Deciphering the Mysteries of the Long-Lived Particles: Perspectives from LHC, FCC-hh and Muon Collider

CHANDRIMA SEN

PhD Student

Indian Institute of Technology Hyderabad

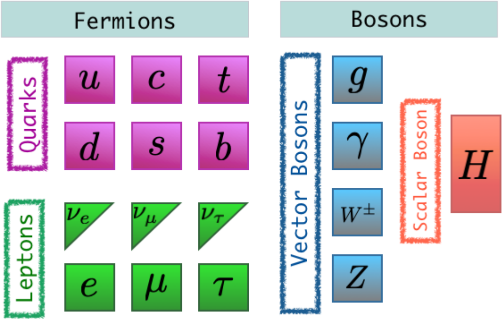
March 11, 2024

Collaborators: P. Bandyopadhyay (IITH), E. J. Chun (Korea Institute for Advance Study), M. Frank (Concordia University), S. Parashar (IITH), J.H. Song (Konkuk University)

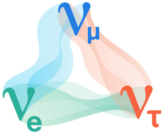
Overviews

- Introduction
- Displaced vertex signatures
- Boosted displaced decay in Type-I seesaw model
- Successive displaced decay in Type-III seesaw model
- Displaced multi-lepton signatures
- Disappearing charge tracks at muon collider
- Conclusions

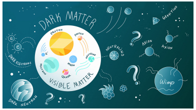
Some puzzles for physics beyond the Standard Model



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



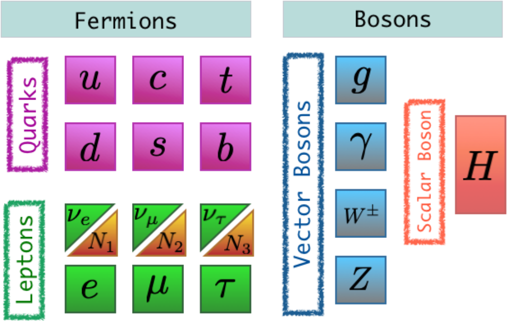
- Can not explain dark energy and dark matter, which contains 95% of our universe.



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

. . . and so on . . .

Extend with the Right-handed Components of Neutrinos



- Since neutrinos are electrically neutral, they can be Majorana in nature.
- 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:

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

- The discovery of the right-handed components of neutrinos is essential to justify the neutrino oscillation data.

- The discovery of the right-handed components of neutrinos is essential to justify the neutrino oscillation data.
- However, since the discovery of the Higgs boson in 2012, there have been no new physics discoveries at the LHC or any other collider experiments.

- The discovery of the right-handed components of neutrinos is essential to justify the neutrino oscillation data.

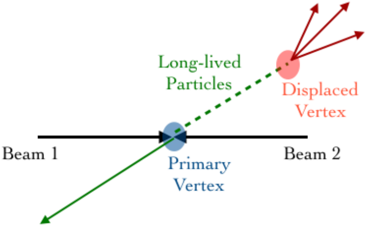
- However, since the discovery of the Higgs boson in 2012, there have been no new physics discoveries at the LHC or any other collider experiments.

- Is the scale of new physics so high that it is beyond our current reach?

- The discovery of the right-handed components of neutrinos is essential to justify the neutrino oscillation data.
- However, since the discovery of the Higgs boson in 2012, there have been no new physics discoveries at the LHC or any other collider experiments.
- Is the scale of new physics so high that it is beyond our current reach?
- Do we need a very high-energy collider, such as the FCC-hh, despite the funding problems?

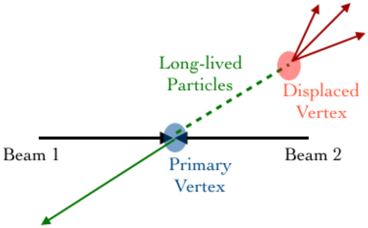
- The discovery of the right-handed components of neutrinos is essential to justify the neutrino oscillation data.
- However, since the discovery of the Higgs boson in 2012, there have been no new physics discoveries at the LHC or any other collider experiments.
- Is the scale of new physics so high that it is beyond our current reach?
- Do we need a very high-energy collider, such as the FCC-hh, despite the funding problems?
- What if we already have some signatures, but we are missing them, such as those from long-lived particles?

Can we get Long Lived Particle (LLP) Signature?

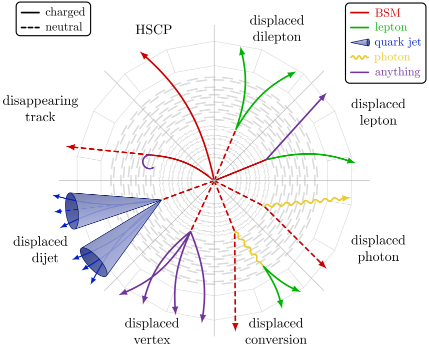


- Production vertex is different from the decay vertex.
- $\frac{1}{\tau} = \Gamma \propto g^2 |\mathcal{M}|^2 \Phi$
  - small couplings
  - heavy intermediary
  - limited phase space

Can we get Long Lived Particle (LLP) Signature?

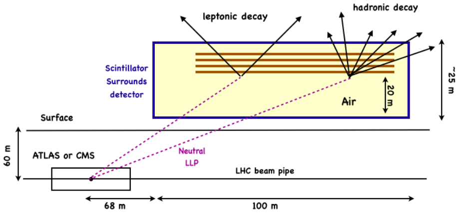


- Production vertex is different from the decay vertex.
- $\frac{1}{\tau} = \Gamma \propto g^2 |\mathcal{M}|^2 \Phi$
  - small couplings
  - heavy intermediary
  - limited phase space



picture courtesy: https://tikz.net/bsm-longlived

Some Proposed LLP Detectors



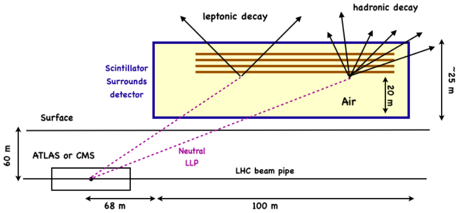
- MATHUSLA is proposed to be built 68 meters from the CMS interaction point in the longitudinal direction, 60 meters in the transverse direction.

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

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

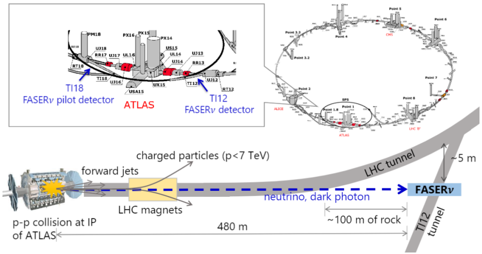
Alpigiani et al. [arXiv:2009.01693 [physics.ins-det]]

Some Proposed LLP Detectors



- MATHUSLA is proposed to be built 68 meters from the CMS 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]]



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

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

Example 1: Type-I Seesaw Model

Example 1: Type-I Seesaw Model

Why displaced signature?

