Deciphering the Secrets of the Long-Lived Particles at the Colliders

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Based on: JHEP 02 (2023) 103, Eur.Phys.J.C 82 (2022) 3, 230, JHEP 03 (2024) 109

17$^{\text{th}}$ International Conference on Interconnections between Particle Physics and Cosmology

PPC 2024

Introduction to Long-Lived Particles

- Despite being massively successful, the Standard Model (SM) leaves much to be desired, including explanations for Dark Matter (DM), neutrino mass, and many more.
- No conclusive evidence for new particles Beyond the SM yet: with searches for prompt physics objects.
- Long-lived particles (LLP) may open new avenues for BSM searches.

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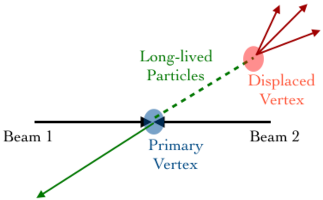
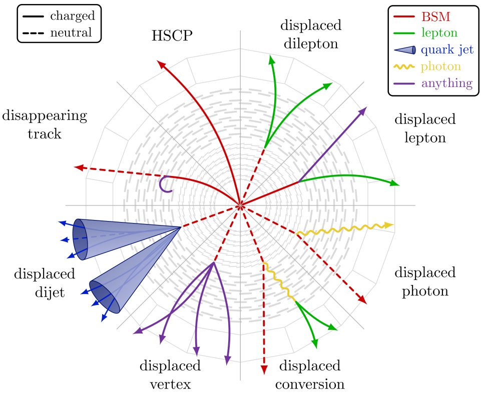


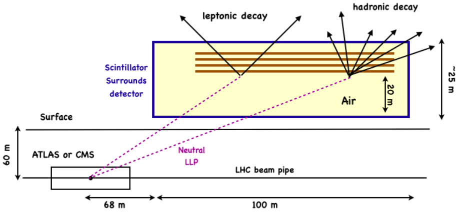
- Production vertex is different from the decay vertex.
- $\frac{1}{\tau} = \Gamma \propto g^2 |\mathcal{M}|^2 \Phi$, which can be small due to:
  - small couplings
  - heavy intermediary particles
  - limited phase space due to compressed spectrum

LLP signatures: what and where to look for?



[https://tikz.net/bsm_longlived]

- Most signatures can be detected in the existing/conventional detectors like CMS and ATLAS.
- For longer lifetimes, dedicated detectors like MATHUSLA and FASER can be handy.



[Alpigiani et al, 2009.01693 [physics.ins-det]]

We will deal with three different Fermionic LLP scenarios in this talk.

For a scalar LLP analysis, please attend Snehashis' talk.

Type-I Seesaw + $U(1)_{B-L}$ extension of SM

Apart from the SM particles we consider,

- three RHNs (N_{R_i}) to cancel the $B-L$ gauge anomaly,
- one $U(1)_{B-L}$ gauge boson Z_{B-L},
- one SM singlet $B-L$ charged complex scalar χ,

Important terms in Yukawa Lagrangian:

$$\mathcal{L}_Y \supset -\underbrace{(Y_N)_{ij}\,\overline{L}_i\,\tilde{\Phi}(N_R)_j}_{\text{Dirac mass term}} - \underbrace{(\lambda_N)_{ij}\,\chi(\overline{N_R})_i^C\,(N_R)_j}_{\text{Majorana mass term}}.$$

$B-L$ charge for all the particles in the model:

	Φ	Q	L	u_R, d_R	e_R	N_{R_i}	χ
$B-L$	0	$1/3$	-1	$1/3$	1	-1	2

P. Bandyopadhyay, E. J. Chun, CS; JHEP 02 (2023) 103

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- Mass of the Z_{B-L} is generated due to spontaneous symmetry breaking of the $B-L$ gauge symmetry:

$$M_{Z_{B-L}} = 2g_{BL}v_{BL}, \qquad \text{where, } <\chi>= \frac{v_{BL}}{\sqrt{2}}$$

