Abstract We investigate a prospect of probing the type-III seesaw neutrino mass generation mechanism at various collider experiments by searching for a disappearing track and a displaced vertex signature originating from the decay of $SU(2)_L$ triplet fermion ($\Sigma$). Since $\Sigma$ is primarily produced at colliders through the electroweak gauge interactions, its production rate is uniquely determined by its mass. We find that a $\Sigma$ particle produces a disappearing track signature from the decay of its charged component, which can be searched at the future HL-LHC. Furthermore, we show that if the lightest observed neutrino has a mass of around $10^{-9}$ eV, the neutral component of $\Sigma$ can be discovered at the proposed MATHUSLA detector. We also show that the charged component of $\Sigma$ can be potentially be observed at FCC-he as a displaced vertex signature.

1 Introduction

The Standard Model (SM) of particle physics is a tremendously successful theory, but it is incomplete in its current form. Among its various shortcomings, we here focus on the fact that the SM offers no explanation about the origin of the tiny observed masses of the observed neutrinos [1–6]. One of the most appealing scenario to naturally generate the tiny neutrino masses is the seesaw mechanism, namely, type-I seesaw [7–11], type-II seesaw [12–16] and type-III seesaw [17], which effectively generates the lepton number violating dimension five operator $O_5 = \frac{\Lambda}{\Lambda} LLHH$ at low energies, where $\Lambda$ is the seesaw scale.

In this paper, we focus on the type-III seesaw, where in addition to the SM particles, at least two $SU(2)_L$ triplet fermions ($\Sigma$) with zero hypercharge are introduced [17]. For example, if the type-III seesaw mechanism is incorporated in the grand unified theory (GUT) framework, the triplet fermion mass $M_{\Sigma}$ are of the intermediate scale [17–21]. However, the type-III seesaw scenario with $M_{\Sigma} \sim O(1)$ TeV is also technically natural. Unlike GUT scenarios, the latter can be explored at collider experiments. See, for example, Refs. [22–29]. The CMS [30] and the ATLAS collaborations [31] for the Large Hadron Collider (LHC) have carried out a dedicated search for an $SU(2)_L$ triplet fermion of the type-III seesaw. Particularly, their search focuses on the prompt decay of the neutral ($\Sigma^0$) and the charged ($\Sigma^\pm$) components of $\Sigma$ produced via an intermediate electroweak gauge bosons that yields two final-state leptons (electrons or muons) of different flavors and charge combinations accompanied by at least two jets. Assuming flavor-universal branching fractions of $\Sigma^{0,\pm}$ into different lepton flavors, $M_{\Sigma} < 840$ GeV is excluded [30].

We explore an interesting possibility that $\Sigma^{0,\pm}$ are long-lived and evade the prompt decay searches at the LHC, thereby explaining the null results from the LHC experiments. The mass-splitting between $\Sigma^\pm$ and $\Sigma^0$ is small, $O(10^2)$ MeV, such that the pion/SM leptons produced in $\Sigma^{\pm}$ decay to $\Sigma^0$ are soft and very challenging to reconstruct at the LHC (a proton and proton (pp)-collider) due to a large hadronic background. If the neutral fermion $\Sigma^0$ lives long enough to pass through the detector undetected, the observed track of the charged $\Sigma^\pm$ disappear after they decay inside the detector. However, a detailed analysis of such a scenario has not been considered in the literature. We will show that this
so-called disappearing track signature can be the primary discovery mode of the long-lived \(\Sigma^\pm\) at the LHC and the future HL-LHC. For comparison, a dedicated disappearing track search for chargino in supersymmetric models, whose production and decay mechanism is very similar to \(\Sigma^\pm\), has already led to a very stringent bound [32].

For a long-lived charged neutral particle, its decay vertex is located away from the collision point. This so-called displaced vertex signature is a very clean with almost zero text is located away from the collision point. This so-called displaced vertex signature is a very clean with almost zero SM background. The current status of the displaced vertex searches at the LHC can be found in Refs. [33–49]. We expect a dramatic improvement in the search for the displaced vertex at future collider experiments, such as the proposed MAssive Timing Hodoscope for Ultra Stable neutral pArticles (MATHUSLA) experiment [50] of the HL-LHC\(^2\), the Large Hadron electron Collider (LHeC) [53] and the Future Circular electron-hadron Colliders (FCC-he) [54]. The MATHUSLA detector is an external detector purposed to detect the decay of long-lived particles which have escaped the detection at the LHC such as \(\Sigma^0\) of the type-III seesaw.\(^3\) Being purposefully placed far away from the LHC, this experiment is ideal to search for a long-lived \(\Sigma^0\). In fact, we find that MATHUSLA can discover \(\Sigma^0\). Compared to the LHC, electron and proton \((ep)\)-colliders such as the LHeC and FCC-he have cleaner environments because they are free from large hadronic background and pile-up events at higher luminosities. This enables explicit reconstruction of the soft final states in \(\Sigma^\pm\) decay to \(\Sigma^0\) for a displaced vertex signature. See, for example, Ref. [55] for the discussion of Higgsino search prospect at the LHeC and FCC-he. Because of the asymmetric beam setup of the \(ep\)-colliders, the charged Higgsinos produced at these colliders are boosted and effectively have a longer lifetime in the lab frame. Thus, \(ep\)-collider can access lifetimes many orders of magnitude shorter than the \(pp\)-colliders. We will show that FCC-he can also probe the type-III seesaw mechanism.

In the following, we will show that the disappearing track and displaced vertex signatures that arise from the decay of \(\Sigma_{\pm,0}\) in type-III seesaw can be probed at HL-LHC, MATHUSLA, and FCC-he experiments. This work is organized as follows: In Sect. 2, we introduce the type-III seesaw mechanism and discuss the neutrino mass generation mechanism. In Sect. 3, we study the production of \(\Sigma_{\pm,0}\) at HL-LHC and FCC-he, and also calculate their decay lengths. After discussing the bounds from the disappearing track search at the LHC we examine in Sect. 5 the prospect of observing the displaced vertex signal of \(\Sigma_{\pm,0}\) decay at MATHUSLA, and FCC-he. Finally, we present our conclusion in Sect. 6.