- Small Yukawa couplings.

Example 1: Type-I Seesaw Model

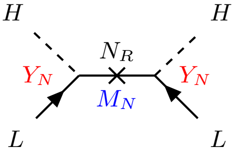
Why displaced signature?

- Small Yukawa couplings.

What kind of signatures?

- Displaced leptons and jets.

Type-I Seesaw Model



- This is the singlet fermionic extension to the Standard Model.
- The lagrangian corresponding to the singlet fermion is:

$$\mathcal{L}_{N_R} = \underbrace{i\bar{N_R}\not{\partial}N_R}_{\text{kinetic term}} - \underbrace{\frac{1}{2}\bar{N_R}M_N N_R^c}_{\text{Majorana mass term}} - \underbrace{Y_N\bar{L}\tilde{\phi}N_R}_{\text{Yukawa interactions}} \quad + h.c.$$

Considering Dirac mass as well as Majorana mass,

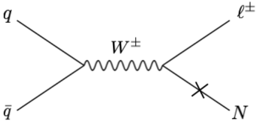
$$\mathcal{L}_{m_\nu} = -(Y_N v)\bar{N_R}\nu_L - \frac{1}{2}M_N\bar{N_R}^c N_R + h.c.$$

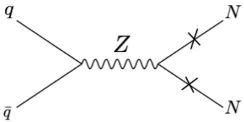
$$\mathcal{L}_{m_\nu} = \frac{1}{2}\begin{pmatrix}\bar{\nu_L^c} & \bar{N_R}\end{pmatrix}\underbrace{\begin{pmatrix}0 & (Y_N v)\\ (Y_N v) & M_N\end{pmatrix}}_{\text{Mass matrix}}\begin{pmatrix}\nu_L\\ N_R^c\end{pmatrix} + h.c.$$

After diagonalisation $D_\nu = \begin{pmatrix}m_1 & 0\\ 0 & m_2\end{pmatrix}$, where, $m_{1,2} = \left|\frac{1}{2}\left(M_N \mp \sqrt{M_N^2 + 4(Y_N v)^2}\right)\right|$

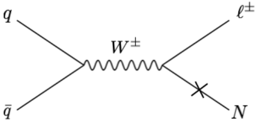
$$\implies m_1 = \frac{Y_N^2 v^2}{M_N} \text{ and, } m_2 = M_N$$

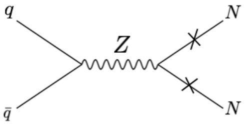
- Production cross-section of singlet right-handed neutrino at the collider is very small due to mixing.
- Pair production is even more difficult.





- Production cross-section of singlet right-handed neutrino at the collider is very small due to mixing.
- Pair production is even more difficult.





Solution!!

Extend the Standard Model gauge group with a $U(1)_{B-L}$ symmetry.
The right-handed neutrinos are charged under this gauge group.

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

Important Terms in Lagrangian

The covariant derivative form:

$$D_\mu = \partial_\mu + ig_2\, T^a\, W^a_\mu + ig_1 Y B_\mu + ig_{BL}\, Y_{B-L}\, B'_\mu$$

The scalar potential:

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

The Yukawa terms of the Lagrangian:

$$\mathcal{L}_Y = -Y^u_{ij}\, \overline{Q}_i\, \tilde{\Phi}(u_R)_j - Y^d_{ij}\, \overline{Q}_i\, \Phi(d_R)_j - Y^e_{ij}\, \overline{L}_i\, \Phi(e_R)_j - \underbrace{(Y_N)_{ij}\, \overline{L}_i\, \tilde{\Phi}(N_R)_j}_{\text{Dirac mass term}} - \underbrace{(\lambda_N)_{ij}\, \chi(\overline{N_R})^C_i\, (N_R)_j}_{\text{Majorana mass term}} .$$

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:

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

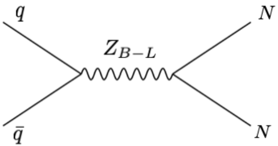
- Majorana masses of RHNs also come from here:

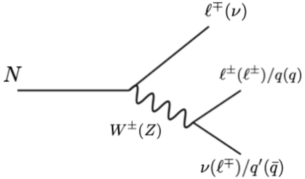
$$M_N = \lambda_N \frac{v_{BL}}{\sqrt{2}}$$

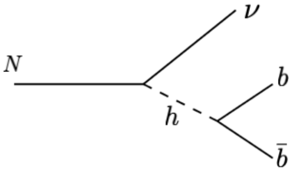
- Light SM neutrino masses are generated by Type-I seesaw mechanism when Φ gets vev:

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

Production and Decay Modes of RHNs







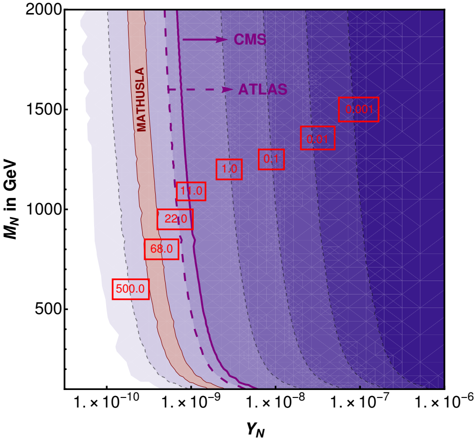
- The RHNs can be pair produced via Z_{B-L}.
- RHNs decay through $Z\nu$, $h\nu$ and $W^{\pm}\ell^{\mp}$, with the decay widths,

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

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

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

Rest Mass Decay Lengths



- Rest mass decay length ($c\tau_0$ in meter) 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.

Priyotosh Bandyopadhyay, Eung Jin Chun, CS
[JHEP 02 (2023) 103]

Boosted Displaced Decays

- Boost effect can enhance the decay length as,

$$\begin{aligned} L_\tau &= c\tau\beta\gamma \\ &= \frac{\tau p}{m} \end{aligned}$$

- 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: $L_{||} = \frac{\tau p_z}{m}$.

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-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.

