Displaced Higgs production in Type-III Seesaw at the LHC/FCC, MATHUSLA and Muon collider

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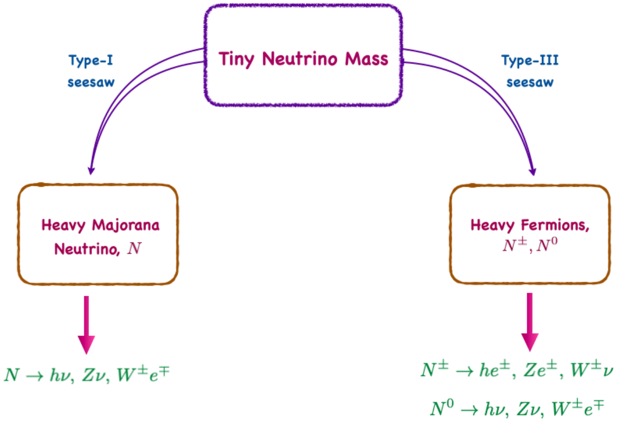
Overview

- Model description
- Displaced decay
- Transverse and longitudinal decay length
- Results at the LHC
- Results at muon collider

Seesaw Mechanism

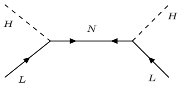


$\Gamma \propto Y_N^2$ for both the cases

- For lower Yukawa couplings $N^\pm \to N^0 \pi^\pm$ dominates.

Strumia et al. [Phys.Rev.D78:(2008)]

Model: Type-III Seesaw



- Extend SM by an $SU(2)$ triplet fermions (N) with $Y = 0$,

$$\mathcal{L}_N = \mathrm{Tr}(\bar{\mathrm{N}} \not{D} \mathrm{N}) \; - \; \frac{1}{4} \mathrm{M_N} \, \mathrm{Tr}\left[\bar{\mathrm{N}}\mathrm{N}\right] \; - \; \mathrm{Y_N} \left(\tilde{\phi}^{\dagger} \bar{\mathrm{N}} \mathrm{L} \; + \; \bar{\mathrm{L}} \mathrm{N} \tilde{\phi}\right).$$

- $SU(2)$ triplet representation of N,

$$N = \begin{pmatrix} N^0 & \sqrt{2}N^+ \\ \sqrt{2}N^- & -N^0 \end{pmatrix}$$

	N^+	N^-	N^0
T_3	+1	-1	0
Y	0	0	0

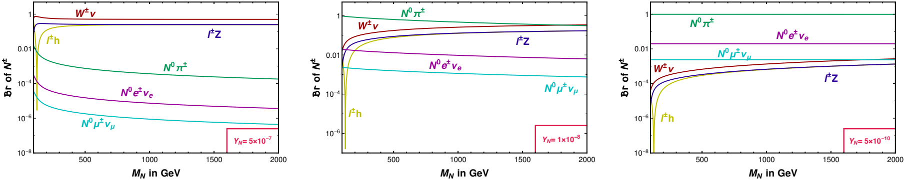
After EWSB, the light neutrino mass is generated as,

$$m_\nu = \frac{Y_N^2 v^2}{2M_N}.$$

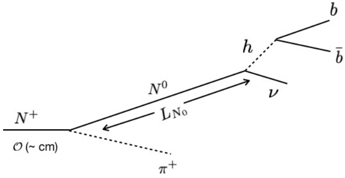
- For $m_\nu = 0.05\,\mathrm{eV}$, the choice of Yukawa coupling is $Y_N \sim \mathcal{O}(5 \times 10^{-7})$, and
- for $m_\nu = 0.001\,\mathrm{eV}$, the choice of Yukawa coupling is $Y_N \sim \mathcal{O}(10^{-8})$

for $\mathcal{O}(100)$ GeV Type-III fermion mass.

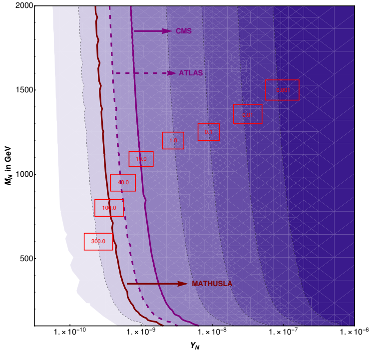
$N^{\pm} \to \pi^{\pm} N^0$ decay and displaced nature



- Low Yukawa couplings $\implies$ $N^{\pm} \to \pi^{\pm} N^0$ dominates.
- This makes decay length of $N^{\pm}$ very small ($\sim$ few cm).
- We can produce displaced Higgs from N^0 decay.