2 The type-III seesaw

We consider the extension of the SM with three generation of \(SU(2)_L\) triplet (right-handed) fermions, \(\Sigma_i (i = 1, 2, 3)\), and the Lagrangian is given by

\[
\mathcal{L}_\Sigma = \text{Tr} [\Sigma_i \phi \Sigma_i] - \frac{1}{2} M_{ij}^{(\Sigma)} \text{Tr} [\Sigma_i \Sigma_j] + h.c. - \left( Y^{ij}_\Sigma \bar{T}_i \Sigma_j H + h.c. \right),
\]

where \(D\) is the covariant derivative for \(\Sigma_i\), \(M_{ij}^{(\Sigma)}\) are Majorana masses of the triplet fermions, \(Y_{ij}^{\Sigma}\) are the Dirac-type Yukawa couplings, \(L_i \equiv (v_i, l_i)^T\) is the left-handed SM \(SU(2)_L\) lepton doublet, \(H \equiv (H^0, H^-)^T = (v + h + i\eta)/\sqrt{2}, H^-\) and \(v = 246\) GeV. The \(SU(2)_L\) triplet fermion contains charged (\(\Sigma^\pm\)) and charge neutral (\(\Sigma^0\)) components which can be expressed as

\[
\Sigma_i = \begin{pmatrix} \Sigma^0_i \sqrt{2} \\ \Sigma^+_i - \Sigma^-_i \sqrt{2} \end{pmatrix},
\]

and its conjugate is given by \(\Sigma_i^c \equiv C \Sigma_i^T\), where \(C\) denotes the charge conjugation operator.

Let us first consider the masses of \(\Sigma^\pm_i\) and \(\Sigma^0_i\). Although their masses are degenerate at the tree-level, radiative corrections induced by the electroweak gauge boson loops remove the degeneracy and generate mass-splitting between \(\Sigma^+_i\) and \(\Sigma^-_i\). The resulting mass difference (\(\Delta M_i\)) at the one-loop order is given by [67]

\[
\Delta M_i = \frac{\alpha_2 m_{\Sigma_i}}{4\pi} \left[ f \left( \frac{m_W}{m_{\Sigma_i}} \right) - \cos^2 \theta_W \times f \left( \frac{M_Z}{m_{\Sigma_i}} \right) \right],
\]

where \(\alpha_2 = 0.034, \cos^2 \theta_W \simeq 0.769\) [68], the function \(f\) is defined as

\[
f(r) = r \left[ 2 \sqrt{r^2 - 2} \ln r - 2r + \left( r^2 - 4 \right)^{1/2} \right] / 2,
\]

with \(A = \left( r^2 - 2 - r \sqrt{r^2 - 4} \right) / 2\). We show \(\Delta M_i\) as a function of \(m_{\Sigma_i}\) in Fig. 1. The dashed line denotes the \(\pi\).

The Yukawa couplings between \(H\) and \(\Sigma\) generate mass-mixings between \(\Sigma_{\pm,0}, v_i\) and \(\ell_L\). The mass matrices involving the charged fermion states, \(M_{\pm,0}\) in (\(l^\pm, \Sigma^\pm\)) basis and

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In this work, for simplicity, we set the Majorana $C P$-phases, $\rho_{1,2} = 0$ while we use the best fit values for neutrino masses, mixing angles ($c_{ij} \equiv \cos \theta_{ij}$ and $s_{ij} \equiv \sin \theta_{ij}$) and the Dirac $C P$-phase ($\delta$) from NuFIT’s global analysis [69] of neutrino oscillation data. Their values depend on the observed neutrino mass hierarchy, namely, normal hierarchy (NH), $m_1 < m_2 < m_3$, and inverted hierarchy (IH), $m_3 < m_1 < m_2$. For the NH (IH), the best fit central values are $\theta_{12} \approx 33.4^\circ (33.5^\circ)$, $\theta_{23} \approx 49.2^\circ (49.3^\circ)$, $\theta_{13} \approx 8.57^\circ (8.60^\circ)$, $\delta \approx 197^\circ (282^\circ)$, $\Delta m^2_{21} \approx m^2_2 - m^2_1 = 7.42(7.42) \times 10^{-5}$ eV$^2$, and $m^2_3 \approx m^2_3 - m^2_2 = 2.51(-2.50) \times 10^{-3}$ eV$^2$, respectively.

From Eqs. (2.6) and (2.7), the Dirac mass matrix can be parameterized as [70]

\[ i m_D = U_{\text{MNS}}^* \sqrt{D_v} \, O \sqrt{M_\Sigma}, \]

where $\sqrt{D_v} = \text{diag} (\sqrt{m_1}, \sqrt{m_2}, \sqrt{m_3})$, $\sqrt{M_\Sigma} = \text{diag} (\sqrt{m_{\Sigma_1}}, \sqrt{m_{\Sigma_2}}, \sqrt{m_{\Sigma_3}})$ and $O$ is a $3 \times 3$ orthogonal matrix. A general $3 \times 3$ orthogonal matrix $O$ is given by

\[
O = \begin{pmatrix}
1 & 0 & 0 \\
0 & \cos \theta_1 & \sin \theta_1 \\
0 & -\sin \theta_1 & \cos \theta_1
\end{pmatrix}
\begin{pmatrix}
\cos \theta_2 & 0 & \sin \theta_2 \\
0 & 1 & 0 \\
-\sin \theta_2 & 0 & \cos \theta_2
\end{pmatrix}
\begin{pmatrix}
\cos \theta_3 & 0 & \sin \theta_3 \\
0 & 1 & 0 \\
-\sin \theta_3 & 0 & \cos \theta_3
\end{pmatrix}
\]

where $\theta_{1,2,3}$ are generally complex valued.

3 Production and search for fermion triplets at current and future colliders

Let us discuss the production of $\Sigma^{0,\pm}$ at various collider experiments. Since $\Sigma$ is an $SU(2)_L$ triplet, in the type-III seesaw scenario, $\Sigma^{0,\pm}$ are produced at colliders through their electroweak gauge interactions as shown in Fig. 3. All these processes only involve SM gauge interactions, and therefore $\Sigma^{0,\pm}$ production cross sections are solely determined by the triplet mass ($m_\Sigma$).