	BP1	BP2	BP3
M_N	10 GeV	60 GeV	100 GeV
Y_N	8.1×10^{-8}	1.98×10^{-7}	2.56×10^{-7}
$c\tau_0$	193.00 m	3.96 m	0.02 m

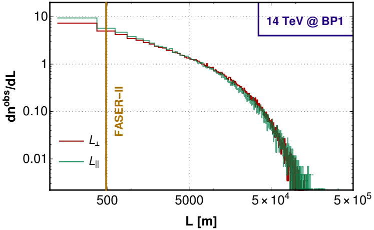
Scenario-2

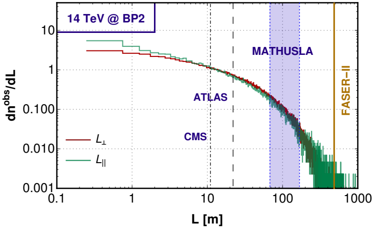
- According to neutrino oscillation data, mass square difference for normal ordering is,

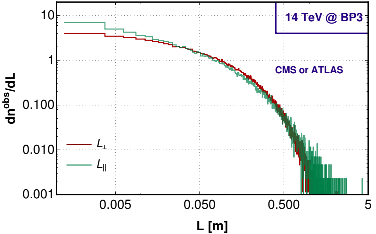
$$\Delta m_{21}^2 = m_2^2 - m_1^2 \approx 7.42 \times 10^{-5}\,\mathrm{eV}^2 \qquad \text{and} \qquad \Delta \mathrm{m}_{31}^2 = \mathrm{m}_3^2 - \mathrm{m}_1^2 \approx 2.51 \times 10^{-3}\,\mathrm{eV}^2.$$

- 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.
- Yukawa couplings can be treated as a free parameter.

Displaced Decays: Scenario-1

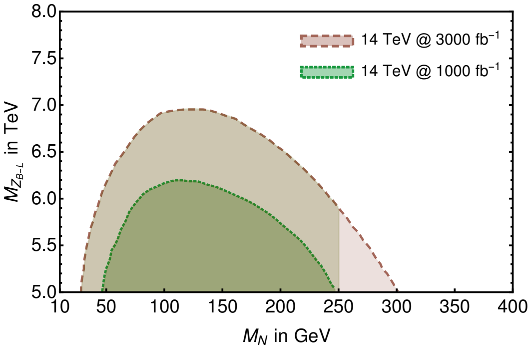






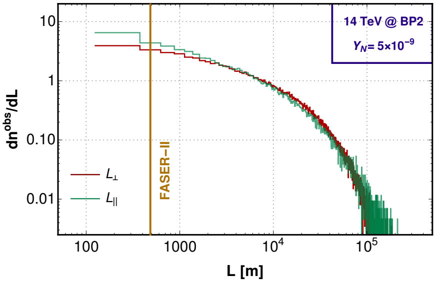
- For $M_N = 10\,\text{GeV}$ and $Y_N \sim 8.1 \times 10^{-8}$, most of the events fall outside the reach of CMS, ATLAS or MATHUSLA detectors.
- For $M_N = 60\,\text{GeV}$ and $Y_N \sim 1.98 \times 10^{-7}$, there can be adequate number of events in each of the three detectors.
- For $M_N = 100\,\text{GeV}$ 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.

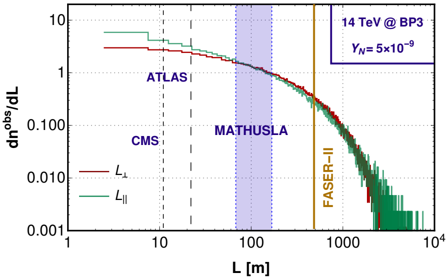
Parameter Region: $M_{Z_{B-L}}$ versus M_N plane



- 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.

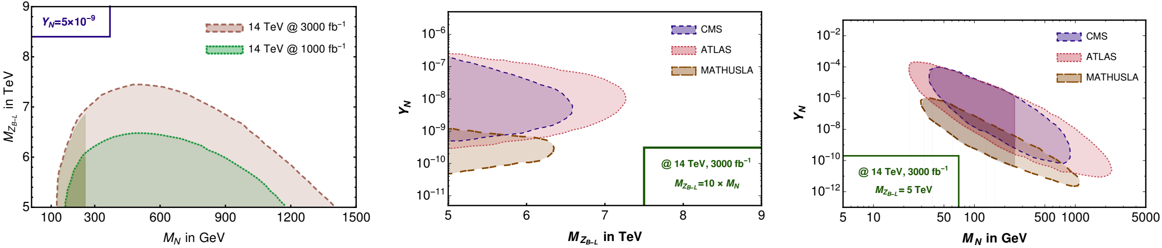
Displaced Decays: Scenario-2





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

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 $M_N \sim 25\,\text{GeV}$ via displaced vertex.

Example 2: Type-III Seesaw Model

Example 2: Type-III Seesaw Model

Why displaced signature?

- Small Yukawa couplings.
- Compressed mass spectrum between the charged and neutral component.

Example 2: Type-III Seesaw Model

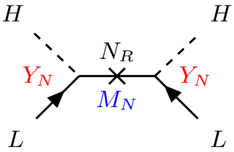
Why displaced signature?

- Small Yukawa couplings.
- Compressed mass spectrum between the charged and neutral component.

What kind of signatures?

- Disappearing charged tracks.
- Displaced leptons and jets.

Type-III Seesaw Model



- The $SU(2)$ triplet fermion (N_R) with zero hypercharge is added with the Standard Model.

- N_R has one pair of charged fermion $(N^{\pm})$ and one neutral component (N^0),

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

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

- The Lagrangian corresponding to the triplet fermion is:

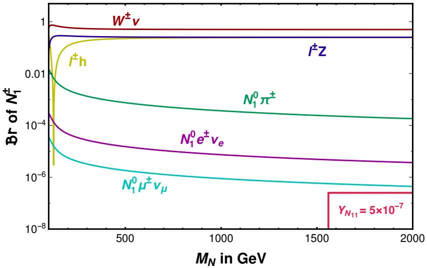
$$\mathcal{L}_{N_R} = \mathrm{Tr}(\overline{\mathrm{N_R}}\not{D}\mathrm{N_R}) \; - \; \frac{1}{4}\mathrm{M_N}\,\mathrm{Tr}\left[\overline{\mathrm{N_R}}\mathrm{N_R}\right] \; - \; \mathrm{Y_N}\left(\tilde{\phi}^{\dagger}\overline{\mathrm{N_R}}\mathrm{L} \; + \; \overline{\mathrm{L}}\mathrm{N_R}\tilde{\phi}\right).$$

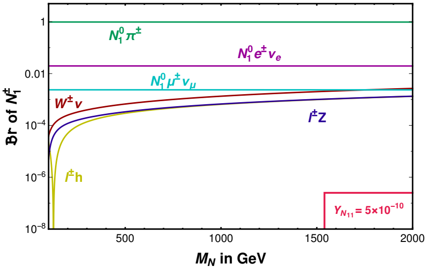
- The neutral component (N^0) behaves like a majorana fermion and generates the small neutrino mass.

Branching Ratio depending on Yukawa Couplings

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

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



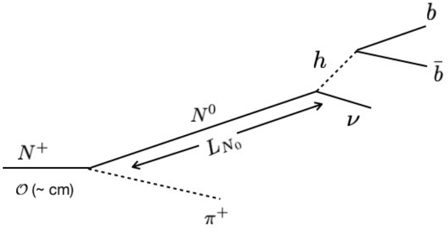


- Another decay mode possible considering the loop generated mass of $N^\pm$ and N^0,

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

- 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%.

