|y|^2 v_2^2}{M}, \quad (2.4)$$

where $v_2 = \langle H_2^0 \rangle$.

Let us now briefly describe the properties of the scalar dark matter triplet $\tilde{\Sigma}$ [8]. Including supersymmetric and soft supersymmetry breaking terms, we get the mass terms of the dark matter triplet from

$$V_{mass} = (M^2 + \tilde{m}^2)(|\tilde{\Sigma}^+|^2 + |\tilde{\Sigma}^-|^2) + (M^2 + \tilde{m}^2)|\tilde{\Sigma}^0|^2 \quad (2.5)$$

$$+ BM \left[\tilde{\Sigma}^+ \tilde{\Sigma}^- + \frac{1}{2} \tilde{\Sigma}^0 \tilde{\Sigma}^0 + h.c. \right] + \frac{g^2}{8} \left[|H_1^0|^2 - |H_2^0|^2 + 2|\tilde{\Sigma}^+|^2 - 2|\tilde{\Sigma}^-|^2 \right]^2,$$

where we assume that B is positive definite without loss of generality. Because of the off-diagonal B term, the mass eigenstates become $\tilde{\Sigma}_{1,2}^0 = \frac{1}{\sqrt{2i}}(\tilde{\Sigma}^0 - \tilde{\Sigma}^{0*})$, $\tilde{\Sigma}_2^0 = \frac{1}{\sqrt{2}}(\tilde{\Sigma}^0 + \tilde{\Sigma}^{0*})$ and $\tilde{\Sigma}_{1,2}^\pm = \frac{1}{\sqrt{2}}(\tilde{\Sigma}^\pm \mp \tilde{\Sigma}^{-*})$. The neutral scalar components with $T_3 = 0$ take the mass-squareds given by

$$m_{\tilde{\Sigma}_{2,1}^0}^2 = M^2 + \tilde{m}^2 \pm BM, \quad (2.6)$$

where \tilde{m} is the soft supersymmetry breaking mass. Including the D-term contribution, the mass-squared eigenvalues of the charged scalar components $\tilde{\Sigma}^\pm$ carrying $T_3 = \pm 1$ are

$$m_{\tilde{\Sigma}_{2,1}^\pm}^2 = M^2 + \tilde{m}^2 \pm \sqrt{B^2 M^2 + c_W^4 m_Z^4 c_{2\beta}^2}. \quad (2.7)$$

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 $\Delta m_{\tilde{\Sigma}} \equiv m_{\tilde{\Sigma}_1^\pm} - m_{\tilde{\Sigma}_1^0}$ which is composed of the negative tree-level contribution [Eqs. (2.6, 2.7)] and the positive one-loop contribution [$\Delta m_{\text{loop}} \simeq 167$ MeV] [9]. Thus the total mass splitting $\Delta m_{\tilde{\Sigma}}$ is smaller than 167 MeV but can remain positive depending on the values of BM . In this case, $\tilde{\Sigma}_1^0$ can be the LSP dark matter, and $\tilde{\Sigma}_1^\pm$ decays to $\pi^\pm \tilde{\Sigma}_1^0$ or $e^\pm \nu_e \tilde{\Sigma}_1^0$. The charged scalar triplets have decay length larger than 5.5 cm and thus leaves slowly-moving and highly-ionizing tracks that can be detected at the LHC [8].

2.2 Couplings of dark matter triplet

From the superpotential in Eq. (2.3) one can find the F-term couplings involving the neutral Higgs bosons $H_{1,2}^0$:

$$V_F = y_\nu \left[-\sqrt{2} M \tilde{l} \tilde{\Sigma}^{-*} H_2^0 - M \tilde{\nu} \tilde{\Sigma}^{0*} H_2^0 + \sqrt{2} \mu \tilde{l} \tilde{\Sigma}^+ H_1^{0*} + \mu \tilde{\nu} \tilde{\Sigma}^0 H_1^{0*} \right] + h.c., \quad (2.8)$$

where the μ terms come from the Higgs bilinear term in the superpotential, $W_H = \mu H_1 H_2$. The soft supersymmetry breaking interactions are given by

$$V_{\text{soft}} = -\sqrt{2}y_\nu A \tilde{l}\tilde{\Sigma}^+ H_2^0 - y_\nu A \tilde{\nu}\tilde{\Sigma}^0 H_2^0 + h.c., \quad (2.9)$$