The Drell–Yan processes dominate the $\Sigma$ production at a $pp$-collider such as the LHC. The singly charged fermion $\Sigma^\pm$ is pair-produced from a $q\bar{q}$ fusion through the $s$-channel $Z/\gamma$ exchange as shown in the left diagram of Fig. 3. Similarly, the $s$-channel $W^\pm$ exchange produces $\Sigma^\pm$ and $\Sigma^0$ as shown in the middle diagram of Fig. 3. The $\Sigma^\pm$ can also be pair-
produced via vector boson-fusion process in association with two forward jets (its diagram is similar to the right diagram in Fig. 3). Despite a large production rate, this process suffers from larger QCD background due to the forward jets activity and is sub-dominant compared to the Drell–Yan processes. Hence, we do not include vector boson-fusion process in our LHC analysis. On the other hand, the vector boson-fusion process shown in the right diagram of Fig. 3 dominates the production at the ep-colliders such as FCC-he. Because of the clean (low pile-up) environment of the ep-colliders, as we have discussed earlier, the FCC-he can probe much shorter lifetimes and are complementary to LHC disappearing track search of $\Sigma^{\pm}$ decay. The FCC-he will look for the displaced vertex signature from $\Sigma^{\pm}$ decay.

We generate the signal sample for fermion triplet with MadGraph5aMC@NLO [74] event-generator to evaluate the production cross section of the $\Sigma^{0,\pm}$ at LHC and FCC-he. Our results are shown in Fig. 4 as a function of $m_{\Sigma}$. In the left panel of Fig. 4, we show the production cross section for the processes at the LHC with the center of mass energy $\sqrt{s} = 13$ TeV. In the right panel of Fig. 4, we show the production cross section for the FCC-he collider, respectively, where the proton and $e^{-}$ beam energy is set to be 50 TeV and 60 TeV, respectively.

We conclude this section by discussing the prospect of probing the type-III seesaw at various current and planned collider experiments. After being produced at the collider, the triplet fermion $\Sigma$ decays to the SM particles. The type of signal observed at collider depends on the lifetime ($\tau$) of the charged ($\Sigma^{\pm}$) and the neutral component ($\Sigma^{0}$) of the triplet fermion. The Feynman diagrams representing their decays are shown in Figs. 5 and 6. Both $\Sigma^{0}$ and $\Sigma^{\pm}$ decay to $W^{\pm}/Z/h$ plus SM leptons (hereafter, WZh) while $\Sigma^{\pm}$ can additionally decay to $\Sigma^{0}$ in association with soft pions/SM leptons. The CMS experiment have searched for $\Sigma^{0,\pm}$ decaying promptly to WZh inside the LHC detector ($\tau < 10$ m) and excluded the triplet mass $m_{\Sigma} < 840$ GeV [30]. As we will show in the next section, $\Sigma^{0}$ can have lifetime $\tau > 10$ m and hence evade prompt-detection at the LHC. In this case, the CMS prompt-search bound is not applicable. The soft pion/SM lepton accompanying the long-lived $\Sigma^{0}$ in $\Sigma^{\pm}$ decay also avoid prompt-detection at the LHC. However, as we have discussed earlier, in this case the LHC and HL-LHC can search for the disappearing track signature [75,76]. Meanwhile, if the lifetime of $\Sigma^{0}$ is around 100 m, we will show that MATHUSLA detector can discover it. Additionally, the clean (low pile up) environment at the proposed ep-collider such as the FCC-he enable the reconstruction of the displaced pion and SM leptons from the $\Sigma^{\pm}$ decay. We will also examine the prospect of FCC-he to search for the displaced track signature of a decaying long-lived $\Sigma^{\pm}$. Besides these, other interesting scenarios are also possible in the type-III seesaw. For example, $\Sigma^{0,\pm}$ could all decay non-promptly inside the LHC detector such that one could simultaneously look for a displaced vertex signature from $\Sigma^{0}$ decay and displaced or disappearing track signature from $\Sigma^{\pm}$ decay.

4 Branching ratio and decay width of the fermion triplets

The partial decay width of $\Sigma^{0}$ to SM Higgs (h) and gauge bosons ($Z, W^{\pm}$) are given by [23,24]

$$\Gamma(\Sigma^{0} \rightarrow h\nu_{\alpha}) = \Gamma(\Sigma^{0} \rightarrow h\bar{\nu}_{\alpha}) = \frac{1}{8\pi} \frac{m_{\Sigma}^{3}}{v^{2}} \left(1 - \frac{m_{h}^{2}}{m_{\Sigma}^{2}}\right)^{2},$$
$$\Gamma(\Sigma^{0} \rightarrow Z\nu_{\alpha}) = \Gamma(\Sigma^{0} \rightarrow Z\bar{\nu}_{\alpha}) = \frac{1}{8\pi} \frac{m_{\Sigma}^{3}}{v^{2}} \left(1 - \frac{M_{Z}^{2}}{m_{\Sigma}^{2}}\right)^{2} \left(1 + \frac{2M_{Z}^{2}}{m_{\Sigma}^{2}}\right),$$
$$\Gamma(\Sigma^{0} \rightarrow W^{\pm}\ell_{\alpha}) = \Gamma(\Sigma^{0} \rightarrow W^{\pm}\ell_{\alpha}) = \frac{1}{4\pi} \frac{m_{\Sigma}^{3}}{v^{2}} \left(1 - \frac{M_{W}^{2}}{m_{\Sigma}^{2}}\right)^{2} \left(1 + \frac{2M_{W}^{2}}{m_{\Sigma}^{2}}\right),$$

where $\alpha = e, \mu, \tau$ denotes different lepton flavors and $R_{\alpha i} = (m_{D})_{\alpha i}(M_{\Sigma})^{-1} = U_{\alpha MNS}^{*}D_{i}O^{\dagger}M_{\Sigma}(M_{\Sigma})^{-1}$.