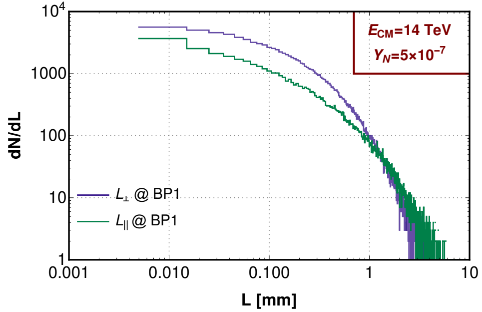
Successive Displaced Decays

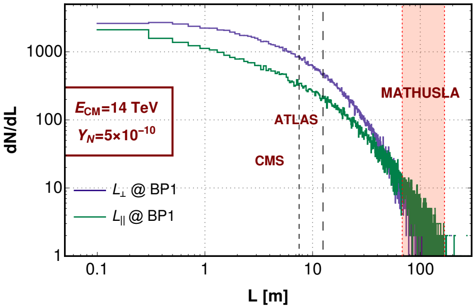


- Lower Yukawa couplings, i.e. $Y_N \lesssim 5 \times 10^{-8}$, the decay mode of $N^{\pm} \to \pi^{\pm} N^0$ dominates.
- First recoil: Decay length of $N^{\pm}$ is $\mathcal{O}(5\,)$cm.
- Second recoil: Decay length of N^0 depends on Y_N.

Priyotosh Bandyopadhyay, Saunak Dutta, Aleesha K T, CS
[Eur.Phys.J.C 82 (2022) 3, 230]

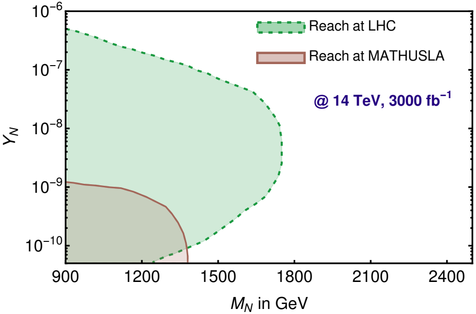
Displaced Decay @14 TeV collider





- $M_N = 1\,\text{TeV}$ (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.

Example 3: Inert Higgs Doublet Model (IDM) + $SU(2)$ Triplet, Z_2 odd Vector Like Lepton (VLL)

Example 3: Inert Higgs Doublet Model (IDM) + $SU(2)$ Triplet, Z_2 odd Vector Like Lepton (VLL)

Why displaced signature?

- Compressed mass spectrum between the Z_2 odd scalar and fermionic sector.
- Small Yukawa coupling between these two sectors.

Example 3: Inert Higgs Doublet Model (IDM) + $SU(2)$ Triplet, Z_2 odd Vector Like Lepton (VLL)

Why displaced signature?

- Compressed mass spectrum between the Z_2 odd scalar and fermionic sector.
- Small Yukawa coupling between these two sectors.

What kind of signatures?

- Displaced multi-lepton final states.

The Model

- We extend the SM with an $SU(2)_L$ scalar doublet Φ_2, and an vector-like $SU(2)$ triplet fermion N with $Y = 1$, both are odd under Z_2 symmetry.

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	$-$

- Scalar potential:

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

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

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

Physical masses of the particles

- Φ_2 does not get vev being an Z_2 odd particle.
- The physical scalar masses after electroweak symmetry breaking are:

$$\begin{aligned} M_h^2 &= 2\lambda_1 v^2 \\ M_{H^0/A^0}^2 &= m_{\Phi_2}^2 + \frac{1}{2}v^2\lambda_{L/S} \\ M_{H^\pm}^2 &= m_{\Phi_2}^2 + \frac{1}{2}v^2\lambda_3, \end{aligned}$$

where, $\lambda_{L/S} = \lambda_3 + \lambda_4 \pm 2\lambda_5$.

Physical masses of the particles

- Φ_2 does not get vev being an Z_2 odd particle.
- The physical scalar masses after electroweak symmetry breaking are:

$$\begin{aligned} M_h^2 &= 2\lambda_1 v^2 \\ M_{H^0/A^0}^2 &= m_{\Phi_2}^2 + \frac{1}{2}v^2\lambda_{L/S} \\ M_{H^\pm}^2 &= m_{\Phi_2}^2 + \frac{1}{2}v^2\lambda_3, \end{aligned}$$

where, $\lambda_{L/S} = \lambda_3 + \lambda_4 \pm 2\lambda_5$.

- Masses of each components of N are degenerate at the tree level, and they are equal to M_N.
- At one-loop level, mass splitting occurs as:

$$\begin{aligned} \Delta M_{N^\pm N^0} &= \frac{\alpha_2 M_N}{4\pi}\left[(s_W^2+1)\mathcal{G}\left(\frac{M_Z}{M_N}\right) - \mathcal{G}\left(\frac{M_W}{M_N}\right)\right], \\ \Delta M_{N^{\pm\pm} N^0} &= \frac{\alpha_2 M_N}{4\pi}\left[4\, s_W^2\mathcal{G}\left(\frac{M_Z}{M_N}\right)\right]. \end{aligned}$$

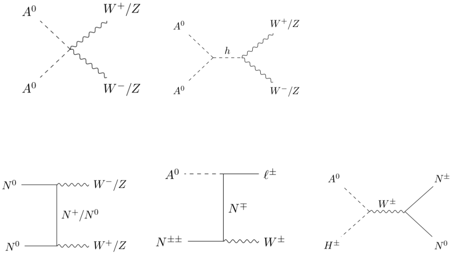
where, $\mathcal{G}(x) = \frac{x}{2}\left[2x^3 \ln x - 2x + (x^2+2)\sqrt{x^2-4}\,\ln(\frac{x^2-2-x\sqrt{x^2-4}}{2})\right]$.

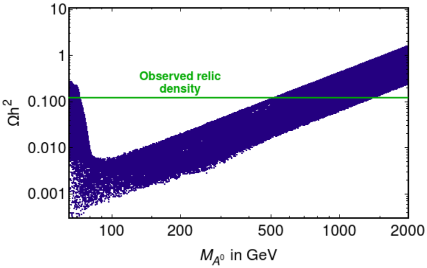
- For $M_N \geq 400\,\text{GeV}$, $\Delta M_{N^\pm N^0} \sim 500\,\text{MeV}$, $\quad \Delta M_{N^{\pm\pm} N^0} \sim 1.4\,\text{GeV}$.