where A is the trilinear soft parameter. Now, taking only the vertices of $\tilde{\Sigma}_1^0$ and $\tilde{\Sigma}_1^\pm$, we have

$$\begin{aligned} -\mathcal{L}_{\text{scalar}} = & y_\nu(M - A) \left[\tilde{l}\tilde{\Sigma}_1^+ H_2^0 - \frac{1}{2}\tilde{\nu}_I \tilde{\Sigma}_1^0 H_2^0 \right] \\ & + y_\nu \mu \left[\tilde{l}\tilde{\Sigma}_1^+ H_1^0 - \frac{1}{2}\tilde{\nu}_I \tilde{\Sigma}_1^0 H_1^0 \right] + h.c.. \end{aligned} \quad (2.10)$$

where $\tilde{\nu}_I \equiv \sqrt{2}\Im(\tilde{\nu})$. This gives rise to the \tilde{l}^\pm - $\tilde{\Sigma}_1^\pm$ and $\tilde{\nu}$ - $\tilde{\Sigma}_1^0$ mixing and the corresponding mixing angles are given by

$$\theta_{\tilde{l}} \approx \frac{y_\nu v_2 (M - A + \mu/\tan\beta)}{(m_{\tilde{l}}^2 - m_{\tilde{\Sigma}_1^+}^2)} \quad \text{and} \quad (2.11)$$

$$\theta_{\tilde{\nu}} \approx -\frac{y_\nu v_2 (M - A + \mu/\tan\beta)}{(m_{\tilde{\nu}}^2 - m_{\tilde{\Sigma}_1^0}^2)} \quad (2.12)$$

for the charged and neutral parts, respectively.¹ Taking only the real degrees of freedom of $H_{1,2}^0$: $H_1^0 = v_1 - \sin\alpha h/\sqrt{2}$ and $H_2^0 = v_2 + \cos\alpha h/\sqrt{2}$, and neglecting heavy Higgs bosons in Eq. (2.10), we get the light Higgs boson couplings:

$$-\mathcal{L}_h = \frac{y_\nu \cos\alpha}{\sqrt{2}} (M - A - \mu \tan\alpha) h \left[\tilde{l}^- \tilde{\Sigma}_1^+ + \tilde{l}^+ \tilde{\Sigma}_1^- - \tilde{\nu}_I \tilde{\Sigma}_1^0 \right] \quad (2.13)$$

Note also that the fermion couplings from Eq. (2.3) give the mixing between l (ν) and Σ^- (Σ^0):

$$\theta_l \approx \frac{\sqrt{2}y_\nu v_2}{M} \quad \text{and} \quad \theta_\nu \approx \frac{y_\nu v_2}{M}. \quad (2.14)$$

The mixing in Eqs. (2.11,2.12, 2.14) induces the gaugino-lepton-dark matter triplet interactions as follows:

$$\begin{aligned} \mathcal{L}_{\text{gaugino}} = & -\frac{g'}{2} \left[i\theta_{\tilde{\nu}} \tilde{B}\nu\tilde{\Sigma}_1^0 + \theta_{\tilde{l}} \tilde{B}l\tilde{\Sigma}_1^+ \right] \\ & + \frac{g}{2} \left[i\theta_{\tilde{\nu}} \tilde{W}_3\nu\tilde{\Sigma}_1^0 - (\theta_{\tilde{l}} + 2\theta_l) \tilde{W}_3 l\tilde{\Sigma}_1^+ \right] + h.c.. \end{aligned} \quad (2.15)$$

Together with the fermion-fermion-scalar couplings from Eq. (2.3), Eqs. (2.13,2.15) define the interactions required for our calculation. Figs. 1 and 2 summarize the neutralino NLSP decay diagrams relevant for our analysis.

¹Note that these mixing angles contain the μ term which was ignored in Ref. [8].

