Displaced Decay Signatures in Probing Seesaw

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arXiv: 2205.12511

P Bandyopadhyay, EJ Chun, CS

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P Bandyopadhyay, S Dutta, Aleesha KT, CS

भारतीय प्रौद्योगिकी संस्थान हैदराबाद

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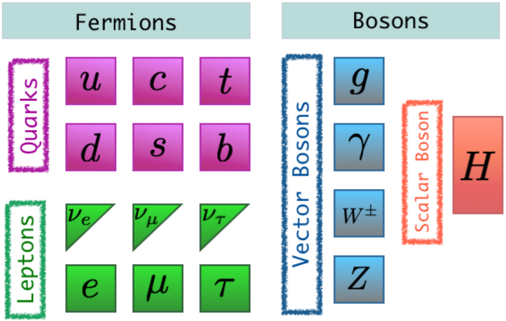
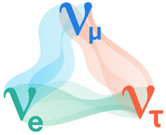
Overviews

- Introduction
- Boosted displaced decay in Type-I seesaw model
- Boosted displaced decay in Type-III seesaw model
- Conclusions

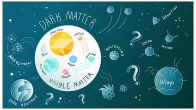
Some puzzles for physics beyond the Standard Model



- Can not explain the tiny neutrino mass, which is evident from the neutrino oscillation data.



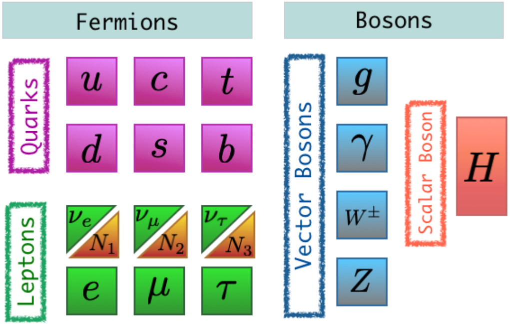
- Can not explain dark energy and dark matter, which contains 95% of our universe.



- Can not explain the matter-antimatter asymmetry in the present universe.

. . . and so on . . .

Extend with the Right-handed Components of Neutrinos



- If neutrinos are only Dirac type, possible mass term is $Y_N \bar{L}\widetilde{\phi}N_R$.
- To explain small ν mass ($\mathcal{O}(0.1)$eV), $Y_N \sim \mathcal{O}(10^{-12})$, not natural.

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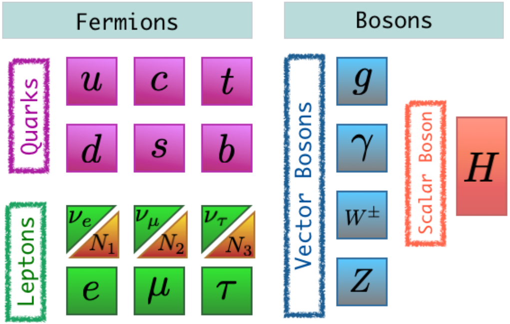

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Solution!!

Neutrinos are electrically neutral $\implies$ can be Majorana also.

Seesaw Mechanism

- Seesaw mechanism is one where the smallness of neutrino mass is explained by a large scale.
- The mass term can be written as

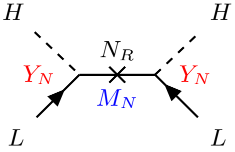
$$\mathcal{L} \supset \frac{1}{2} M_L \overline{(\psi_L)^c} \psi_L + \frac{1}{2} M_R \overline{(\psi_R)^c} \psi_R + \text{h.c.}$$

- The light neutrino has the basic structure as:

$$m_\nu \approx \frac{(\text{Yukawa coupling})^2 \times < \phi >^2}{M_{\text{Seesaw}}} \approx \frac{\text{MeV}^2}{\text{TeV}} \approx \text{eV}$$