Nucl.Phys.B 753 (2006) 178-194

Dark Matter Relic Density

- Annihilation modes of $\mathbb{Z}_2$ particles: $\Phi_2\,\Phi_2 \to \text{SM SM}$ and $N\,N \to \text{SM SM}$.
- Co-annihilation modes of $\mathbb{Z}_2$ particles: $N\,\Phi_2 \to \text{SM SM}$.
- Co-scattering of $\mathbb{Z}_2$ particles: $\Phi_2\,\Phi_2 \leftrightarrow N\,N$.
- Late decay effect: $N \to \Phi_2\ \text{SM}$.

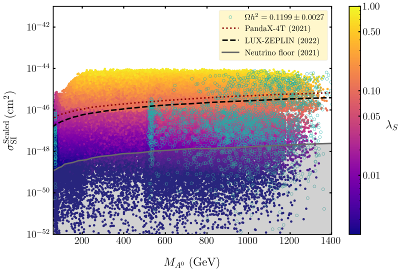




- The observed relic of $\Omega h^2 = 0.1199 \pm 0.0027$.
- A lower mass region satisfying relic around 70 GeV is due to the annihilation via s-channel Higgs boson exchange.
- Masses above 1.4 TeV are ruled out being overabundant.

Planck collaboration, Astron. Astrophys. 641 (2020) A6

Dark Matter Direct Detection



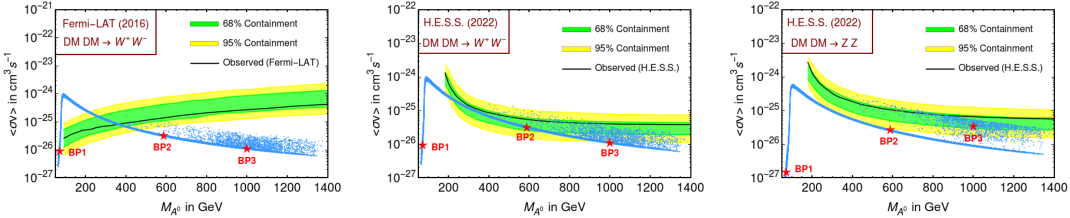
- Spin-independent scattering cross-section depends on the Higgs portal coupling as

$$\sigma_{\rm SI} \simeq \frac{\lambda_S^2 f_n^2}{4\pi M_h^4}\frac{M_n^4}{(M_n + M_{A^0})^2}.$$

- The most stringent upper bound on Higgs portal coupling is from LUX-ZEPLIN experiment, excludes $|\lambda_S| \geq 0.5$ for $M_{A^0} > 500$ GeV.
- $|\lambda_S| \leq 0.01$ is excluded by neutrino floor bound.

PandaX-4T collaboration, Phys. Rev. Lett. 127 (2021) 261802
LZ collaboration, Phys.Rev.Lett. 131 (2023) 4, 041002
APPEC committee report, Rept. Prog. Phys. 85 no. 5, (2022) 056201

Dark Matter Indirect Detection



- The dominant annihilation modes of A^0 are $W^\pm W^\mp$ and ZZ.
- Fermi-LAT and HESS detect high energy photons that can come from dark matter halos annihilating into $W^\pm W^\mp$ or ZZ.

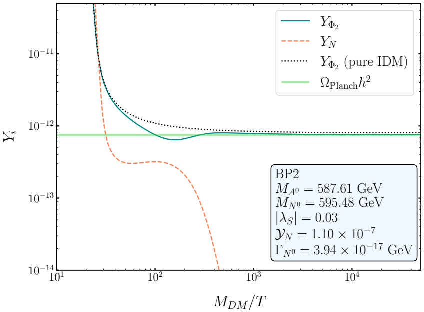
H.E.S.S. collaboration, Phys. Rev. Lett. 129 (2022) 111101
MAGIC, Fermi-LAT collaboration, JCAP 02 (2016) 039

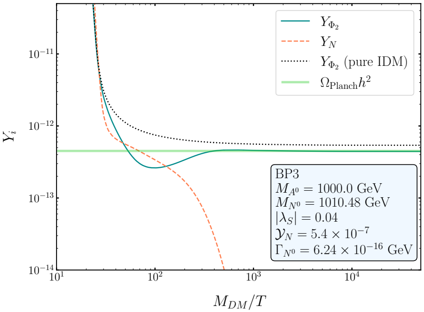
Benchmark Points

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.

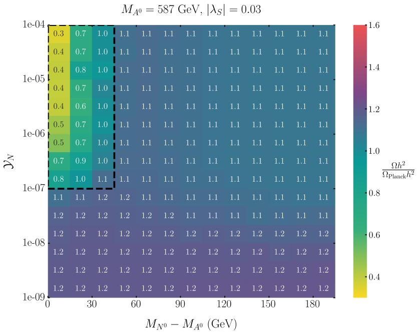
VLL and IDM Interplay

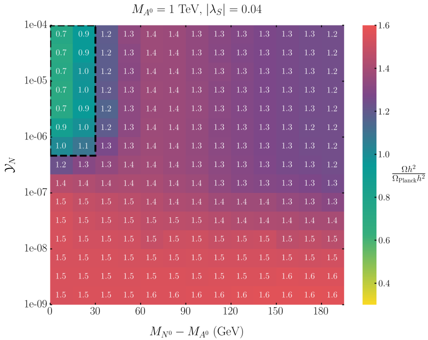




- The yield of A^0 suffers a dip for more co-annihilation due to compressed spectra.
- Number density of A^0 increases when N decays off completely.
- Pure Inert doublet scalar shows overabundant, but the interplay (co-annihilation and decay) of N sector can bring back the DM yield in correct ballpark.

Effect of mass gap and Yukawa couplings



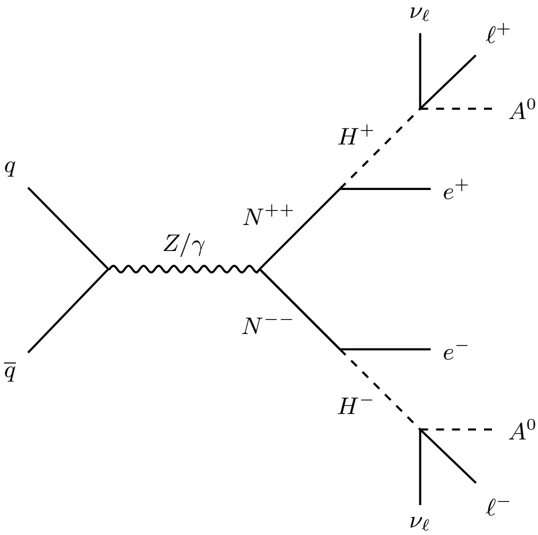


- Lower the Yukawa couplings: less co-annihilation + very late decay of the fermions.
- Higher the mass splitting: less phase space for co-annihilation.