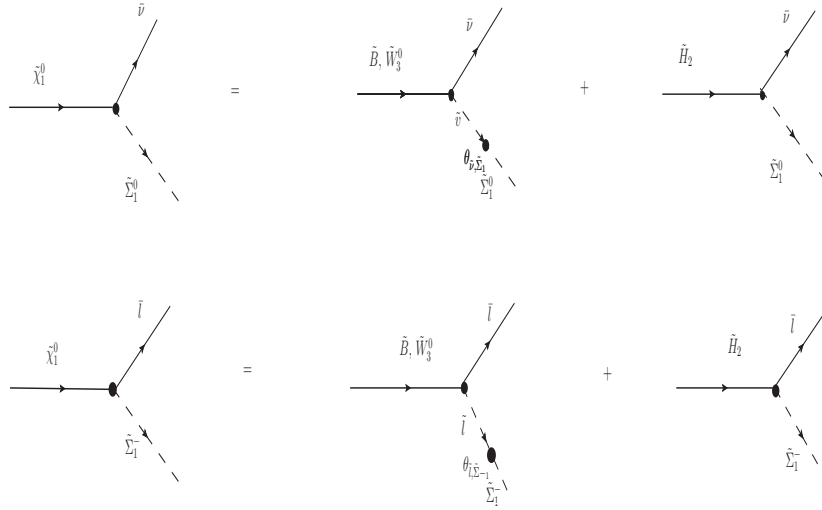


Figure 1: Feynman diagrams for the gaugino NLSP two-body decay: $\chi_1^0 \rightarrow \nu\tilde{\Sigma}_1^0$ and $l^\pm\tilde{\Sigma}_1^\mp$.

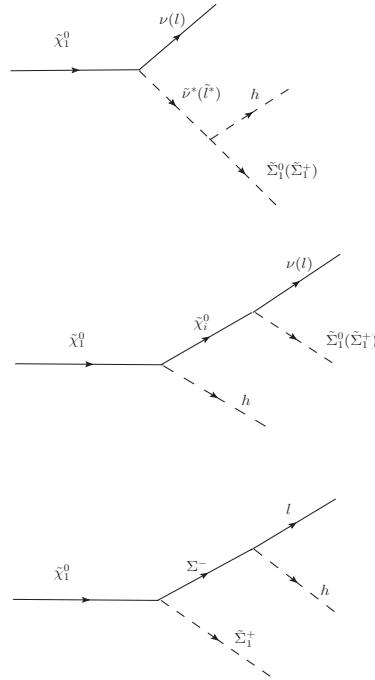


Figure 2: Feynman diagrams for the gaugino NLSP three-body decay: $\chi_1^0 \rightarrow \nu h\tilde{\Sigma}_1^0$ and $l^\pm h\tilde{\Sigma}_1^\mp$.

3. Cascade Higgs production at displaced vertices

3.1 Bino-like NLSP

Let us first consider the bino-like NLSP as a typical example. Since our dark matter candidate has a heavy mass $m_{\tilde{\Sigma}} > 520$ GeV, we choose a compact supersymmetric spectrum

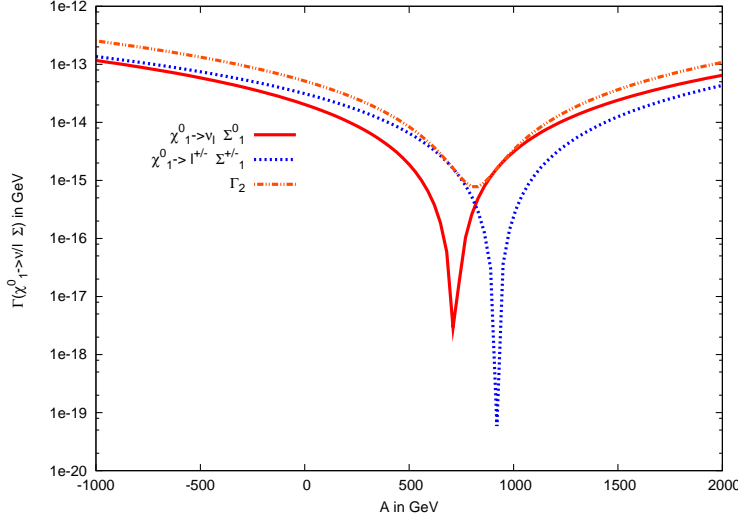


Figure 3: Partial and total two-body decay width of $\chi_1^0 \rightarrow \nu_e(l)\Sigma_1^0(\Sigma_1^+)$ with $M=1$ TeV and A varied in the x axis. The effective neutrino mass is taken to be $\tilde{m}_\nu = 0.05$ eV.