Similarly, the partial decay width of $\Sigma^{\pm}$ to SM Higgs (h) and gauge bosons ($Z, W^{\pm}$) are given by [23,24]

$$\Gamma(\Sigma^{\pm}_{i} \rightarrow h\ell_{\alpha}) = \frac{1}{8\pi} \frac{m_{\Sigma}^{3}}{v^{2}} \left(1 - \frac{m_{h}^{2}}{m_{\Sigma}^{2}}\right)^{2},$$
$$\Gamma(\Sigma^{\pm}_{i} \rightarrow Z\ell_{\alpha}) = \frac{1}{4\pi} \frac{m_{\Sigma}^{3}}{v^{2}} \left(1 - \frac{M_{Z}^{2}}{m_{\Sigma}^{2}}\right)^{2} \left(1 + \frac{2M_{Z}^{2}}{m_{\Sigma}^{2}}\right).$$

4 Similarly, the photon initiated vector-boson processes [71–73] contribution is sub-dominant.
Fig. 4 The left (right) shows the production cross section of $\Sigma^\pm_i$ and $\Sigma^0_i$ at $pp$ ($ep$)-collider as a function of its mass $m_{\Sigma_i}$.

Fig. 5 Representative Feynman diagrams for $\Sigma^0$ decay

Fig. 6 Representative Feynman diagrams for $\Sigma^\pm$ decay

Fig. 7 shows the production cross section of $\Sigma^\pm_i$ and $\Sigma^0_i$ at $pp$ ($ep$)-collider as a function of its mass $m_{\Sigma_i}$.

\[ \Gamma(\Sigma^\pm_i \to W^{\pm} \nu_\alpha) = \frac{1}{2} \frac{m_{\Sigma_i}}{8\pi} \left( \frac{|R_{\alpha i}|^2}{v^2} \right) \left( 1 - \frac{2M_W^2}{m_{\Sigma_i}^2} \right)^2 \times \left( 1 + \frac{2M_{W}^{2}}{m_{\Sigma_i}^{2}} \right). \]  

Because of the mass-splittings, $\Sigma^\pm$ can also decay to $\Sigma^0$ and pions or light SM leptons. The partial decay widths for these processes are given by [23, 24, 67]

\[ \Gamma(\Sigma^\pm_i \to \Sigma^0_i \pi^\pm) = \frac{2G_F^2 v_\pi^2}{\pi} \Delta M_i^2 f_{\pi}^2 \sqrt{1 - \frac{m_{\pi}^2}{\Delta M_i^2}}, \]

\[ \Gamma(\Sigma^\pm_i \to \Sigma^0_i e^\pm \nu_e) = \frac{2G_F^2 \Delta M_i^2}{15\pi} \]

\[ \Gamma(\Sigma^\pm_i \to \Sigma^0_i \mu^\pm \nu_\mu) = 0.12 \Gamma(\Sigma^\pm_i \to \Sigma^0_i e^\pm \nu_e). \]  

The branching ratios of $\Sigma^{0,\pm}$ decaying to WZh and $\Sigma^0$ are defined as the ratio of the sum of partial decay widths for each decay mode to the total decay width of $\Sigma^{0,\pm}, \Gamma^{0,\pm}_{\text{total}}$. The decay length of $\Sigma^{0,\pm}$ are given by $c\tau = 1/\Gamma^{0,\pm}_{\text{total}}$. From Eqs. (4.1)–(4.4), all the particle decay widths of $\Sigma^{0,\pm}$ are determined by $m_{1,2,3}$, $m_{\Sigma 1,2,3}$, and complex angles $\theta_{1,2,3}$. The observed light neutrino mass spectrum is uniquely determined by the lightest neutrino mass, particularly, $m_1$ (NH) and $m_3$ (IH). For the rest of our analysis, we will also fix $m_{\Sigma_{2,3}} = 600$ GeV for NH (IH), respectively, which will be justified later. Therefore, the branching ratios and decay length of $\Sigma^{0,\pm}$ are determined by five free parameters, namely, $m_{1}$ and $m_{\Sigma 1}$ for NH (IH), respectively, and $\theta_{1,2,3}$. We will consider the two cases, $\theta_{1,2,3} = 0$ and $\theta_{1,2,3} \neq 0$, separately.

In Fig. 7, we consider the case with the $\theta_{1,2,3} = 0$ for NH for fixed $m_{\Sigma 1} = 600$ GeV. We show the branching ratio for $\Sigma^\pm_i$ as a function of $m_1$ in the top left panel of Fig. 7. The blue (red) lines depict branching ratio for $\Sigma^0_i$ (WZh), respectively. The solid, dashed and dotted red/blue lines denote $\Sigma_{1,2,3}^\pm$, respectively, as indicated in the figure legend. The red dashed and dotted lines overlap indistinguishably and indicate that $\Sigma_{2,3}^\pm$ decay 100% to WZh independent...
For NH with $\theta_{1,2,3} = 0$, $m_{\Sigma_1} = 600$ GeV, and $m_{\Sigma_{1,2}} = 1$ TeV, the plots show the branching ratio and decay length of $\Sigma_i^\pm$ in top left and right panels, respectively, and decay length of $\Sigma_i^0$ as a function of lightest observed neutrino mass $m_1$ in the bottom panel. The blue (red) lines depict branching ratio for $\Sigma_i^\pm$ decay to $\Sigma_i^0$ (WZh).

of $m_1$ values. On the other hand, $\Sigma_i^\pm$ decays only to WZh for $m_1 \gg 10^{-4}$ eV. For $m_1 \lesssim 10^{-4}$ eV, $\Sigma_i^\pm$’s branching ratio to WZh drops significantly such that $\Sigma_i^\pm$ decays 100% to $\Sigma_i^0$ for $m_1 \ll 10^{-6}$. In the top right panel of Fig. 7, we show the decay length of $\Sigma_i^\pm$ as a function of $m_1$. The solid, dashed and dotted lines denote $\Sigma_{i,2,3}$, respectively. The decay length for $\Sigma_{1,2,3}$ all approach constant values for $m_1 \to 0$. In this limit, the decay length of $\Sigma_i^\pm$ approaches a constant value because $\Sigma_i^\pm$ decays to $\Sigma_i^0$ independently of light neutrino masses. On the other hand, $\Sigma_{2,3}^\pm$ decays to WZh for any values of $m_1$. The WZh partial decay widths of $\Sigma_i^\pm$ in Eq. (4.3) are all proportional to $|R_{ai}|^2$, which is given by $\Sigma_{ai}|R_{ai}|^2 = m_i/m_{\Sigma_i}$ for $\theta_{1,2,3} = 0$ and is independent of $U_{MNS}$ matrix [56]. Hence, the decay length of $\Sigma_i^\pm$ is inversely proportional to $m_i$. For NH $(m_1 < m_2 < m_3)$, $m_2 = \sqrt{\Delta m_{21}^2 + m_1^2}$ and $m_3 = \sqrt{m_2^2 + \Delta m_{32}^2}$, both of which approach constant values for $m_1 \to 0$. Corresponding to the asymptotic values of $m_{2,3}$, the decay length of $\Sigma_{2,3}^\pm$ also approach constant values in the limit $m_1 \to 0$. For larger values of $m_1^2 \gg \Delta m_{32}^2$, both $m_{2,3}$ are proportional to $m_1$, which explains the decreasing behavior of $\Sigma_i^\pm$’s decay lengths for large $m_1$ values. In the bottom panel of Fig. 7, we show the decay length of $\Sigma_i^0$ as a function of $m_1$. The solid, dashed and dotted lines denote $\Sigma_{1,2,3}$, respectively. The partial decay widths of $\Sigma_i^0$ in Eq. (4.1) are all proportional to $|R_{ai}|^2$. Therefore, in the limit of $m_1 \to 0$, the decay length of $\Sigma_i^0$ diverges while the decay length of $\Sigma_i^0$ and $\Sigma_i^0$ approach constant values corresponding to the asymptotic values of $m_{2,3}$.