- Majorana masses of RHNs can also be generated spontaneously via the breaking of $U(1)_{B-L}$ gauge symmetry:

$$M_N = \lambda_N \frac{v_{BL}}{\sqrt{2}}$$

- Light SM neutrino masses are generated by Type-I seesaw mechanism when Φ gets vev:

$$m_\nu = \frac{Y_N^2 v^2}{2M_N}, \qquad \text{where, } <\Phi>= \frac{v}{\sqrt{2}}$$

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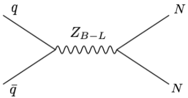
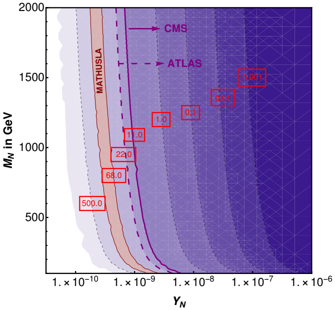
Collider Signatures: Type-I Seesaw in $B-L$ Scenario

- RHN can be pair produced via Z_{B-L} gauge boson in Drell-Yan process.



- RHNs decay through $Z\nu$, $h\nu$ and $W^{\pm}\ell^{\mp}$, with the decay widths, $\Gamma_N^{Z\nu} \approx \Gamma_N^{h\nu} \approx \frac{1}{2}\Gamma_N^{W\ell} \approx \frac{Y_N^2\, M_N}{64\pi}$



- Rest mass decay length contours in meter unit.
- Boost effect can enhance the decay length as, $L_\tau = c\tau\beta\gamma = \frac{\tau p}{m}$
- Decay vertex position with the boost effect: $v' = v + \frac{\tau p}{m}$.

[P. Bandyopadhyay, E. J. Chun, C. Sen; JHEP 02 (2023) 103]

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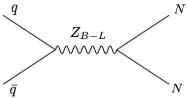

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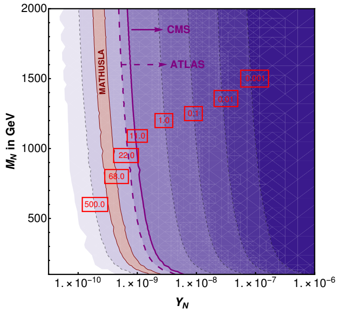

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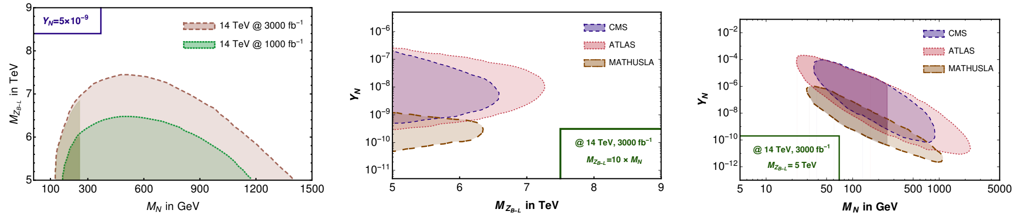
- Boost effect can enhance the decay length as, $L_\tau = c\tau\beta\gamma = \frac{\tau p}{m}$
- Decay vertex position with the boost effect: $v' = v + \frac{\tau p}{m}$.

  - Most dominant final states come from the $N \to W^{\pm}\ell^{\mp}$ mode.
  - For lower masses and higher boost, W-jets are collimated to one (fat) jet.
  - Lower masses: $2\ell + 2j$ (also contributed from $N \to Z\nu$). Higher masses: $2\ell + 4j$.
  - All these decay products are displaced.

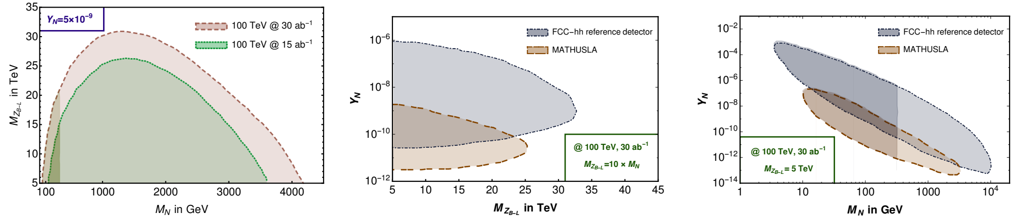
[P. Bandyopadhyay, E. J. Chun, C. Sen; JHEP 02 (2023) 103]