to enhance a cascade production of the light higgs boson and dark matter triplet. For the illustration of our main points, we take input parameters as follows:

$$\begin{aligned}
m_{\tilde{\Sigma}} &= 550 \text{ GeV}, & M &= 1 \text{ TeV} \\
m_{\tilde{q}, \tilde{g}} &= 900 \text{ GeV}, & m_{\tilde{l}, \tilde{\nu}} &= 900 \text{ GeV} \\
m_A &= 600 \text{ GeV}, & \mu &= -2000 \text{ GeV}, & \tan \beta &= 10 & A_t &= -1000 \text{ GeV}, & A_{b,\tau} &= 0 \\
M_1 &= 750 \text{ GeV}, & M_2 &= 800 \text{ GeV}, & M_3 &= 900 \text{ GeV}.
\end{aligned}$$

With this set of input parameters, we get the corresponding Higgs mass spectrum and the gaugino mass spectrum as follows.

$$\begin{aligned}
m_h &= 119 \text{ GeV}, & m_H &= 599 \text{ GeV}, & m_A &= 600 \text{ GeV}, & m_{H^\pm} &= 604 \text{ GeV}, \\
m_{\chi_1^0} &= 745 \text{ GeV}, & m_{\chi_2^0} &= 810 \text{ GeV}, & m_{\chi_3^0} &= 1983 \text{ GeV}, & m_{\chi_4^0} &= 1984 \text{ GeV}.
\end{aligned}$$

Now we calculate the two- and three-body decays of the bino-like NLSP, $\chi_1^0 \rightarrow \nu \tilde{\Sigma}_1^0$, $l^\pm \tilde{\Sigma}_1^\mp$ and $\chi_1^0 \rightarrow \nu h \tilde{\Sigma}_1^0$, $l^\pm h \tilde{\Sigma}_1^\mp$, whose Feynman diagrams are shown in Figs. 1 and 2. For two-body decay widths there are two contributions; one through the mixing with sleptons and the other one is through the direct coupling to H_2 which is evident from Fig. 1. In Fig. 3, we plot the two-body decay rates varying the A parameter of the neutrino Yukawa couplings. The deeps in the plot appear due to the cancellation of different contributions shown in Fig. 1. In particular the cancellation for the charged leptons and the neutrinos occur at different points owing to the difference of $\sqrt{2}$ in the field definitions 2.2. Due to this the total two-body decay is not much suppressed as the partial decay widths. From Fig. 2 we can see the different Feynman diagrams contributing to the three-body decays. In the case of charged lepton three-body decay mode there is one more contribution through the off-shell Σ^\pm . Note that the decay rates are proportional to the effective neutrino mass \tilde{m}_ν (2.4) which is taken to be 0.05 GeV corresponding the atmospheric neutrino mass scale. In Fig. 4, we present the branching ratios of the two-body decays as well as three-

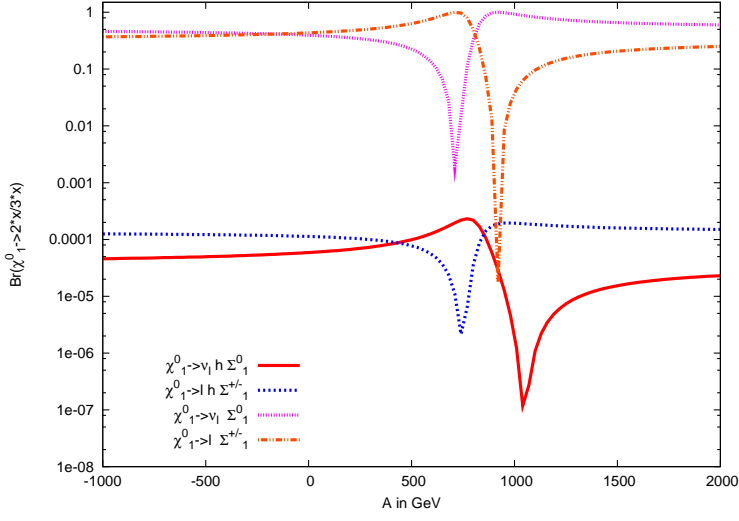


Figure 4: Branching fractions of different modes on of χ_1^0 . Input parameters are the same as in Fig. 3.