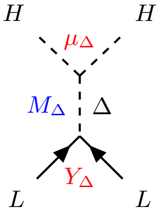
Three basic Seesaw Models

1. **Type-I Seesaw:**
   Singlet fermionic extension



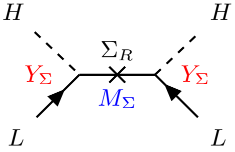
- $m_\nu = Y_N^T \frac{1}{M_N} Y_N v^2$

2. **Type-II Seesaw:**
   Triplet scalar extension



- $m_\nu = Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} v^2$

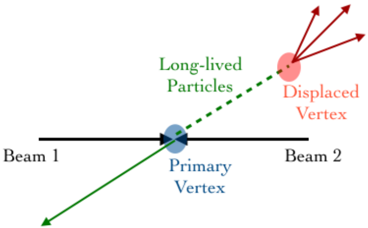
3. **Type-III Seesaw:**
   Triplet fermionic extension



- $m_\nu = Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma v^2$

Senjanovic, Ma; Ma, Mohapatra, Gloashow, Ramon, Joshi, Strumia, Foot, Hambye . . .

Can we get Long Lived Particle (LLP) Signature?



- Production vertex is different from the decay vertex.
- $\frac{1}{\tau} = \Gamma \propto g^2 |\mathcal{M}|^2 \Phi$
  - small couplings
  - heavy intermediary
  - limited phase space

Idea: Dr. S S Ghosh, IIT Hyderabad

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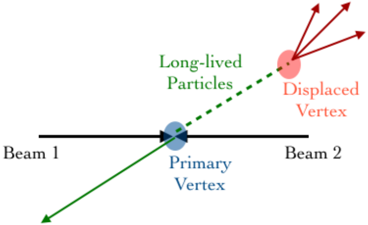

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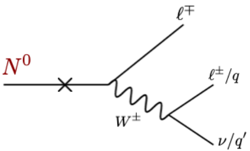
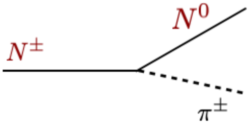
Possibilities for Seesaw Models

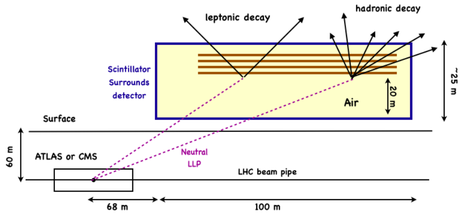
- Heavy neutral leptons, small left-handed neutrino mixing



- Small mass splitting between $N^\pm$ and N^0



Some Proposed LLP Detectors



- MATHUSLA is proposed to be built 68 meters from the CMS/ATLAS interaction point in the longitudinal direction, 60 meters in the transverse direction.

- MATHUSLA should be able to search for the long-lived particles with near-zero backgrounds.

- MATHUSLA geometry: $25 \times 100 \times 100\,\mathrm{m}^3$.

Alpigiani et al. [arXiv:2009.01693 [physics.ins-det]]

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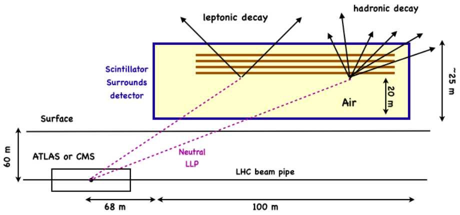

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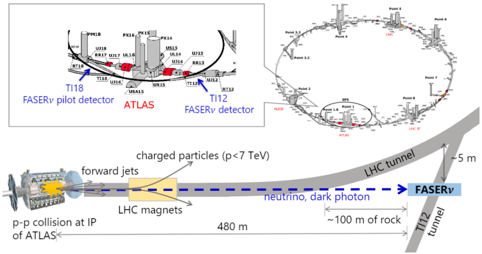

- FASER-II is proposed to be situated 480 m east of ATLAS collision point.
- Detector length $\sim 5\,\mathrm{m}$, radius $\sim 1\,\mathrm{m}$.
- Projected luminosity $3\,\mathrm{ab}^{-1}$.
- Angular acceptance, $\theta \leq 0.0573^\circ$.