Collider reach of the Type-I displaced decay parameter space

- Reach plots for 14 TeV LHC



- Reach plots for 100 TeV FCC-hh



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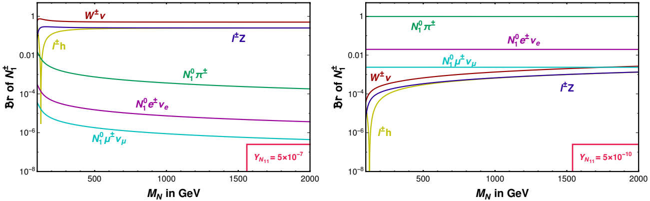
Successive Displaced Decays in Type-III Seesaw

- The $SU(2)$ triplet fermion, $N_R = \begin{pmatrix} N^0 & \sqrt{2}N^+ \\ \sqrt{2}N^- & -N^0 \end{pmatrix}$, with zero hypercharge is added with the SM.
- The Lagrangian corresponding to the triplet fermion is:

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



- Heavy charged fermion ($N^\pm$) decays to $Z\ell^\pm$, $h\ell^\pm$ and $W^\pm\nu$, with the decay widths,

$$\Gamma^{Z\ell}_{N^\pm} \approx \Gamma^{h\ell}_{N^\pm} \approx \frac{1}{2}\Gamma^{W\nu}_{N^\pm} \approx \frac{Y_N^2 M_N}{32\pi}.$$

- Another decay mode is dominant for lower Yukawa:

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

[Cirelli et al, Nucl. Phys. B 753 (2006) 178-194]

CS, P. Bandyopadhyay, S. Dutta, Aleesha KT; Eur.Phys.J.C 82 (2022) 3, 230

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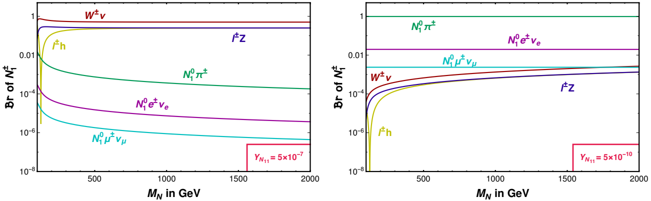

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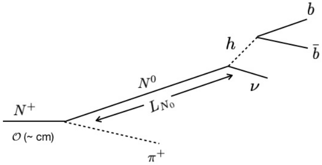

- First recoil: Decay length of $N^\pm$ is $\mathcal{O}(5)$cm.
- Second recoil: Decay length of N^0 depends on Y_N.

A displaced double recoil is predicted.

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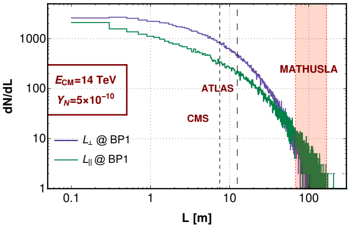
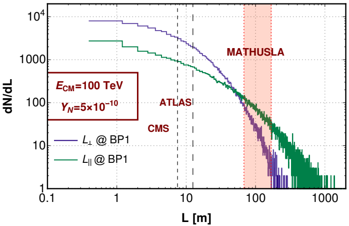
Collider Reach for Displaced Higgs boson





- Decay length increases due to the boost effect as the centre-of-mass energy increases from LHC @14 TeV to FCC-hh @100 TeV.
- Boost effect is more in the longitudinal direction compared to the transverse one.

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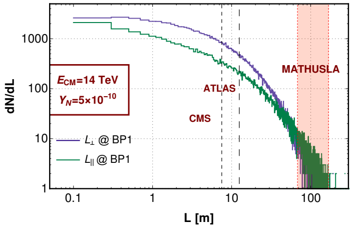

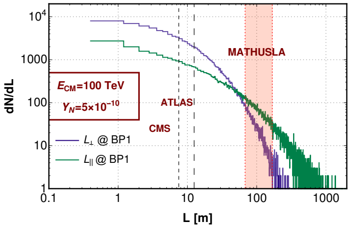

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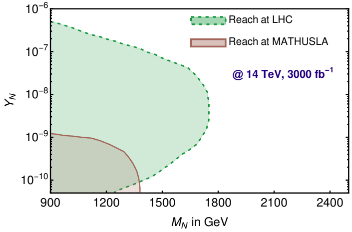