In Fig. 8, we consider the IH $(m_3 < m_1 < m_2)$ case with $\theta_{1,2,3} = 0$, $m_{\Sigma_3} = 600$ GeV and $m_{\Sigma_{1,2}} = 1$ TeV. The line codings of all the figures are the same as Fig. 7. The branching ratio and decay length are determined as a function of $m_3$, the lightest mass eigenvalue among the observed neutrinos for the IH case. The top left panel shows that $\Sigma_i^\pm$, depicted as indistinguishably overlapped solid and dashed.
red lines, decay 100% to WZh independently of $m_3$ values. It also shows that $\Sigma^\pm_3$ decays 100% to $\Sigma^0_3$ (WZh) in the limit $m_3 \to 0$ ($m_3 \to 0.3$ eV). The discussion to understand the behavior of the decay width of $\Sigma^\pm_3$ is very much analogous to that of the NH case. For example, the longest decay length is realized for $\Sigma^+_3$ and $\Sigma^0_3$ corresponding to the lightest neutrino mass in the IH case. The decay length of $\Sigma^+_3$, depicted as indistinguishably overlapped solid and dashed lines, approaches a constant value because the corresponding partial decay widths are independent of neutrino masses while the decay length of $\Sigma^0_3$ diverges because it decays dominantly to WZh with the partial decay width proportional to $m_3$. Similarly, $\Sigma^\pm_{1,2}$ decay is also dominated decay to WZh and is proportional to $m_{1,2}$, respectively. Therefore, the decay length $\Sigma^\pm_{1,2}$ approach the same constant value in the limit $m_3 \to 0$ because for the IH, $m_2 \to \sqrt{-\Delta m^2_{32}}$ and $m_1 \to \sqrt{-\Delta m^2_{32} - \Delta m^2_{21}} \simeq \sqrt{-\Delta m^2_{32}}$.

Next, we consider the case $\theta_{1,2,3} \neq 0$. Let us parameterize $\theta_1 = x_1 + iy_1$, $\theta_2 = x_2 + iy_2$, and $\theta_3 = x_3 + iy_3$. In the following we set $x_{1,2,3} = 0$ for simplicity. In this case, $\cos(x_i + iy_i) \simeq \sin(x_i + iy_i) \simeq e^{iy_i}$ for $y_i \gtrsim 1$. Hence, $|R_{\alpha i}|^2$ can be exponentially enhanced for nonzero values of $y_i$. To see this effect, we consider $\Sigma^\pm_1$ decay in Fig. 9 with $m_{\Sigma_1^{(3)}} = 600$ GeV, $m_{\Sigma_{2,3}^{(1,2)}} = 1$ TeV, respectively, and the angles $x_{1,2,3} = 0$ and $y_{1,2,3} = 10^{-3}$ ($10^{-5}$) for NH (IH). In this figure, for both NH and IH, curves corresponding to $\Sigma^\pm_3$ are depicted by solid, dashed and dotted lines. Also for both NH and IH, the red (blue) colored lines denote the branching ratio to WZh ($\Sigma_0$). The $y_i$ values for the NH (IH) are chosen specifically to suppress the branching ratio of $\Sigma^\pm_1$ ($\Sigma^\pm_3$) to WZh and also realize the lifetime for $\Sigma^0_1$ associated with the lightest observed neutrino, namely, $\Sigma^0_1$ ($\Sigma^0_3$) to be greater than 10 m.

For completeness, let us also consider the case with even larger $y_i$ values. We show our results in Fig. 10 for $m_{\Sigma_1^{(3)}} = 600$ GeV, $m_{\Sigma_{2,3}^{(1,2)}} = 1$ TeV for NH (IH), respectively, with $x_{1,2,3} = 0$ and $y_{1,2,3} = 1$. The line codings for all the figures are the same as in Fig. 9. The branching ratio plots (top panel) shows that the decay of all triplets $\Sigma^\pm_1$, for both NH and IH, are dominated by their decay to WZh. In this case, the total decay width for both charged and neutral triplets in each $\Sigma_i$ are identical as shown in Eqs. (4.1) and (4.3). Hence, the decay length of $\Sigma^0_1$ is same as that of $\Sigma^\pm_1$ shown in the bottom...
Fig. 9 For IH with 
\( m_{\Sigma_1} = 600 \text{ GeV} \), 
\( m_{\Sigma_{1,3}} = 1 \text{ TeV} \), \( x_{1,2,3} = 0 \) and 
\( y_{1,2,3} = 10^{-3} \), the left panels show the branching ratio (top), decay length of \( \Sigma_{1}^{\pm} \) (middle) and \( \Sigma_{1}^{0} \) (bottom) as a function of the lightest observed neutrino mass (\( m_{3} \)). All the line codings are the same as Fig. 7. The right panels show the same for the IH case, with \( m_{\Sigma_1} = 600 \text{ GeV} \), 
\( m_{\Sigma_{1,2}} = 1 \text{ TeV} \), \( x_{1,2,3} = 0 \) and 
\( y_{1,2,3} = 10^{-3} \) as a function of \( m_{3} \) and all the line codings are the same as Fig. 8.

panels of Fig. 10. This shows that their decays are effectively prompt and therefore the choice of \( m_{\Sigma_{1(3)}} = 600 \text{ GeV} \) for NH (IH) is inconsistent with the lower bound on promptly decaying triplet fermions of the type-III seesaw of 840 GeV.