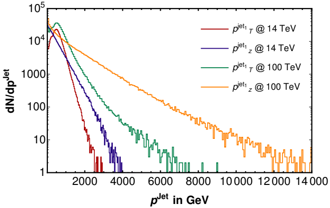
Displaced decay length in $Y_N - M_N$ plane

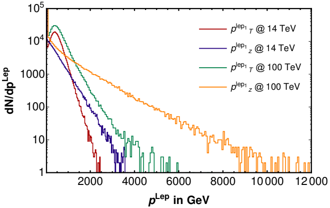


- CMS boundary: 10 m and ATLAS boundary: 40 m.
- The proposed detector MATHUSLA is around 100 m from the CMS or ATLAS in the beam axis as well as in the transverse direction.
- It is evident that, we need $Y_N \sim \mathcal{O}(10^{-10})$ to reach to MATHUSLA.

Displaced Higgs production at the LHC

p_T and p_z distributions of jets and leptons

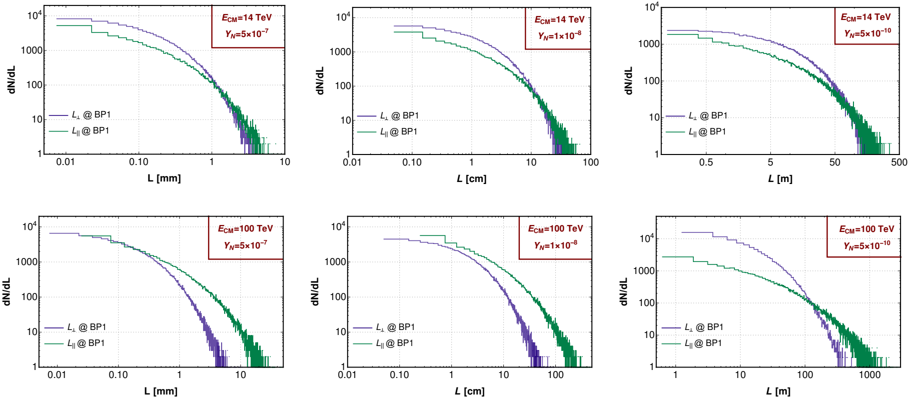




- In case of 14 TeV, p_z^{jet} goes till 3.8 TeV as compared to 2.5 TeV of p_T^{jet}.
- In case of 100 TeV, p_z^{jet} goes till 14 TeV as compared to 8.0 TeV of p_T^{jet}.

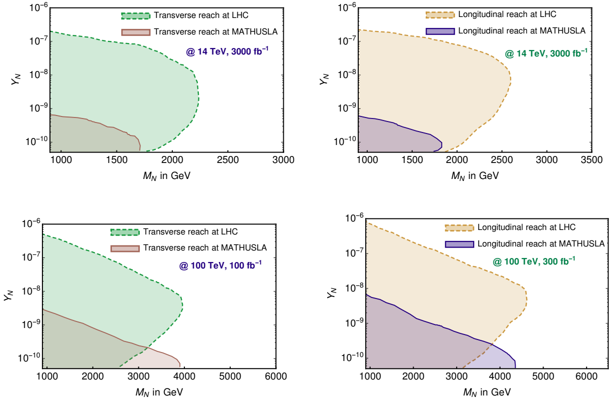
% of events for $P_z^{\text{jet}} > P_c^{\text{jet}}$ with $M_N = 1\,\text{TeV}$	Centre of mass energy		
	14 TeV	27 TeV	100 TeV
	8.4%	18.9%	31.3%

Displaced transverse and longitudinal decay length



- The boost effect is more in the longitudinal direction compared to the transverse one and that reflects in the decay lenghs.