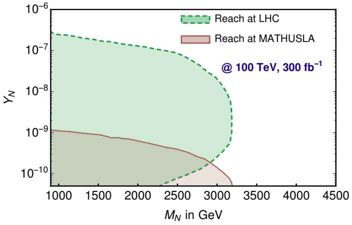

- The regions contain at least one displaced Higgs boson reconstructed from di-b-jet invariant mass.
- Yukawa couplings $\gtrsim 10^{-9}$ is out of the reach of MATHUSLA.

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Extension with Non-zero Hyper-charged $SU(2)$ Triplet Fermions

Description	Field definition	Gauge charges			
		$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	Z_2
Vectorlike lepton (VLL)	$N = \begin{pmatrix} \frac{N^-}{\sqrt{2}} & N^0 \\ N^{--} & -\frac{N^-}{\sqrt{2}} \end{pmatrix}$	1	3	-1	$-$
Scalars	$\Phi_1 = (\phi_1^+ \; \phi_1^0)^T$	1	2	1/2	$+$
	$\Phi_2 = (\phi_2^+ \; \phi_2^0)^T$	1	2	1/2	$-$

- Cannot write a Majorana mass term for $Y = -1$ triplet fermion: hence, assigned vector-like.
- For the vector-like fermions, the left- and right- handed components transforms the same way, making the mass term invariant, independent of the Higgs field.

- Scalar potential:

$$V_{\text{scalar}} = -m_{\Phi_1}^2 \Phi_1^\dagger \Phi_1 - m_{\Phi_2}^2 \Phi_2^\dagger \Phi_2 + \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) \\ + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \left[\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + h.c\right]$$

- $\mathbb{Z}_2$ odd scalar doublet couples with VLL as

$$\mathcal{L}_{VLL} \supset \left[-\frac{M_N}{2} \overline{N_L} N_R + \mathcal{Y}_N \overline{L_L^e} N_R \Phi_2\right] + h.c.$$

- Non-Majorana with $Y \neq 0$: N^0 couples to Z boson, which forbids fermionic and multi-component DM, owing to large DM-neucleon cross-sections.

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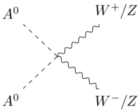
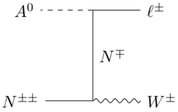
Interplay between IDM and VLL and Boltzmann equations

Convention: Sector 0: SM particles; Sector 1: IDM $[A^0, H^0, H^\pm]$; Sector 2: Inert VLL $[N^0, N^\pm, N^{\pm\pm}]$

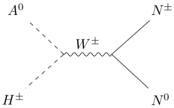
Pair-annihilation



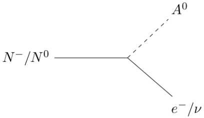
Co-annihilation



Co-scattering



Decay effect



$$\frac{dY_{\Phi_2}}{dx} = -\frac{1}{x^2}\frac{s(M_{A^0})}{H(M_{A^0})}\left[\langle\sigma v\rangle_{1100}\left(Y_{\Phi_2}^2 - (Y_{\Phi_2}^{eq})^2\right) - \langle\sigma v\rangle_{2211}\left(Y_{\Phi_2}^2 - Y_N^2\frac{(Y_{\Phi_2}^{eq})^2}{(Y_N^{eq})^2}\right)\right.$$

$$\left. + \langle\sigma v\rangle_{1200}\left(Y_{\Phi_2}Y_N - Y_{\Phi_2}^{eq}Y_N^{eq}\right)\right] + \frac{x\,\Gamma_{N\to\Phi_2 X}}{H(M_{A^0})}\left(Y_N - Y_{\Phi_2}\frac{Y_N^{eq}}{Y_{\Phi_2}^{eq}}\right)$$

$$\frac{dY_N}{dx} = -\frac{1}{x^2}\frac{s(M_{A^0})}{H(M_{A^0})}\left[\langle\sigma v\rangle_{2200}\left(Y_N^2 - (Y_N^{eq})^2\right) + \langle\sigma v\rangle_{2211}\left(Y_{\Phi_2}^2 - Y_N^2\frac{(Y_{\Phi_2}^{eq})^2}{(Y_N^{eq})^2}\right)\right.$$