FASER Collaboration [arXiv:1901.04468 [hep-ex]]

Boosted Displaced Decay in Type-I Seesaw Scenario

Type-I Seesaw model with $B-L$ gauge symmetry

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_{BL},
- one SM singlet $B-L$ charged complex scalar χ,

$B-L$ 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

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The scalar potential:

$$V(\Phi,\chi) = m_\Phi^2(\Phi^\dagger\Phi) + m_\chi^2|\chi|^2 + \lambda_1(\Phi^\dagger\Phi)^2 + \lambda_2|\chi|^4 + \lambda_3(\Phi^\dagger\Phi)|\chi|^2 .$$

The Yukawa terms of the Lagrangian:

$$\mathcal{L}_Y = - \quad Y_{ij}^u\,\overline{Q}_i\,\tilde{\Phi}(u_R)_j - Y_{ij}^d\,\overline{Q}_i\,\Phi(d_R)_j - Y_{ij}^e\,\overline{L}_i\,\Phi(e_R)_j - \underbrace{(Y_N)_{ij}\,\overline{L}_i\,\tilde{\Phi}(N_R)_j}_{\text{Dirac mass term}} - \underbrace{(\lambda_N)_{ij}\,\chi(\overline{N_R})_i^C\,(N_R)_j}_{\text{Majorana mass term}} .$$

Basso et al. [Phys.Rev.D 80 (2009) 055030]

Mass Generations After Spontaneous Symmetry Breaking

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

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

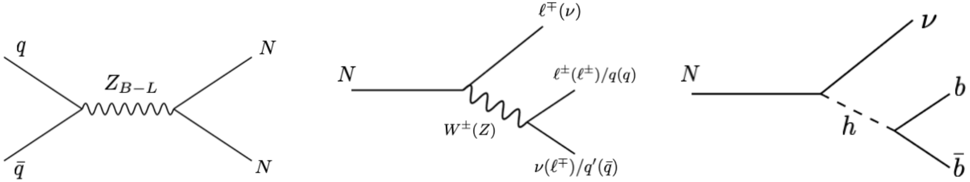
- Majorana masses of RHNs also come from here:

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

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

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

Production and Decay Modes of RHNs



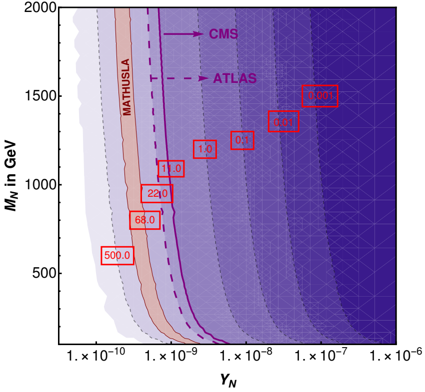
- The RHNs can be pair produced via Z_{B-L}.
- RHNs decay through $Z\nu$, $h\nu$ and $W^{\pm}\ell^{\mp}$, with the decay widths,

$$\Gamma_N^{Z\nu} \approxeq \Gamma_N^{h\nu} \approxeq \frac{1}{2}\Gamma_N^{W\ell} \approxeq \frac{Y_N^2 M_N}{64\pi}$$

- The ratio of $W^{\pm}$, Z and h mode is 2:1:1 for $M_N \gtrsim 400\,\mathrm{GeV}$.

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

Rest Mass Decay and Boosted Decay



- Rest mass decay length ($c\tau_0$) contours in the M_N versus Y_N plane.
- For M_N ~1 TeV, Y_N need to be 5×10^{-10} to reach in MATHUSLA.

- 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:

$$v' = v + \frac{\tau p}{m}.$$

- τ gives the distribution, boost effect comes from $\frac{p}{m}$.
- The transverse decay length: $L_\perp = \frac{\tau p_T}{m}$.
- The longitudinal decay length: $L_{||} = \frac{\tau p_z}{m}$.

Bandyopadhyay et al. [e-Print: 2205.12511]

Two Scenarios for Collider Study

Scenario-1

- Three degenerate right-handed neutrinos, where all of them has same mass M_N.

- Considering the Casas-Ibarra parametrization, we can reconstruct their Yukawa matrix given the active neutrino mass matrix compatible with the neutrino oscillation data.

Scenario-2

- One of the right-handed neutrinos decouples from the observed neutrino mass generations, with the possibility of much smaller Yukawa coupling.
- The other two right-handed neutrinos can explain light neutrino masses.