Reach plots for LHC/FCC

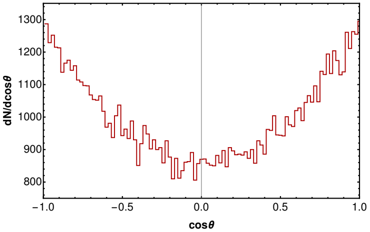


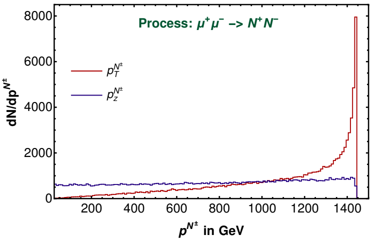
- In the mass range, the maximum reach is upto 2.4 and 2.7 TeV via the transverse and longitudinal decay lengths respectively for $E_{CM} = 14$ TeV.
- The reach is upto 3.8 TeV and 4.3 TeV for the transverse and longitudinal decay lengths respectively with $E_{CM} = 100$ TeV.
- Yukawa coupling $> 10^{-8}$ is out of the reach of MATHUSLA.

G.C. (RHUL), "Statistics (40)."

Displaced Higgs production at the Muon collider

Angular and transverse momentum distribution





- The angular distribution of $\mu^+\mu^- \to N^+N^-$ in the centre of mass frame is

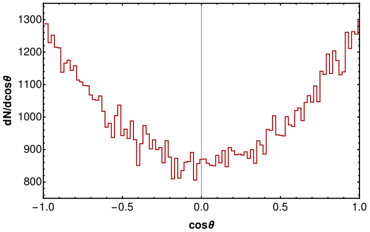
$$\frac{dN}{d\cos\theta} \sim \frac{d\sigma}{d\cos\theta} \sim (1+\cos^2\theta),$$

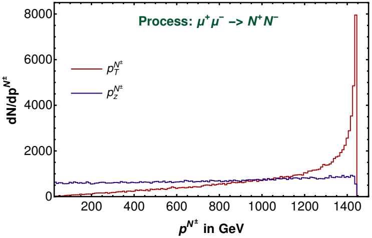
thus the probability is maximum for $\cos\theta = \pm 1$.

- The differential distributions with respect to $p_z^{N^\pm}$ never diverges as,

$$\frac{d\sigma}{dp_z^{N^\pm}} = \frac{d\sigma}{d\cos\theta}\frac{d\cos\theta}{dp_z^{N^\pm}} = \frac{1}{p^{N^\pm}}\frac{d\sigma}{d\cos\theta} \simeq \boxed{\frac{1}{p^{N^\pm}}(1+\cos^2\theta).}$$

Angular and transverse momentum distribution





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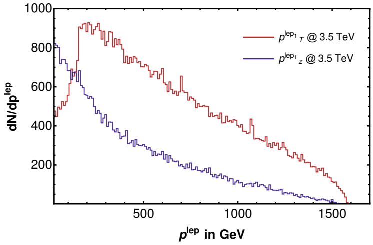
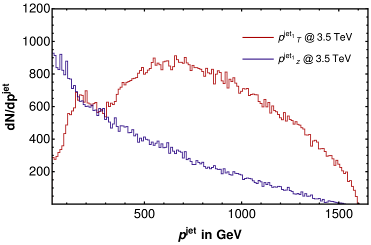
- The differential distributions with respect to $p_T^{N^\pm}$ diverges for $\theta = \pi/2,\ 3\pi/2$,

$$\frac{d\sigma}{dp_T^{N^\pm}} = \frac{d\sigma}{d\cos\theta}\frac{d\cos\theta}{dp_T^{N^\pm}} = \frac{1}{p^{N^\pm}}\frac{d\sigma}{d\cos\theta}\frac{d\cos\theta}{d\sin\theta} \simeq \boxed{\frac{\tan\theta}{-p^{N^\pm}}(1+\cos^2\theta).}$$

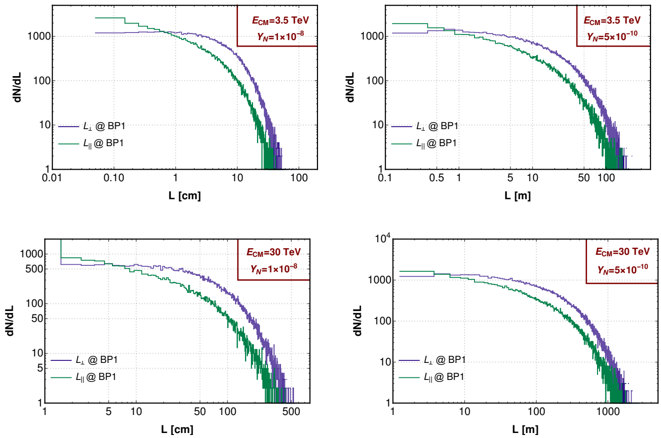
Transverse and longitudinal momentum distribution