$$\left. + \langle\sigma v\rangle_{1200}\left(Y_{\Phi_2}Y_N - Y_{\Phi_2}^{eq}Y_N^{eq}\right)\right] - \frac{x\,\Gamma_{N\to\Phi_2 X}}{H(M_{A^0})}\left(Y_N - Y_{\Phi_2}\frac{Y_N^{eq}}{Y_{\Phi_2}^{eq}}\right)$$

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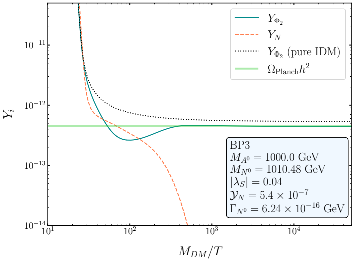
Interplay between IDM and VLL

- Consider the following mass spectrum for the study of interplay:

M_{A^0} (GeV)	M_{H^0} (GeV)	$M_{H^\pm}$ (GeV)	M_{N^0} (GeV)	M_{N^-} (GeV)	$M_{N^{--}}$ (GeV)	$\mathcal{Y}_N$	Ωh^2
1000.0	1010.5	1001.0	1010.5	1011.0	1011.9	5.4×10^{-7}	0.121



- The yield of A^0 suffers a dip for more co-annihilation due to compressed spectra.
- Number density of A^0 increases when N decays off completely.
- Pure Inert doublet scalar shows overabundant, but the interplay (co-annihilation and decay) of N sector can bring back the DM yield in correct ballpark.

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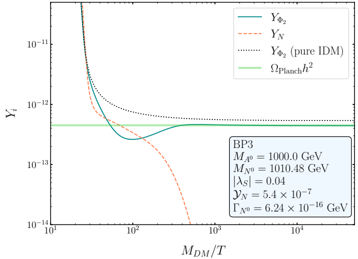
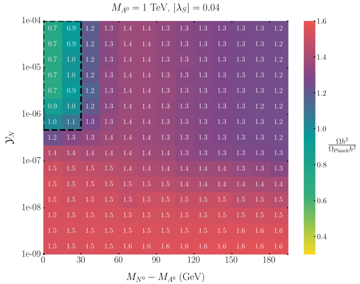
1000.0	1010.5	1001.0	1010.5	1011.0	1011.9	5.4×10^{-7}	0.121





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- Number density of A^0 increases when N decays off completely.
- Pure Inert doublet scalar shows overabundant, but the interplay (co-annihilation and decay) of N sector can bring back the DM yield in correct ballpark.

- Lower the Yukawa couplings: less co-annihilation + very late decay of the fermions.
- Higher the mass splitting: less phase space for co-annihilation, that leads to overabundance of DM number density.

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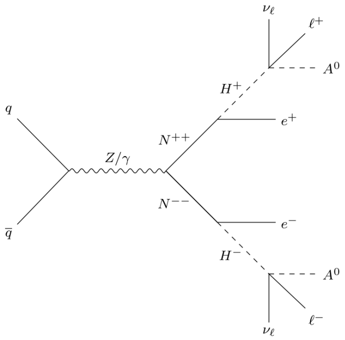
Collider Signatures: Displaced decay of $N^{\pm\pm}$



- The decay width of $N^{\pm\pm}$:

$$\Gamma_{N^{\pm\pm}\to H^{\pm}\ell^{\pm}} = \frac{\mathcal{Y}_N^2 M_{N^{\pm\pm}}}{32\pi}\left(1 - \frac{M_{H^\pm}^2}{M_{N^{\pm\pm}}^2}\right)^2 .$$

- Small $\mathcal{Y}_N$ and compressed mass spectrum lead to small decay width $\implies$ larger decay length.

- Hadronically quiet, displaced multi-lepton final states, with leptons as soft as ≥ 5 GeV.