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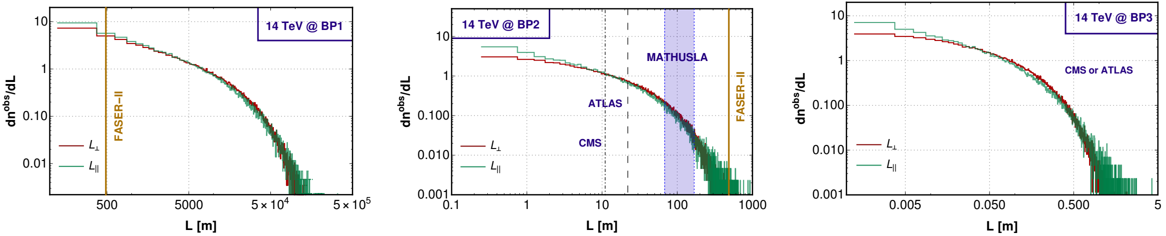
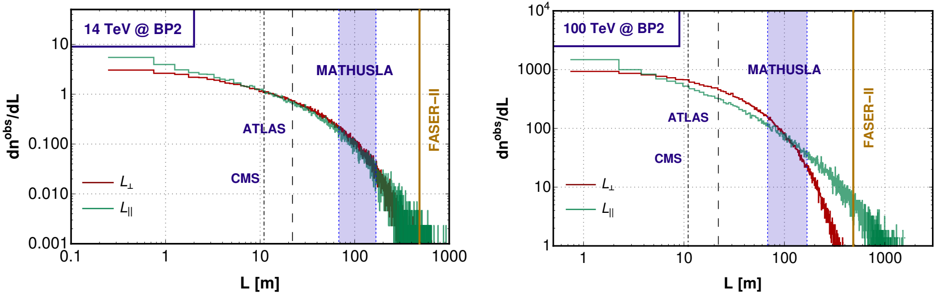
	BP1	BP2	BP3
M_N	10 GeV	60 GeV	100 GeV

Displaced Decays: Scenario-1



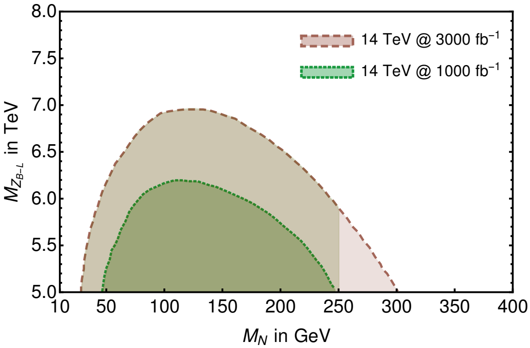
- For $M_N = 10\,\mathrm{GeV}$ and $Y_N \sim 8.1 \times 10^{-8}$, most of the events fall outside the reach of CMS, ATLAS or MATHUSLA detectors.
- For $M_N = 60\,\mathrm{GeV}$ and $Y_N \sim 1.98 \times 10^{-7}$, there can be adequate number of events in each of the three detectors.
- For $M_N = 100\,\mathrm{GeV}$ and $Y_N \sim 2.56 \times 10^{-7}$, the maximum displacement is around 4 meter, hence, all of the events are inside CMS or ATLAS.

Displaced Decays @LHC versus FCC-hh

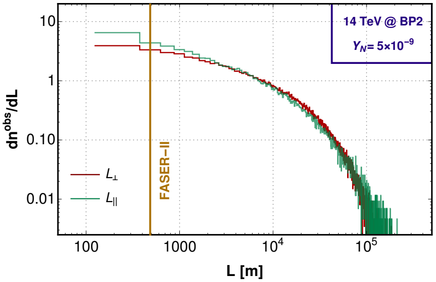


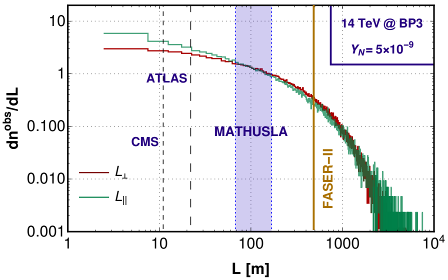
- Decay length increases with the increase in centre of mass energy due to the boost effect.
- Boost effect is more in the longitudinal direction compared to the transverse one.