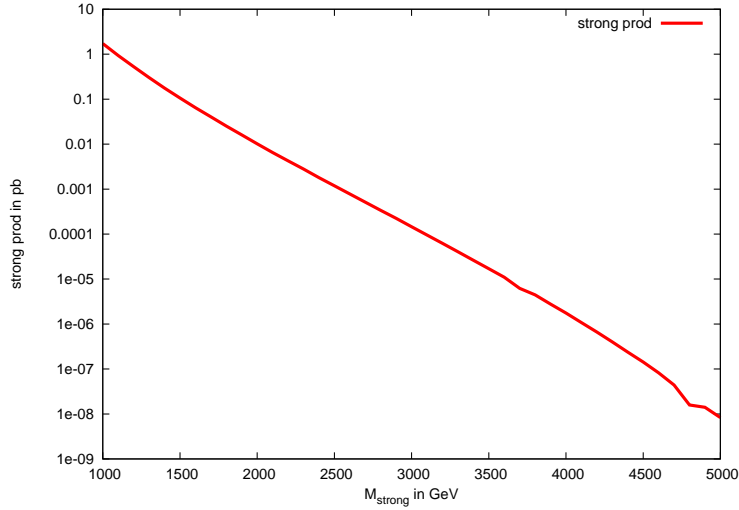


Figure 5: Strong Supersymmetric production cross-section in pb in y-axis and $M_{\tilde{q}} = M_{\tilde{g}} = M_{\text{strong}}$ in GeV in x-axis

body decays involving the Higgs production. The Higgs production is suppressed due to a small three-body phase space. However, the cascade Higgs boson production can be sizable if the supersymmetric particles have a compact mass spectrum near 1 TeV. To show this, we calculate the gluino/squark production cross-section as a function of a common gluino/squark mass in Fig. 5. The total strong supersymmetric production cross-section for our mass spectrum, $m_{\tilde{q}} \approx m_{\tilde{g}} \approx 900$ GeV, is 2.65 pb. Thus, we get the cross-section of about 0.5 fb for the Higgs production accompanied with two charged particles, $\chi_1^0 \rightarrow hl^\pm \tilde{\Sigma}^\mp$, as its branching fraction is about 2×10^{-4} .

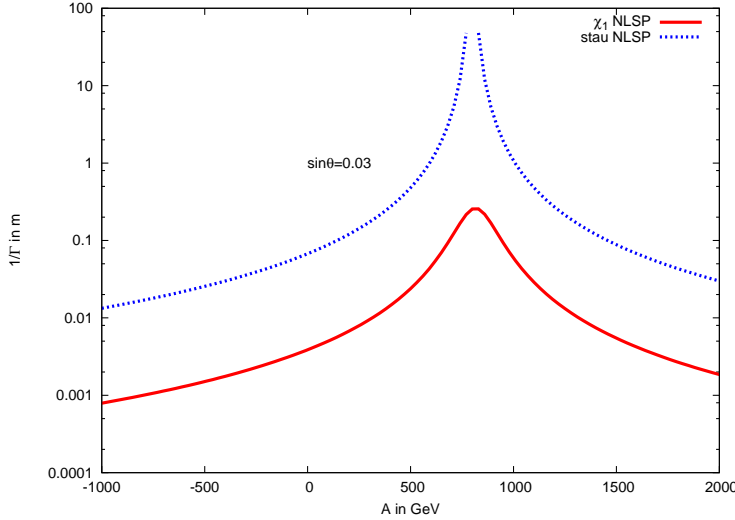


Figure 6: Decay length in meter for the bino and stau NLSP with $M=1$ TeV and $\tilde{m}_\nu = 0.05$ eV. Both decay lengths are inversely proportional to \tilde{m}_ν , and the stau decay length scales with $1/\sin^2\theta$. For this plot we take $\sin\theta = 0.03$ and $m_{\tilde{\tau}_1} = 700$ GeV