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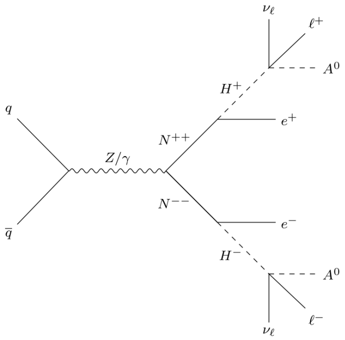
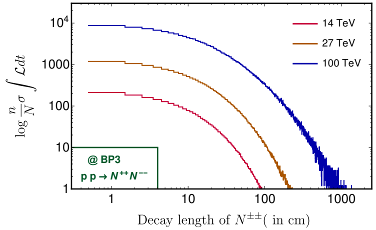


- $M_{N^{\pm\pm}} =$ 1012 GeV and the corresponding Yukawa coupling $\mathcal{Y}_N = 5.4 \times 10^{-7}$.
  - Total decay width: $\Gamma_{\text{tot}} = 1.34 \times 10^{-15}$ GeV.
  - Rest mass decay length: $c\tau_0 =$ 15 cm
- Boost effect enhances the decay length; the maximum reach is around 10 m in a 100 TeV FCC-hh.

- The decay width of $N^{\pm\pm}$:

$$\Gamma_{N^{\pm\pm}\to H^\pm \ell^\pm} = \frac{\mathcal{Y}_N^2 M_{N^{\pm\pm}}}{32\pi}\left(1 - \frac{M_{H^\pm}^2}{M_{N^{\pm\pm}}^2}\right)^2 .$$

- Small $\mathcal{Y}_N$ and compressed mass spectrum lead to small decay width $\implies$ larger decay length.
- Hadronically quiet, displaced multi-lepton final states, with leptons as soft as $\geq$ 5 GeV.



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Conclusions

- Displaced decays can be used as non-standard searches to probe *new physics* scenarios.
- Displace decays of neutral fermions, i.e. N^0 in case of Type-I Seesaw, and charged fermions in case of Type-III Seesaw and VLL can probe the models for the unexplored territory.
- Lower Yukawa couplings and compressed mass spectrum can alter the DM phenomenology as well as can give displaced final state signatures at the colliders.
- Two successive displacements (double recoil) can be observed for triplet extension of SM in case of lower Yukawa couplings ($Y_N \lesssim 10^{-8}$).
- $\mathcal{O}(100)$ m decay lengths can be probed inside MATHUSLA detector.


Thank you

Backup Slides

One generation of RHN with low Yukawa

From the neutrino oscillation data,

$$\Delta m_{21}^2 = m_2^2 - m_1^2 \approx 7.42 \times 10^{-5}\,\mathrm{eV}^2$$

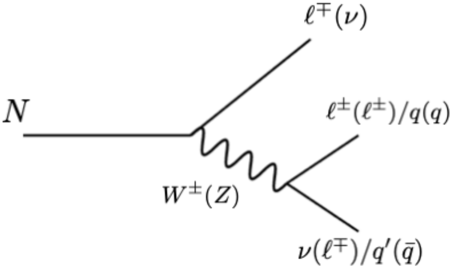
Suppose for one generation of RHN (N_1), the Yukawa coupling is very small, i.e. $Y_{N_1} = 5 \times 10^{-10}$.
Hence, the SM neutrino mass,

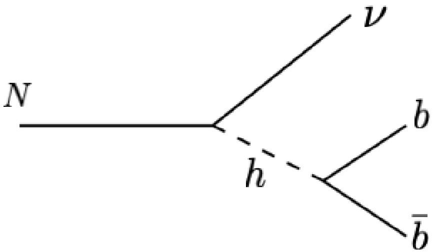
$$m_1 = \frac{Y_{N_1}^2 v^2}{2 M_{N_1}} = 7.56 \times 10^{-9}\,\mathrm{eV}, \qquad \text{if,} \mathrm{M_{N_1}} = 1\,\mathrm{TeV}$$

This makes, $m_2 = 8.6 \times 10^{-3}\,\mathrm{eV}$. The corresponding Yukawa coupling, $Y_{N_2} = 7.5 \times 10^{-7}$, which fails to give displaced signature.