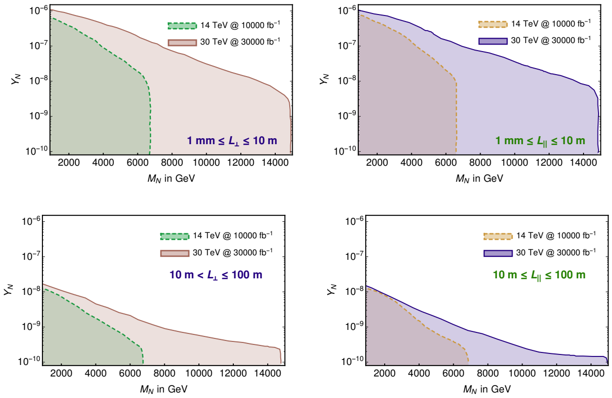
- The transverse momentum dominates over the longitudinal one for both jets and leptons, because,
  - the momentum conservation restricts the boost effect,
  - p_T tends to diverge around $|\eta| \sim 0$.
- The longer longitudinal decay length as compared to the transverse one should not be seen here.

Displaced transverse and longitudinal decay length



- The displaced transverse and longitudinal decay lengths are almost equal.
- The decay length is increasing almost 10 times as we increase the centre of mass energy from 3.5 TeV to 30 TeV.

Reach plots for muon collider



- Due to momentum conservation, the maximum mass range that can be probed are restricted to 7 and 15 TeV respectively for the centre of mass energies of 14 and 30 TeV.
- The longer decay lengths, $\mathcal{O}(10-100)$m, can be probed with very low Yukawa couplings $\lesssim 10^{-8}$.

Conclusion

- Type-III seesaw model is motivated to explain the tiny neutrino mass scale which predicts the heavy charged and neutral leptons.

- Depending on the Yukawa couplings, the displaced decay can be seen for $N^{\pm}$ and N^{0} and hence we can observe displaced Higgs production from that decay.

- The longitudinal boost at the LHC/FCC can lead to the enhancement of the displaced decay lengths, and thus has a better reach compared to the transverse one.

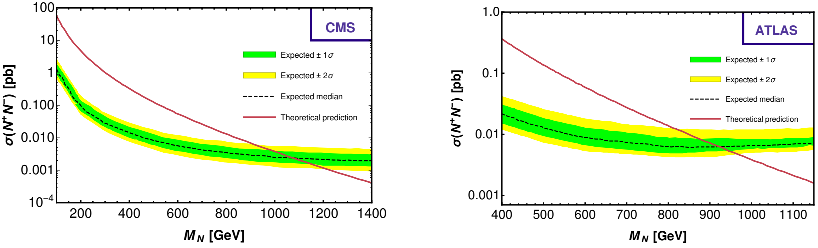
- However, at the muon collider we observe that the transverse momentum of $N^{\pm}$ diverges perpendicular to the beam axis.

- Reach is more at the muon collider, and it is evident that a detector with length around 10 m is sufficient in probing the larger ranges of the Yukawa coupling.


Thank you

Backup Slides

Type-III fermion mass bound from CMS and ATLAS

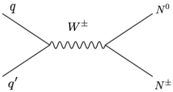


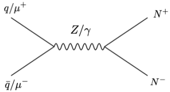
- The lower mass limit of $SU(2)$ triplet fermion is from prompt charged lepton finalstate.
- The lower limit of mass is 900 GeV from CMS and 830 GeV from ATLAS in 2σ level.

CMS, JHEP 03 (2020) 051 and ATLAS, Eur. Phys. J. C 81 (2021) 218

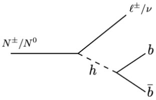
Feynmann Diagrams

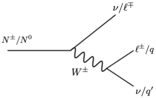
- At the LHC, associated $N^0 N^{\pm}$ can be produced via $W^{\pm}$ boson exchange as well as the pair of $N^{\pm}$ via photon and Z boson.