Note that the displacement of the χ_1^0 decay is larger than 1 mm for $\tilde{m}_\nu = 0.05$ eV as shown in Fig. 6. The effective neutrino mass of 0.05 eV corresponds to the atmospheric neutrino oscillation scale is the maximum value excluding the degenerate neutrino mass pattern. Thus, the displacement is generally expected to be larger than 1 mm as it is inversely proportional to \tilde{m}_ν . This can be compared with the displacement of the fermion triplet Σ decay [2] which becomes $\tau_\Sigma \approx 3\mu\text{m}$ for the same parameters as above: $\tilde{m}_\nu = 0.05$ eV and $M = 1$ TeV. The bino-like NLSP decay length is larger than the Σ decay because the former involves an additional gauge coupling g' and the mixing angle $\theta_{\tilde{l},\tilde{\nu}}$ typically smaller than the neutrino Yukawa coupling y_ν . Furthermore, the Higgsino contribution to the decay [see Fig. 1] is generically suppressed by its small mixture in χ_1^0 .

LHC detectors should be able to reconstruct the position of a displaced vertex from the χ_1^0 decay by observing two charged tracks induced by a lepton l^\pm and a dark matter triplet component $\tilde{\Sigma}^\mp$. Depending on the mass gap $\Delta m_{\tilde{\Sigma}}$, $\tilde{\Sigma}^\pm$ leaves a slowly-moving and highly-ionizing track of 5.5 cm – 6.3 m [8] before it decays to $\pi^\pm\tilde{\Sigma}^0$. Such signals can be probed at the early stage of the LHC experiment if the squark/gluino is not too heavy so that the NLSP production cross-section is large enough [see Fig. 5]. This is a unique signature of the dark matter triplet of type III seesaw. In addition to this, the Higgs bosons associated with two charged particles are produced to yield displaced vertices with $l^\pm\tilde{\Sigma}^\mp b\bar{b}$. These are clean signatures free from backgrounds and may help us to probe the Higgs boson property confirming the major Higgs decay to $b\bar{b}$ although its cross-section is small. Here let us compare the above events with the electroweak production of the fermion triplet components $\Sigma^{\pm,0}$ and their decays. The cross-section of the $\Sigma^\pm\Sigma^{\mp,0}$ is about 2 fb for our parameter region [2] whereas the cascade production of $pp \rightarrow \chi_1^0\chi_1^0 \rightarrow hl^+\tilde{\Sigma}^- l^-\tilde{\Sigma}^\mp$ is about 0.5 fb. Note that we can have same-sign and opposite-sign dileptons with the

same possibility. The bino-like NLSP decay leaves sizable displaced vertices whereas $\Sigma^{\pm,0}$ promptly decays $l^{\pm}h$ or νh as discussed above. Recall that the usual Higgs signals of $h \rightarrow \gamma\gamma$ becomes about 1 fb in two jet analysis [7]. Thus the cascade production of displaced Higgs bosons associated with two charged tracks can be useful to probe the Higgs property through its main decay $h \rightarrow b\bar{b}$.

3.2 Wino-like NLSP

The wino-like NLSP have similar properties as the bino-like NLSP except that its decay length is generically shorter. This comes from the larger gauge coupling constant ($g > g'$) which leads to a suppression factor of $(g'/g)^2 \sim 0.5$ for the decay length.

3.3 Higgsino-like NLSP

In the case of the Higgsino-like NLSP, the decay length becomes even shorter. Since it decays to $l^{\pm}\tilde{\Sigma}^{\mp}$ or $\nu\tilde{\Sigma}^0$ through the neutrino Yukawa coupling y_{ν} , its decay length is comparable to that of Σ and it cannot lead to a displaced Higgs production.

3.4 Stau NLSP

In the case of the stau (or any slepton) NLSP, the two-body decay through the neutrino Yukawa coupling y_{ν} , $\tilde{\tau}_1^{\pm} \rightarrow h\tilde{\Sigma}^{\pm}$, is the main decay mode. Thus, it leads to a huge cascade production cross-section (2.65 pb) for our parameter choice. Even for a larger squark/gluino mass, one may have a sizable production. For instance, requiring the cross-section of 1 fb, the signals of $\tilde{\Sigma}^{\pm}b\bar{b}$ can be observed for the squark/gluino mass of 2.5 TeV as shown in Fig. 5. Whether it can have a observable displacement depends on the mixing angle of the stau NLSP to the left-handed stau. The dotted (blue) line in Fig. 6 shows the displacement which is inversely proportional to the stau NLSP mass and the mixing angle. One can see that the decay length can be larger 100 μm as long as the mixing parameter $\sin\theta$ is smaller than 0.3.