Parameter Region: $M_{Z_{B-L}}$ versus M_N plane



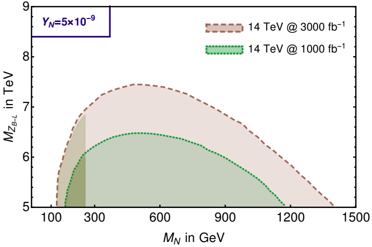
- The regions are obtained from the most dominant final states: $2\ell + 2j$ (dark shaded region), $2\ell + 4j$ (light shaded region).
- We only consider the events that are displaced and can be detected in either of the detectors CMS, ATLAS and MATHUSLA.
- Reach is $\sim$ 300 GeV in M_N plane and $\sim$ 6.8 TeV in $M_{Z_{B-L}}$ plane for 14 TeV collider with 3000 fb^{-1} luminosity.

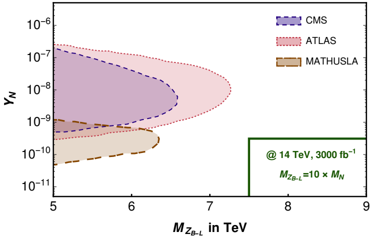


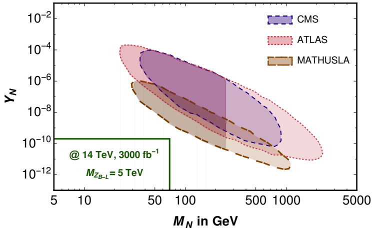


- Choice of Yukawa coupling is a free parameter, we consider $Y_N = 5 \times 10^{-9}$.
- For $M_N = 60\,\mathrm{GeV}$, the events are outside the reach of any of the three detectors.
- We can get the events inside MATHUSLA for $M_N = 100\,\mathrm{GeV}$.

Parameter Regions

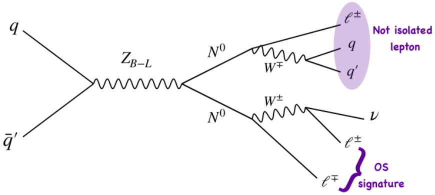


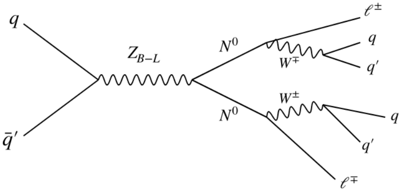




- Reach is ~ 1.35 TeV in M_N plane and ~ 7.5 TeV in $M_{Z_{B-L}}$ plane for 14 TeV collider with 3000 fb^{-1} luminosity $\implies$ Choice of the small Yukawa couplings increases the parameter space compared to scenario-1.
- MATHUSLA is sensitive for lower Yukawa couplings.
- The maximum Yukawa coupling of $\mathcal{O}(10^{-4})$ can be probed in this case for 14 TeV collider with $M_N \sim 25\,\mathrm{GeV}$ via displaced vertex.

Boost Effect in Di-lepton Final State and Majorana Nature





- The leptons coming from one of the RHNs are often co-linear to the hadronic jet due to the boost effect and can not be tagged as a separate lepton.
- We can get the di-lepton signature from the other RHN, which are opposite in sign.

- Majorana nature of RHN anticipates **same sign di-lepton : opposite sign di-lepton = 1:1**.
- The leptons coming from two different RHNs can only depict the Majorana nature.
- Since MATHUSLA will be situated in one of the hemispheres, it can only tag one RHN leg, thus will be failed to probe the Majorana nature of the RHNs.