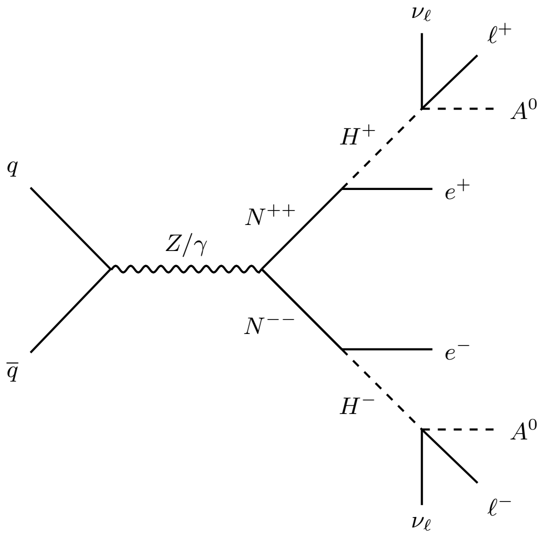
$\Longrightarrow$ enhancement of dark matter number density leads to overabundance.

- Higher the DM mass, lesser the annihilation $\Longrightarrow$ more compressed spectrum and higher Yukawa couplings for obtaining correct relic.

Collider Signature: Production and Decay of $N^{\pm\pm}$



Collider Signature: Production and Decay of $N^{\pm\pm}$



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

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

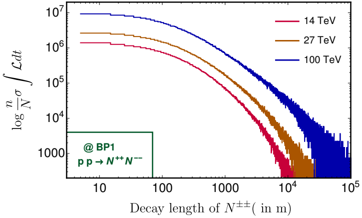
- Small $\mathcal{Y}_N$ and compressed mass spectrum lead to small decay width $\implies$ larger decay length.
- Displaced four-lepton final state.

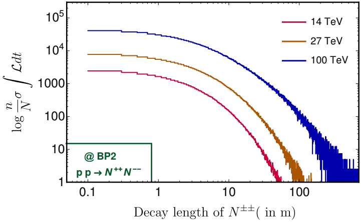
Displaced decay length distribution of $N^{\pm\pm}$

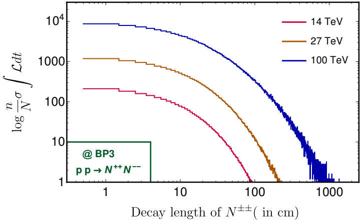
- The decay width and rest mass decay length off $N^{\pm\pm}$ for three benchmark points:

$N^{\pm\pm}$	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

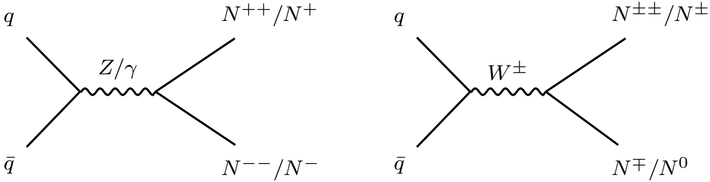
- The decay length distribution considering the boost effect:







Various Production Modes and Number of Events with 2-Displaced Leptons



- The electrons, produced displaced, can be identified by reconstructing the tracker hits at CMS/ATLAS ECal.

Final States: 2 displaced leptons + 0 jet with	BPs	Centre of mass energies at				
		14 TeV		27 TeV		100 TeV
		CMS	ATLAS	CMS	ATLAS	FCC-hh detector
$p_{T_{\ell_1}} \geq 20\,\text{GeV}$ & $p_{T_{\ell_2}} \geq 10\,\text{GeV}$	BP1	1108.2	2112.5	2107.0	3831.5	40162.2
$p_{T_{\ell_{1,2}}} \geq 10\,\text{GeV}$	BP2	647.3	1068.5	2300.2	3927.4	28388.6
	BP3	329.7	329.7	2113.5	2113.5	11401.5

Example 4: Inert Triplet Model (ITM) at Muon Collider

Example 4: Inert Triplet Model (ITM) at Muon Collider

What kind of signatures?

- Disappearing charged track(s) + forward muon(s).

Example 4: Inert Triplet Model (ITM) at Muon Collider

What kind of signatures?

- Disappearing charged track(s) + forward muon(s).

Cause of this unique signature

- Compressed mass spectrum between the charged and neutral component.

The Model

- Extend the Standard Model scalar with an $SU(2)$ triplet having zero hypercharge.

$$\mathcal{T} = \frac{1}{2}\begin{pmatrix} T^0 & \sqrt{2}T^+ \\ \sqrt{2}T^- & -T^0 \end{pmatrix}.$$

- The scalar potential:

$$V(\Phi,\mathcal{T}) \;= \mu_h^2\,\Phi^\dagger\Phi + \mu_T^2\,Tr\left(\mathcal{T}^\dagger\mathcal{T}\right) + \lambda_h\left|\Phi^\dagger\Phi\right|^2 + \lambda_t\left(Tr\left|\mathcal{T}^\dagger\mathcal{T}\right|\right)^2 + \lambda_{ht}\left(\Phi^\dagger\Phi\right)Tr\left(\mathcal{T}^\dagger\mathcal{T}\right).$$

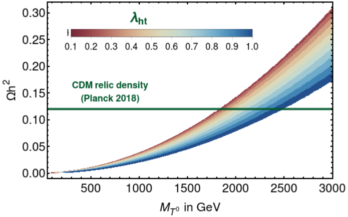
- $\mathcal{T}$ is odd under a discrete symmetry, all the SM fields are even $\implies$ T^0 does not get a vev.
- After EWSB, scalar mass spectrum: $M_h^2 = 2\lambda_h v^2$, $\quad M_{T^0}^2 = M_{T^\pm}^2 = \frac{1}{2}\lambda_{ht}v^2 + \mu_T^2$.
- At tree-level, T^0 and $T^\pm$ are degenerate; at one-loop level, $M_{T^\pm} - M_{T^0} \sim 166\,\mathrm{MeV}$.
- T^0 is the lightest inert particle $\implies$ dark matter candidate!
- Small mass splitting leads to long lifetimes $\implies$ displaced decays. Rest mass decay length $\sim$ 5.7 cm.
- Decay branching ratios:

$$\begin{aligned} \Gamma(T^\pm \to T^0\pi^\pm) &\quad Br \sim 97.7\%, \\ \Gamma(T^\pm \to T^0 e^\pm \nu_e) &\quad Br \sim 2\%, \\ \Gamma(T^\pm \to T^0 \mu^\pm \nu_\mu) &\quad Br \sim 0.25\%, \end{aligned}$$

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

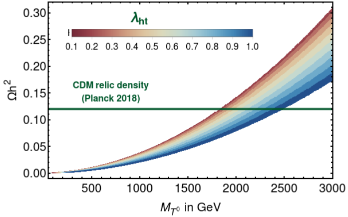
Constrains from Dark Matter (DM) Experiments