4. Conclusion

It is pointed out that the type III seesaw model for generating light neutrino masses can lead to a displaced Higgs production which can play an important role for the Higgs discovery at the LHC. Higgs bosons can be produced through the decay of a heavy seesaw particle and a sizable displacement occurs primarily due to a small neutrino Yukawa coupling. A peculiar feature of the type III seesaw, introducing a $SU(2)_L$ triplet seesaw particle, is that the charged component yields a Higgs production associated with a charged particle. This makes observable a light Higgs boson through its main decay to two bottom quarks.

Considering the supersymmetric type III seesaw mechanism where the neutral scalar component $\tilde{\Sigma}^0$ of the triplet superfield can form dark matter, we investigated the Higgs production through the cascade decay of strongly produced squarks and gluinos assuming a neutralino and a stau NLSP. In the case of the neutralino (bino or wino) NLSP, Higgs bosons are produced by three body decays, $\chi_1^0 \rightarrow hl^{\pm}\tilde{\Sigma}^{\mp}$ or $h\nu\tilde{\Sigma}^0$. Although this process is suppressed compared to the main two body decay, $\chi_1^0 \rightarrow l^{\pm}\tilde{\Sigma}^{\mp}$ or $\nu\tilde{\Sigma}^0$, the cross-section of

the cascade Higgs production is larger than about 0.5 fb for the squark/gluino mass below 1 TeV. This requires a rather compact supersymmetric spectrum as the dark matter mass has a tight lower bound of 520 GeV coming from various astrophysical and cosmological observations. Once such a spectrum is realized, the cascade Higgs signals can be cleanly identified as it involves two charged tracks corresponding to a charge lepton and a heavy scalar charged particle $\tilde{\Sigma}^\pm$ which leaves slowly-moving and highly-ionizing tracks of the length longer than 5.5 cm. Furthermore, the decay length of χ_1^0 turns out to be typically larger than 1 mm even for the largest neutrino Yukawa coupling corresponding to the atmospheric neutrino mass scale $m_\nu = 0.05$ eV. Thus we would be able to find the Higgs boson through the channel $h \rightarrow b\bar{b}$ in addition to a conventional channel of $h \rightarrow \gamma\gamma$.

In the case of stau NLSP, the cascade production of Higgs bosons is much more efficient as Higgs bosons arise through the main decay channel $\tilde{\tau}_1^\pm \rightarrow h\tilde{\Sigma}^\pm$. The stau decay length turns out to be larger than 0.1 mm if $\sin\theta \lesssim 0.3$ where θ is the stau NLSP mixing angle with the left-handed stau. Then, the displaced Higgs signal can be observed even at the earlier stage of the LHC experiment as the cascade production cross-section lies in the range of 2 pb – 1 fb for the squark/gluino mass of 1 TeV – 2.5 TeV.

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References

- [1] R. Foot, H. Lew, X. G. He and G. C. Joshi, *Z. Phys. C* **44** (1989) 441.
- [2] R. Franceschini, T. Hambye and A. Strumia, *Phys. Rev. D* **78** (2008) 033002 [arXiv:0805.1613 [hep-ph]];
- [3] F. del Aguila and J. A. Aguilar-Saavedra, *Nucl. Phys. B* **813** (2009) 22 [arXiv:0808.2468 [hep-ph]];
- [4] A. Arhrib, B. Bajc, D. K. Ghosh, T. Han, G. Y. Huang, I. Puljak and G. Senjanovic, arXiv:0904.2390 [hep-ph];
- [5] P. Bandyopadhyay, S. Choubey and M. Mitra, *JHEP* **0910** (2009) 012 [arXiv:0906.5330 [hep-ph]].
- [6] T. Li and X. G. He, *Phys. Rev. D* **80** (2009) 093003 [arXiv:0907.4193 [hep-ph]].
- [7] ATLAS Collaboration, arXiv:0901.0512 [hep-ex].
- [8] E. J. Chun, *JHEP* **0912** (2009) 055 [arXiv:0909.3408 [hep-ph]].
- [9] M. Cirelli, N. Fornengo and A. Strumia, *Nucl. Phys. B* **753** (2006) 178 [arXiv:hep-ph/0512090].