In general, we find that all the triplet fermions, except for the one associated with the lightest observed neutrino (\( \Sigma_{1(3)} \) for NH (IH), respectively), always decays promptly for all values of \( y_{i} \geq 0 \). See, for example, Figs. 7, 8, 9 and 10. Therefore, for NH (IH), \( \Sigma_{1(3)} \) masses are subject to the CMS bound, namely, \( m_{\Sigma_{1}} > 840 \text{ GeV} \). For example, this excludes the IH scenario with \( m_{\Sigma_{1}} = 600 \text{ GeV} \) and \( m_{\Sigma_{2,3}} = 1 \text{ TeV} \).

5 Prospect to search for fermion triplets at current/future colliders

In the previous section we have shown that the neutral lepton associated with the lightest observed neutrino, particularly \( \Sigma_{1(3)}^{0} \) for NH (IH), respectively, can have lifetime \( c \tau \gg 10 \text{ m} \) and evade prompt detection at collider while their respective charged partners \( \Sigma_{1(3)}^{\pm} \) have a much shorter lifetime and decay inside the detector. For the remainder of this paper, we will refer both of them as \( \tilde{\Sigma} \) and their masses as \( m_{\tilde{\Sigma}} \), which is effectively the same for both the charged and the neutral components of \( \tilde{\Sigma} \). In this section, we will study the prospect to search for the disappearing track signature from \( \tilde{\Sigma}^{\pm} \) decaying inside the LHC and the displaced vertex signature from \( \tilde{\Sigma}^{0} \) decaying inside the MATHUSLA detector. We will also study the prospect to search for the displaced vertex signature from \( \tilde{\Sigma}^{\pm} \) decaying inside the FCC-he.

5.1 Disappearing track searches for \( \Sigma^{\pm} \) at the LHC and HL-LHC

Although there is no dedicated LHC analysis of the disappearing track signature for the type-III seesaw, we can apply
Fig. 10 For NH with $m_{\Sigma_1} = 600$ GeV, $m_{\Sigma_{2,3}} = 1$ TeV, $x_{1,2,3} = 0$ and $y_{1,2,3} = 1$, the left panels show the branching ratio (top) and decay length of $\Sigma_1^\pm$ (middle) as a function of the lightest observed neutrino mass ($m_1$). All the line codings are the same as Fig. 7. The right panels show the same for the IH case, with $m_{\Sigma_3} = 600$ GeV, $m_{\Sigma_{1,2}} = 1$ TeV, $x_{1,2,3} = 0$ and $y_{1,2,3} = 10^{-3}$ as a function of $m_3$ and all the line codings are the same as Fig. 8. For both NH and IH, the decay length of the neutral components is the same as the decay length of its charged partner. (See text for details)

the LHC search result for disappearing track signal from chargino decay [75,76]. The CMS collaboration in Ref. [75] set an upper bound on the product of the production cross section (including both charged and neutral chargino) and its branching fraction of the chargino decaying to a neutralino plus a pion which is assumed to be 100%. Such a branching ratio is realized in the type-III seesaw in the limit $m_1(3) \to 0$ for NH (IH) as shown in Figs. 7, 8 and 9. In this limit, we can identify the bound in Ref. [75] as a upper bound on the total production cross section of $\tilde{\chi}_1^\pm$, which includes $\tilde{\chi}_1^0 \tilde{\Sigma}^\pm$ and $\tilde{\Sigma}_1^\pm \tilde{\Sigma}_2^\pm$ final states. We show our result in the left panel of Fig. 11, where the diagonal red line denotes the total production cross section for $\tilde{\Sigma}_1^\pm$ as a function of $m_{\tilde{\Sigma}_1}$. The red line in Fig. 11 is taken from the left panel of Fig. 4. The solid (dashed) black horizontal lines are the observed (expected) cross section limits from Ref. [75] while the green (yellow) band are expected 1(2)-$\sigma$ upper limit on the production cross section. As indicated in the Fig. 11, this bound was obtained for the chargino lifetime fixed to be 10 cm, which is longer than $\tau_{\tilde{\chi}_1^\pm} \simeq 5$ cm$^3$ for $\tilde{\Sigma}_1^\pm$ in the limit $m_{1(3)} \to 0$ for NH (IH), respectively.

In the right panel of Fig. 11 we show the decay length of $\tilde{\Sigma}_1^\pm$ along with the disappearing track search bound for wino-like chargino by the ATLAS collaboration [76] with $140$ fb$^{-1}$ with the branching ratio of $\tilde{\chi}_1^\pm$ to $\tilde{\chi}_1^0$ fixed to be 95.5%. The solid horizontal black line depict the decay length of $\tilde{\Sigma}_1^\pm$ for both NH (IH) and the benchmark values $\theta_{1,2,3} = 0$, $m_{\tilde{\chi}_1} = 600$ GeV, $m_{\Sigma_{2,3}}(m_{\Sigma_{1,2}}) = 1$ TeV and $m_{1(3)} = 10^{-9}$ eV, respectively. For the chosen benchmark values, the lines depicting decay length for NH and IH are completely overlapping and indistinguishable. The HL-LHC prospect in the right panel of Fig. 11 is obtained