- DM Relic Density

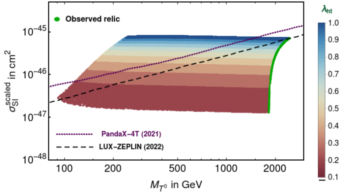


Constrains from Dark Matter (DM) Experiments

- DM Relic Density

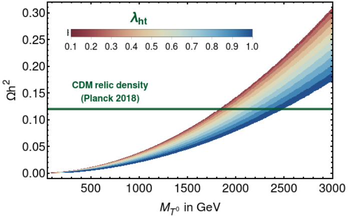


- DM Direct Detection

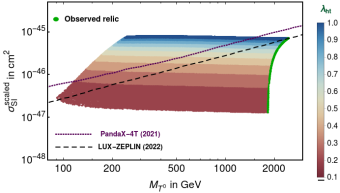


Constrains from Dark Matter (DM) Experiments

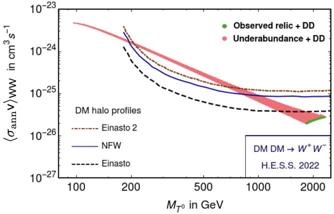
- DM Relic Density



- DM Direct Detection

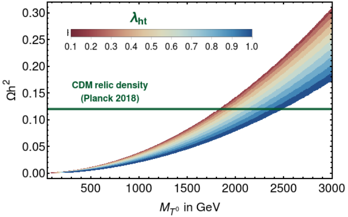


- DM Indirect Detection

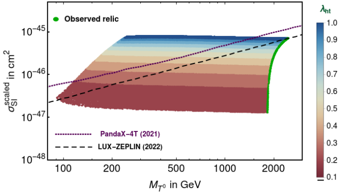


Constrains from Dark Matter (DM) Experiments

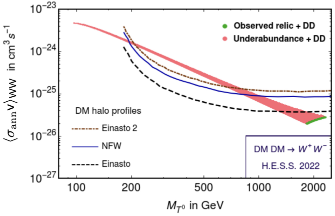
- DM Relic Density



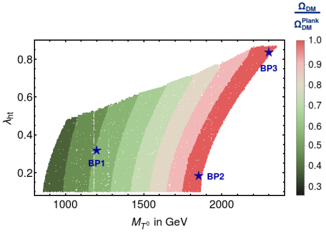
- DM Direct Detection



- DM Indirect Detection



- Benchmarks for collider study



Why a muon collider?

- Production rates of TeV scale particles are very small at the 14 TeV LHC, as well as a 27 TeV upgrade.
- Muons are fundamental particles: all of the centre-of-mass energy is available for collision.
- Less background from QCD processes: hadronically clean environment: higher precision.
- Aimed to be a high-precision, high-luminosity discovery machine for BSM particles.
- Centre of mass energies and luminosities goal:
    - $3\,\text{TeV} \rightarrow 1\ \text{ab}^{-1}$
    - $6\,\text{TeV} \rightarrow 4\ \text{ab}^{-1}$
    - $10\,\text{TeV} \rightarrow 10\ \text{ab}^{-1}$

Why a muon collider?

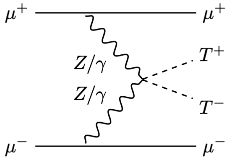
- Production rates of TeV scale particles are very small at the 14 TeV LHC, as well as a 27 TeV upgrade.
- Muons are fundamental particles: all of the centre-of-mass energy is available for collision.
- Less background from QCD processes: hadronically clean environment: higher precision.
- Aimed to be a high-precision, high-luminosity discovery machine for BSM particles.
- Centre of mass energies and luminosities goal:
  - $3\,\text{TeV} \to 1\ \text{ab}^{-1}$
  - $6\,\text{TeV} \to 4\ \text{ab}^{-1}$
  - $10\,\text{TeV} \to 10\ \text{ab}^{-1}$

Muon collider detector

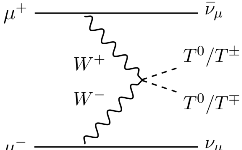
- Less SM QCD backgrounds, but muon collider suffers from Beam Induced Backgrounds (BIB): soft photons, leptons and charged hadrons coming from beam muons decaying in flight.
- BIB is mostly in the forward directions with $|\eta| \geq 2.5$: Tungsten nozzles to be installed so they can be absorbed.Tracking system and calorimeter coverage upto $|\eta| \leq 2.5$ only.
- VBF spectator muons are high-energy and highly forward: can pass through nozzles, can be detected at dedicated forward muon facility.

Simulated Detector Performance at the Muon Collider, International Muon Collider Collaboration, arXiv: 2203.07964 [hep-ex]

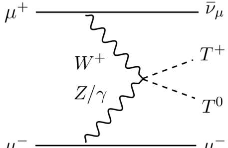
Production of ITM scalars from VBF at a muon collider



(a)

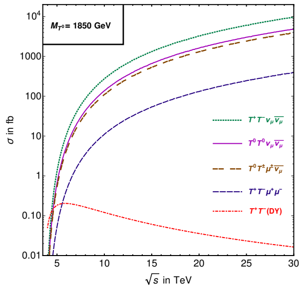


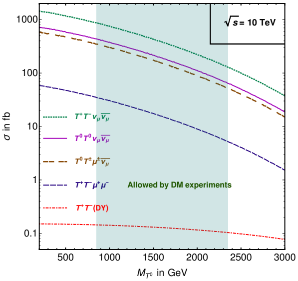
(b)



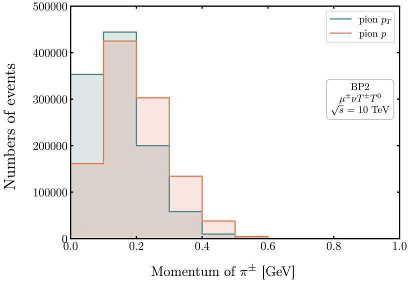
(c)

- At higher energies, muon colliders are essentially vector boson fusion (VBF) machines, as cross-sections grow $\propto \log^n(s/M_V^2)$.





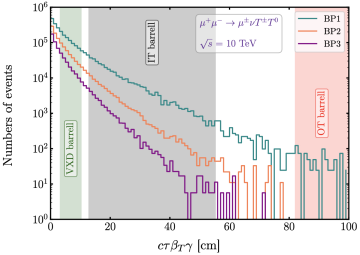
Final States for Model Signatures



- Displaced decay of $T^{\pm} \to \pi^{\pm} T^{0}$ gives very soft pions: difficult to detect due to BIB.
- Invisible decay product → Disappearing charged tracks (DCTs) for $T^{\pm}$
- High-energy VBF muons with high pseudorapidity: Forward muons : can be tagged
- VBF spectator neutrinos are not detectable.