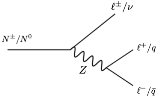




- The decay modes of the neutral heavy fermion (N^0) to $W^{\pm}\ell^{\mp}$, $Z\nu$ and $h\nu$ is around 2:1:1 for all the benchmark points.
- The charged heavy fermions ($N^{\pm}$) decay to $W^{\pm}\nu$, $Z\ell^{\pm}$ and $h\ell^{\pm}$ mostly but depending on Yukawa couplings the branching ratio of the mode $N^{\pm} \to N^0 \pi^{\pm}$ increases.
- The SM Higgs boson mass is around 125.5 GeV, which dominantly decays to $b\bar{b}$.







Decays of neutral heavy fermion N_0

The two-body decay widths for N^0 are proportional to Y_N^2 and are given by

$$\Gamma(N^0 \to \nu_\ell h) = \Gamma(N^0 \to \bar{\nu_\ell} h) = \frac{1}{8}\frac{Y_N^2 M_N}{8\pi}\left(1 - \frac{M_h^2}{M_N^2}\right)^2,$$

$$\Gamma(N^0 \to \nu_\ell Z) = \Gamma(N^0 \to \bar{\nu_\ell} Z) = \frac{1}{8}\frac{Y_N^2 M_N}{8\pi}\left(1 - \frac{M_Z^2}{M_N^2}\right)^2\left(1 + 2\frac{M_Z^2}{M_N^2}\right),$$

$$\Gamma(N^0 \to W^+\ell^-) = \Gamma(N^0 \to W^-\ell^+) = \frac{1}{4}\frac{Y_N^2 M_N}{8\pi}\left(1 - \frac{M_W^2}{M_N^2}\right)^2\left(1 + 2\frac{M_W^2}{M_N^2}\right).$$

Strumia et al. [Phys.Rev.D78:(2008)]

Decays of charged heavy fermions $N^\pm$

The two-body decay widths for $N^\pm$

$$\Gamma(N^\pm \to \ell^\pm h) = \frac{1}{4}\frac{Y_N^2 M_N}{8\pi}\left(1-\frac{M_h^2}{M_N^2}\right)^2,$$

$$\Gamma(N^\pm \to \ell^\pm Z) = \frac{1}{4}\frac{Y_N^2 M_N}{8\pi}\left(1-\frac{M_Z^2}{M_N^2}\right)^2\left(1+2\frac{M_Z^2}{M_N^2}\right),$$

$$\Gamma(N^\pm \to \nu_\ell W^\pm) = \frac{1}{2}\frac{Y_N^2 M_N}{8\pi}\left(1-\frac{M_W^2}{M_N^2}\right)^2\left(1+2\frac{M_W^2}{M_N^2}\right),$$

respectively. There are another decay modes possible considering the loop generated mass of $N^\pm$ and N^0,

$$\Gamma(N^\pm \to N^0\pi^\pm) = \frac{2G_F^2 V_{ud}^2 \Delta M^3 f_\pi^2}{\pi}\sqrt{1-\frac{m_\pi^2}{\Delta M^2}},$$

$$\Gamma(N^\pm \to N^0 e^\pm \nu_e) = \frac{2G_F^2 \Delta M^5}{15\pi^3},$$

$$\Gamma(N^\pm \to N^0 \mu^\pm \nu_\mu) = 0.12\,\Gamma(N^\pm \to N^0 e^\pm \nu_e).$$

This branching ratio is very small ($< 1\%$) for $Y_N \sim 10^{-7}$, however, can be dominant for further lower Yukawa couplings.

Strumia et al. [Phys.Rev.D78:(2008)]

Mass Reconstruction

- Higgs mass of ~ 125 GeV is reconstructed with $b\bar{b}$ invariant mass.
- $N^{\pm}$ mass is reconstructed from $bb\ell$ invariant mass: peaks at 1.0 and 1.5 TeV for the corresponding BPs.
- N^0 transverse invariant mass is reconstructed from $b\bar{b}\nu$ (when the other two legs are tagged via complete vissible mode) with the expression:

$$M_T^2 = m_h^2 + 2\left(E_T^h \not{E}_T - \vec{p_T^h}.\vec{\not{p}_T}\right)$$

with the edges of distributions at N^0 masses for the BPs.