Boosted Displaced Decay in Type-III Seesaw Scenario

Type-III Seesaw Model

- $SU(2)$ triplet fermions (N) with zero hypercharge can be added to the SM Lagrangian with the addition of the following terms

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

- N has one pair of charged fermion $(N^\pm)$ and one neutral component (N^0) for each generation,

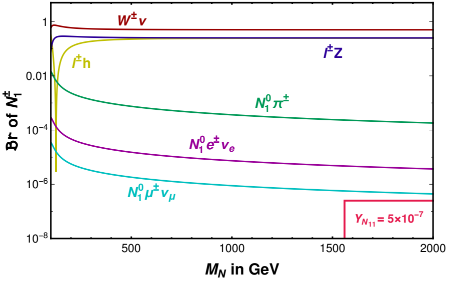
$$N = \begin{pmatrix} N^0 & \sqrt{2}N^+ \\ \sqrt{2}N^- & -N^0 \end{pmatrix}$$

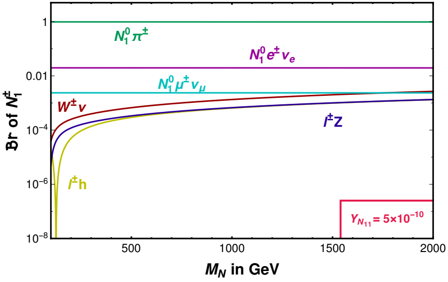
	N^+	N^-	N^0
T_3	+1	-1	0
Y	0	0	0

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

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

Branching Ratio depending on Yukawa Couplings



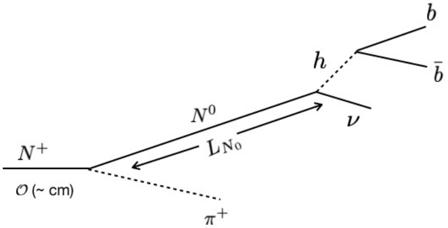


- Another decay mode possible considering the loop generated mass of $N^\pm$ and N^0,

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

- This branching ratio is very small ($< 1\%$) for $Y_N \sim 5\times10^{-7}$.
- For $M_N \sim 1\,\text{TeV}$ and $Y_N \sim 5\times10^{-10}$, $Br(N^\pm \to N^0\pi^\pm)$ is 97.5%.

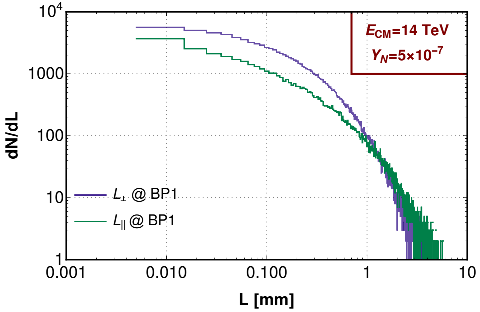
Successive Displaced Decays

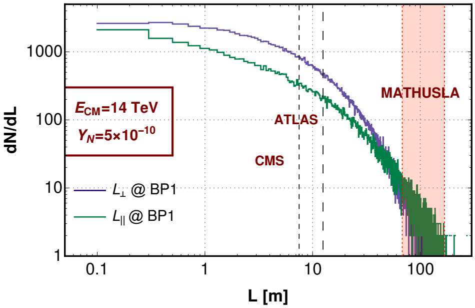


- Lower Yukawa couplings, i.e. $Y_N \lesssim 5 \times 10^{-8}$, the decay mode of $N^{\pm} \to \pi^{\pm} N^0$ dominates.
- First recoil: Decay length of $N^{\pm}$ is $\mathcal{O}(5\,)$cm.
- Second recoil: Decay length of N^0 depends on Y_N.

Bandyopadhyay et al. [Eur.Phys.J.C 82 (2022) 3, 230]

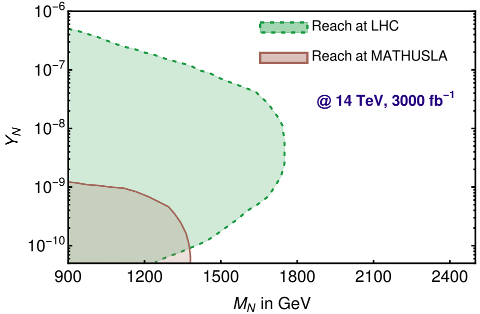
Displaced Decay @14 TeV collider





- $M_N = 1\,\text{TeV}$ (BP1).
- Lower the Yukawa couplings, longer the decay lengths.
- For larger Yukawa couplings, $Y_N \sim 5 \times 10^{-7}$, decay is within CMS/ ATLAS.
- Decay products can reach to MATHUSLA for $Y_N \sim 5 \times 10^{-10}$, even in 14 TeV collider.