5 This result was obtained by using the mass-splitting formula that only included one-loop contributions. Taking into account the two-loop contribution, the decay length of $\tilde{\Sigma}_1^\pm$ can increase by as much as 10% [77].
by re-interpreting the Higgsino disappearing track search prospect in Ref. [79] (namely, Fig. 9(c)) with the assumption of “improved detector tracking”. To obtain the bound, we take into consideration various similarities and differences between the production and decay of Higgsino and the type-III seesaw triplets. The production processes of $\tilde{\Sigma}^\pm$ ($\tilde{\Sigma}^0$) are the same as the charged (neutral) components of Higgsino whereas their production rates differ due to their $SU(2)_L$ representations, namely, Higgsino belong to the $SU(2)_L$ doublet while $\tilde{\Sigma}$ is $SU(2)_L$ triplet. Unlike the triplets, the Higgsino (charged and neutral) do not decay to W/Z at the tree-level. In the type-III seesaw case, this can be achieved in the limiting case $m_{1(3)} \to 0$ for NH (IH). On the other hand, the charged Higgsino decays to neutral Higgsino plus soft pions/SM leptons is the same as $\tilde{\Sigma}^\pm$ decay. However, the decay length of a charged Higgsino is essentially a free parameter because the mass-splitting between the charged and neutral Higgsinos, which determines the decay length, is a free parameter in the supersymmetric SM. In the type-III seesaw case, the decay length depends on the mass-splitting, which is fixed to be around the pion mass, and neutrino oscillation parameters as we have shown in the previous section. Taking into account all these factors, we can conclude that there is a one-to-one correspondence between the production rate of Higgsino and $\tilde{\Sigma}$ (for a fixed value of mass) that results in a one-to-one correspondence between the Higgsino mass, its production rate and lifetime in Ref. [79]. It is worth noting that the authors in Ref. [79] also show the HL-LHC prospect with “standard tracking” assumptions and 3000 fb$^{-1}$ luminosity. Interestingly, we found that the current ATLAS bound is already is comparable if not better that the “standard tracking” prospect. Hence, we expect the HL-LHC with 3000 fb$^{-1}$ luminosity to perform significantly better than the prospect shown in the right panel of Fig. 11.

5.2 Displaced vertex search for $\Sigma^0$ at MATHUSLA

The recently, proposed MATHUSLA [50] is purposefully designed to detect neutral long-lived particles produced at the LHC, and will be located $\sim 100$ m away from the beam collision point with an angle $\theta = [0.38, 0.8]$ from the LHC beam direction. Hence, it is ideally suited to detect long-lived particles with their decay lengths in the range of few hundred meters or even longer [80]. If the particle decays with final state charged leptons and/or jets, the event can be easily reconstructed because the background SM events will be almost zero.

As shown in Fig. 7 (Fig. 8), the decay length of $\tilde{\Sigma}^0$ corresponding to NH (IH), respectively, have decay length of 100 m for the benchmark values $\theta_{1,2,3} = 0, m_{\tilde{\Sigma}^0} = 600 \text{ GeV}, m_{\Sigma_{2,3}}(m_{\Sigma_{1,2}}) = 1 \text{ TeV}$ and $m_{1(3)} = 10^{-9} \text{ eV}$. In the following, we investigate a possibility of detecting $\tilde{\Sigma}^0$ at MATHUSLA. At LHC, $\tilde{\Sigma}^0$ is produced in two ways. One is from $\tilde{\Sigma}^\pm$ production through a s-channel $Z/\gamma$ in the left diagram of Fig. 3, and the other is through s-channel $W^\pm$ exchange process in the middle diagram of Fig. 3. In the first case, $\tilde{\Sigma}^0$ is produced by $\tilde{\Sigma}^\pm$ decay while in the other one $\tilde{\Sigma}^0$ is directly produced. The other particles produced from $\tilde{\Sigma}^\pm$ decay are soft and will not be considered in our analysis.

Since the MATHUSLA detector is very efficient in detecting...
long-lived particles, we will simply require that $\tilde{\Sigma}^0$ particle produced at the LHC reaches the MATHUSLA detector and decays inside the detector. In the following, we assume that the decaying $\tilde{\Sigma}^0$ particle can be detected with 100% efficiency by MATHUSLA because the SM backgrounds are expected to be negligible.

Let us assume that $\tilde{\Sigma}^0$ produced at the LHC is emitted at an angle of $\theta$ away from the LHC beam line such that it decays after traveling a distance of $D_M$. The decay length in the laboratory frame is given by

$$c\tau_{\text{lab}} = \frac{D_M}{\beta}.$$  \hspace{1cm} (5.1)

Here, the $\beta$ is the boost factor for $\tilde{\Sigma}^0$ particle,

$$\beta = \frac{1}{\sqrt{1 + \frac{m_{\tilde{\Sigma}^0}^2}{E^2}}},$$  \hspace{1cm} (5.2)

with a total momentum $E^2 = P_T^2 \cosh \eta$, where $P_T$ is $\tilde{\Sigma}^0$'s transverse momentum and $\eta = -\ln [\tan(\theta/2)]$ is its rapidity. Hence, the proper decay length of $\tilde{\Sigma}^0$ is given by

$$c\tau_{\tilde{\Sigma}^0} = c\tau_{\text{lab}} \times \sqrt{1 - \beta^2} = D_M \frac{\sqrt{1 - \beta^2}}{\beta}.$$  \hspace{1cm} (5.3)

We fix $D_M = 100$ m and set $\theta \simeq 0.5$ corresponding to the location of the MATHUSLA detector. Hence, $P_{\text{tot}} = 2P_T$ and

$$c\tau_{\tilde{\Sigma}^0} \simeq 2D_M \left( \frac{m_{\tilde{\Sigma}^0}}{P_T} \right)^2 = 200 \left( \frac{m_{\tilde{\Sigma}^0}}{P_T} \right).$$  \hspace{1cm} (5.4)

To simulate the production of $\tilde{\Sigma}^0$ observed by MATHUSLA, we employ MadGraph5@NLO [74,78] and calculate the production cross section ($\sigma$) for the process. Since $c\tau_{\tilde{\Sigma}^0} \simeq 5$ cm for our benchmark is smaller than the benchmark value of 9 cm used in the Higgsino search analysis, we expect the lower-bound on $\tilde{\Sigma}^0$ mass to be weaker than $m_{\tilde{\Sigma}^0} \simeq 380$ GeV shown in the left panel of Fig. 11. Thus, in the following, we consider two benchmark values, $m_{\tilde{\Sigma}^0} = 600$ (700) GeV. In the top left (right) panel of Fig. 12, for $m_{\tilde{\Sigma}^0} = 600$ (700) GeV, we show the cross section as a function of transverse momentum ($P_T$) of $\tilde{\Sigma}^0$. Because of low background, let us require 25 events ($N = 25$) for a “$\tilde{\Sigma}^0$ discovery” at MATHUSLA. In the bottom left (right) panel of Fig. 12, for $m_{\tilde{\Sigma}^0} = 600$ (700) GeV, we show the luminosity ($L = N/\sigma$) required for the discovery of $\tilde{\Sigma}^0$ as a function of its decay length, which we evaluated by using Eq. (5.4). The bottom (top) horizontal line denotes the integrated luminosity at HL-LHC with $L = 300$ (3000) fb$^{-1}$. From the bottom panels we find that the MATHUSLA can discover $\tilde{\Sigma}^0$ with a mass 600 GeV and 700 GeV, if their decay lengths are in the range $O(10^2)$–$O(10^3)$ m for both the cases. Since the cross section decreases with increasing $m_{\tilde{\Sigma}}$ values, a heavier $\tilde{\Sigma}_0$ requires a higher luminosity. For example, we find that $m_{\tilde{\Sigma}_0} = 1000$ GeV requires $L > 3000$ fb$^{-1}$ for any $\tau$ values.