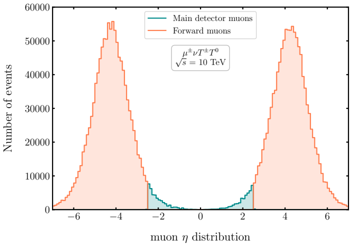
- FS1: 1 DCT + 1 Forward muon $\leftarrow T^{+}T^{-}\mu^{+}\mu^{-}, \quad T^{\pm}T^{0}\mu^{\pm}\mu^{0}$
- FS2: 2 DCT + 2 Forward muon $\leftarrow T^{+}T^{-}\mu^{+}\mu^{-}$
- FS3: 1 DCT + 2 Forward muon $\leftarrow T^{+}T^{-}\mu^{+}\mu^{-}$
- FS4: 2 DCT + 1 Forward muon $\leftarrow T^{+}T^{-}\mu^{+}\mu^{-}$

Signal Kinematics



Signal criteria for displaced charged tracks:

- $0.7\,\text{rad} < \theta < 2.44\,\text{rad}$ (barrell).
- 5.1 cm $<$ decay radius < 148.1 cm.

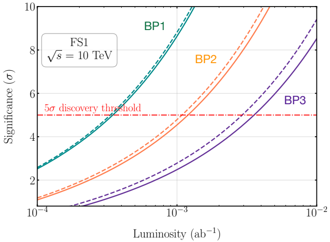


Signal criteria for Forward muons (μ_F):

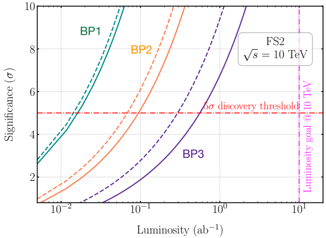
- $2.5 \leq |\eta| \leq 7.0$.
- $p_{\mu_F} \geq 300\,\text{GeV}$.

We simulate the events with Delphes muon collider card.

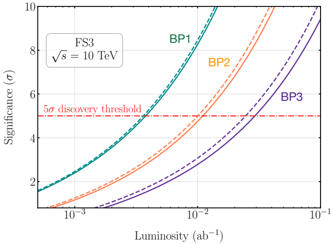
Discovery Projections at 10 TeV Muon Collider



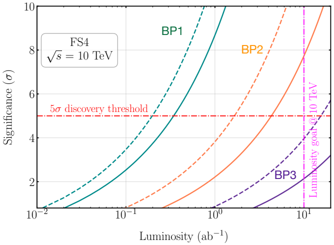
- 1 DCT + 1 Forward muon



- 2 DCT + 2 Forward muon



- 1 DCT + 2 Forward muon



- 2 DCT + 1 Forward muon

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 via LLP searches are discussed.
- Two successive displacements can be observed for triplet extension of SM in case of lower Yukawa couplings ($Y_N \lesssim 10^{-8}$).

- We study the interplay between the Z_2 odd Higgs doublet scalar and the $SU(2)$ triplet vector like lepton, where a compressed spectrum in the dark sector, and small Yukawa couplings lead to interplay between the VLL and the IDM in obtaining the correct relic.
- The same factors lead to displaced multi-lepton signatures at the colliders.

- The Inert Triplet Model is a simple scalar extension providing a DM candidate, where the compressed mass spectrum leads to disappearing charged track signatures at the colliders.
- The triplet scalars can be efficiently produced from VBF at a muon collider.
- Final states of 1-2 DCTs + 1-2 Forward Muons can effectively probe the model over a TeV-scale mass range allowed by DM experiments.

References

1. Displaced Higgs production in Type-III seesaw at the LHC/FCC, MATHUSLA and muon collider, Chandrima Sen, Priyotosh Bandyopadhyay, Saunak Dutta, Aleesha KT, Eur.Phys.J.C 82 (2022) 3, 230.
2. Boosted displaced decay of right-handed neutrinos at CMS, ATLAS and MATHUSLA, Priyotosh Bandyopadhyay, Eung Jin Chun, Chandrima Sen, JHEP 02 (2023) 103
3. Interplay of inert doublet and vector-like lepton triplet with displaced vertices at the LHC/FCC and MATHUSLA, Priyotosh Bandyopadhyay, Mariana Frank, Snehashis Parashar, Chandrima Sen, arXiv: 2310.08883 [hep-ph], accepted in JHEP.
4. Probing Inert Triplet Model at a multi-TeV muon collider via vector boson fusion with forward muon tagging, Priyotosh Bandyopadhyay, Snehashis Parashar, Chandrima Sen, J.H. Song, arXiv: 2401.02697 [hep-ph], in communication with JHEP.


Thank you

Backup Slides

Boltzmann equations

$$\begin{aligned}\frac{dY_{A^0}}{dx} = &- \frac{1}{x^2}\frac{s(M_{A^0})}{H(M_{A^0})}\Bigg[\langle\sigma v\rangle_{1100}\left(Y_{A^0}^2-(Y_{A^0}^{eq})^2\right)+\langle\sigma v\rangle_{1122}\left(Y_{A^0}^2-Y_{N^0}^2\frac{(Y_{A^0}^{eq})^2}{(Y_{N^0}^{eq})^2}\right)\\ &+\langle\sigma v\rangle_{1200}\left(Y_{A^0}Y_{N^0}-Y_{A^0}^{eq}Y_{N^0}^{eq}\right)\Bigg]+\frac{x\Gamma_{N^0\to A^0\nu}}{H(M_{A^0})}\left(Y_{N^0}-Y_{A^0}\frac{Y_{N^0}^{eq}}{Y_{A^0}^{eq}}\right),\end{aligned} \tag{1}$$

$$\begin{aligned}\frac{dY_{N^0}}{dx} = &- \frac{1}{x^2}\frac{s(M_{A^0})}{H(M_{A^0})}\Bigg[\langle\sigma v\rangle_{2200}\left(Y_{N^0}^2-(Y_{N^0}^{eq})^2\right)-\langle\sigma v\rangle_{1122}\left(Y_{A^0}^2-Y_{N^0}^2\frac{(Y_{A^0}^{eq})^2}{(Y_{N^0}^{eq})^2}\right)\\ &+\langle\sigma v\rangle_{1200}\left(Y_{A^0}Y_{N^0}-Y_{A^0}^{eq}Y_{N^0}^{eq}\right)\Bigg]-\frac{x\Gamma_{N^0\to A^0\nu}}{H(M_{A^0})}\left(Y_{N^0}-Y_{A^0}\frac{Y_{N^0}^{eq}}{Y_{A^0}^{eq}}\right).\end{aligned} \tag{2}$$

We denote the scalar dark sector with $1 \equiv [A^0, H^0, H^\pm]$, the fermionic dark sector with $2 \equiv [N^0, N^\pm, N^{\pm\pm}]$ and with $0 \equiv$ all SM particles.