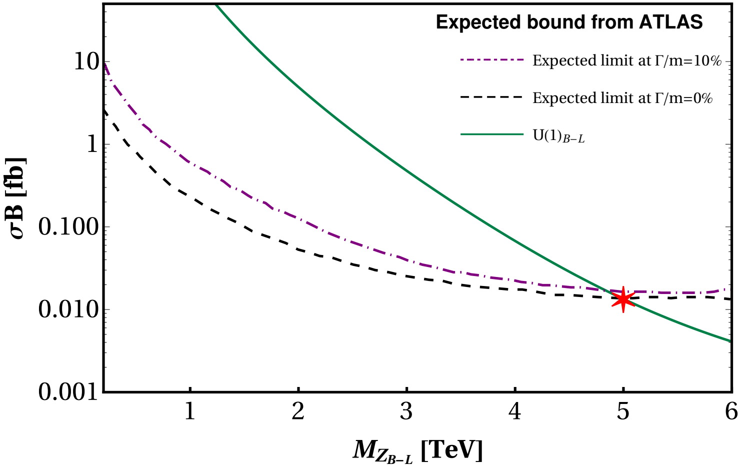
Similarly from $\Delta m_{31}^2 = m_3^2 - m_1^2 \approx 2.51 \times 10^{-3}\,\mathrm{eV}^2$, one can calculate $Y_{N_3} = 1.3 \times 10^{-6}$.

Displaced decay of RHNs





$M_{Z_{B-L}}$ bound



Expected bound from ATLAS
Expected limit at Γ/m=10%
Expected limit at Γ/m=0%
$U(1)_{B-L}$
10
1
0.100
0.010
0.001
σB [fb]
1
2
3
4
5
6
$M_{Z_{B-L}}$ [TeV]

Benchmarks for IDM+VLL

BP	M_{A^0} (GeV)	M_{H^0} (GeV)	$M_{H^\pm}$ (GeV)	M_{N^0} (GeV)	M_{N^-} (GeV)	$M_{N^{--}}$ (GeV)	$\mathcal{Y}_N$
BP1	71.57	117.16	84.76	98.25	98.61	99.28	4.2×10^{-9}
BP2	587.6	589.4	588.2	595.5	595.9	596.8	1.1×10^{-7}
BP3	1000.0	1010.5	1001.0	1010.5	1011.0	1011.9	5.4×10^{-7}

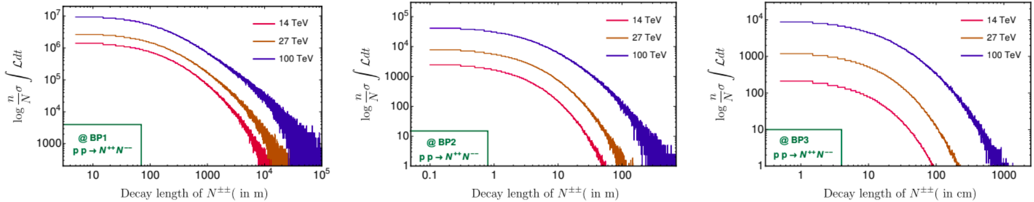
- All of the benchmark points are satisfied by correct relic abundance, direct and indirect detection constraints.
- All of them lead to displaced decays of the VLLs.

Displaced Decay of $N^{\pm}\pm$ in IDM+VLL

- The decay width and rest mass decay length off $N^{\pm\pm}$ for three benchmark points:

$N^{\pm\pm}$	BP1 $\mathcal{Y}_N = 4.2 \times 10^{-9}$		BP2 $\mathcal{Y}_N = 1.1 \times 10^{-7}$		BP3 $\mathcal{Y}_N = 5.4 \times 10^{-7}$	
	Γ_{tot} (GeV)	$c\tau_0$ (m)	Γ_{tot} (GeV)	$c\tau_0$ (m)	Γ_{tot} (GeV)	$c\tau_0$ (m)
	1.27×10^{-18}	155.42	5.92×10^{-17}	3.33	1.34×10^{-15}	0.15

- The decay length distribution considering the boost effect:



- BP1: β not low enough to be an HSCP. comparatively harder leptons. May reach MATHUSLA.
- BP2: β in the HSCP region, a comparative study in detail can be done.
- BP3: Too heavy, decays before ECal.