### 5.3 Displaced vertex searches for $\Sigma^\pm$ at FCC-he

Let us now consider the displaced vertex signature arising from $\Sigma^\pm$ decay at ep-colliders.$^6$ Authors in Ref. [55] have studied the prospect to detect charged Higgsinos at FCC-he experiment to show that these experiments can probe much shorter decay length, $10^{-3}–10$ cm, compared to the pp-colliders. As in the case of HL-LHC, we can recast their search prospect by exploiting the one-to-one correspondence between the Higgsino mass, its production rate and lifetime while taking into account the differences in the production rate of Higgsino and $\Sigma$. Because the charged Higgsino decays 100% to the long-lived neutral Higgsino that evades detection and soft pion/SM leptons, the results in Ref. [55] is only applicable to the type-III seesaw in the limiting case $m_{\tilde{\tau}_1(3)} \rightarrow 0$ for NH (IH). See, for example, Figs. 7 and 8. Particularly, we fix $m_{\tilde{\tau}_1(3)} = 10^{-5}$ eV for the following analysis.

Employing the prospect for detecting the long-lived charged Higgsino presented in Ref. [55], in the left panel of Fig. 13 we show the prospects for FCC-he with 1 ab$^{-1}$ luminosity. The blue and green shaded regions indicate the parameter space where 100 (10) events with at least one long-lived $\Sigma^\pm$ is observed at the FCC-he; the green shaded regions correspond to 2- $\sigma$ exclusion sensitivity. In the right panel, the red shaded regions 2- $\sigma$ exclusion sensitivity if the backgrounds are harder to reject. The grey shaded region in all the plots is excluded for the long-lived Higgsino scenario but is still allowed in our scenario. In each panels of Fig. 13, we also show the 5- $\sigma$ exclusion reach of HL-LHC obtained in the right panel of Fig. 11 from the disappearing track searches. We also show the decay length of $\Sigma^\pm$ corresponding to NH (IH), which are both depicted by the horizontal black line for the benchmark values $\theta_{1,2,3} = 0$, $m_{\tilde{\tau}_1} = 600$ GeV and $m_{\Sigma_{2,3}}(m_{\Sigma_{1,2}}) = 1$ TeV and $m_{\tilde{\tau}_{1(3)}} = 10^{-5}$ eV, respectively.

### 6 Summary

We have investigated the prospect of probing the type III seesaw neutrino mass generation mechanism at various collider experiments by searching for a disappearing track signature as well as a displaced vertex signature originating from the decay of $SU(2)_L$ triplet fermion $\Sigma$. We consider scenario with three triplet fermions, $\Sigma_{i=1,2,3}$, each of which include one neutral component, $\Sigma^0$, and two charged components, $\Sigma^\pm$. Because $\Sigma_i$ is primarily produced at colliders through

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$^6$ The prospect for probing the type-I seesaw scenario at LHeC has been investigated in Ref. [81] with prompt decays of the right-handed neutrinos.
Fig. 12 The top left (right) show the production cross section as a function of $p_T$ for $m_{\Sigma} = 600$ (700) GeV. In the bottom panels, we show the luminosities required to produce $25 \Sigma$ at LHC which are directed towards MATHUSLA, and the horizontal bottom (top) line denote $\mathcal{L} = 300$ (3000) fb$^{-1}$.

Fig. 13 The plots show the prospects of observing displaced vertex from $\Sigma^\pm$ decay at FCC-he. The blue and green shaded regions indicate the parameter space where 100 (10) events with at least one long-lived $\Sigma^\pm$. The light-red shaded region indicate 2-σ exclusion sensitivity if the backgrounds are harder to reject. The grey shaded region are still allowed in our type-III seesaw scenario. The solid horizontal black line depict the decay length of $\Sigma^\pm$ for both NH (IH) and the benchmark values $\theta_{1,2,3} = 0$, $m_{\Sigma} = 600$ GeV and $m_{\Sigma,1,2}(m_{\Sigma,1,3}) = 1$ TeV and $m_{1(3)} = 10^{-9}$ eV, respectively.

their electroweak gauge interactions, its production rate is uniquely determined by its mass $m_{\Sigma_i}$. The type-III seesaw mechanism generates the observed neutrinos masses, which together with $m_{\Sigma_i}$, determine the decay length of $\Sigma_i^{0,\pm}$. We have shown that the neutral lepton associated with the lightest observed neutrino, particularly $\Sigma_i^{0,\pm}$ for NH (IH), respectively, can have lifetime $c\tau \gg 10$ m and evade detection at collider while their respective charged partners $\Sigma_i^{\pm}$ have a much shorter lifetime and decay inside the detector. The $\Sigma_i^{\pm}$ with a mass few hundred GeV and associated with the lightest observed neutrino $m_{1(3)}$ for NH (IH), respectively, decay and produce a disappearing track signature which can be searched at future pp-collider such as the HL-LHC. If the lightest observed neutrino, $m_{1(3)}$ for NH (IH), respectively, has mass around $10^{-9}$ eV, we have shown that both $\Sigma_i^{0,\pm}$ have a decay length of around 100 m and can be discovered at the proposed MATHUSLA detector. On the other hand, for NH (IH), we have also shown that $\Sigma_i^{\pm}$, respectively, decay to produce an observable displaced vertex signature at the FCC-he.

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