Parameter Regions for LHC



- The regions are in Y_N versus M_N plane, that can be probed at LHC
- 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.

Conclusions

- Type-I and -III seesaw models could be interesting in searching for LLPs.
- The parameter space, that can be sensitive to CMS, ATLAS and MATHUSLA detectors can be obtained by
    - considering Casas-Ibarra parametrization to incorporate the light neutrino mass and mixing angle, or,
    - considering only one right-handed neutrino which decouples from the observed neutrino mass generation and thus can have arbitrarily small Y_N.
- Two successive displacements can be observed for triplet extension of SM in case of lower Yukawa couplings ($Y_N \lesssim 10^{-8}$).
- Boost effect can skew the ratio SSD:OSD =1:1, which can probe the Majorana nature. One can restore it via successfully tagging the RHN legs.
- MATHUSLA will be failed to probe the Majorana nature of RHN.


Thank you

Backup Slides

Choice of Yukawa Couplings for One Generation

From the neutrino oscillation data,

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

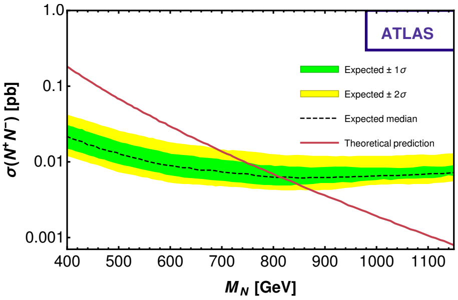
Suppose for one generation of RHN (N_1), the Yukawa coupling is very small, i.e. $Y_{N_1} = 5 \times 10^{-10}$. Hence, the SM neutrino mass,

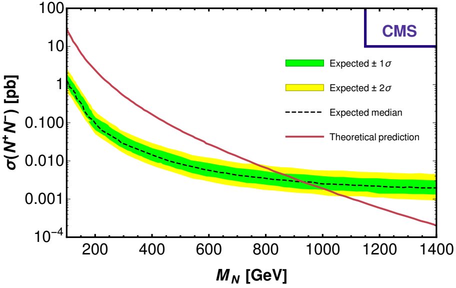
$$m_1 = \frac{Y_{N_1}^2 v^2}{2M_{N_1}} = 7.56 \times 10^{-9}\,\mathrm{eV}, \qquad \mathrm{if, M_{N_1}} = 1\,\mathrm{TeV}$$

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 $Y_{N_3} = 1.3 \times 10^{-6}$.

Constrains on Type-III fermion mass, when pair produced

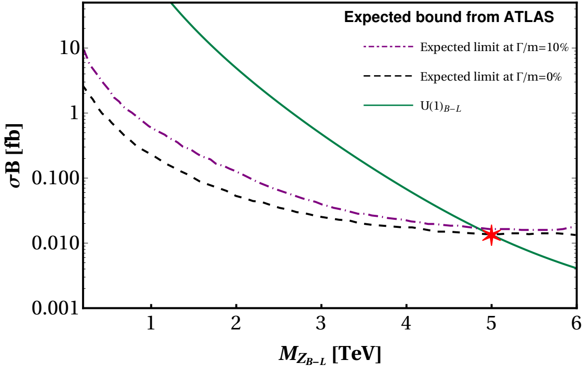




- CMS and ATLAS bounds on the Type-III fermion mass in the di-lepton final state, when only one generation is considered.
- The lower bound on the Type-III fermion mass is 740 GeV and 680 GeV, respectively from CMS and ATLAS at 2σ level.

CMS collaboration [JHEP 03 (2020) 051]

ATLAS collaboration [Eur. Phys. J. C 81 (2021) 218]



- Constraints from σB coming from di-leptonic final state at the LHC with the centre of mass energy of 13 TeV and luminosity of 139 fb^{-1}.
- The red star is the chosen benchmark point for the collider study.

ATLAS collaboration [Phys. Lett. B 796 (2019) 68]

Reconstruction of RHN mass