Interplay between Vector like Lepton and Inert Higgs Doublet in the context of Dark Matter and Collider signature

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based on

arXiv: 2310.08883
P. Bandyopadhyay, M. Frank, S. Parashar, CS

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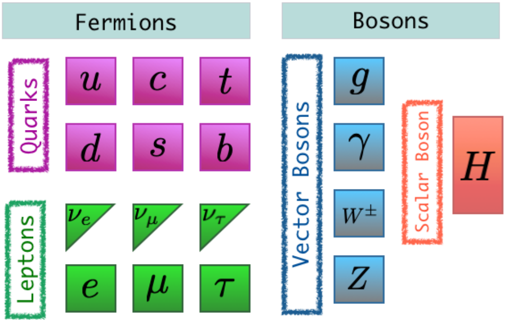
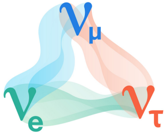
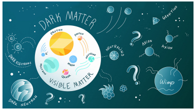
Some puzzles for physics beyond the Standard Model



- 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 . . .

Vector Like Lepton + Inert Higgs Doublet Model

We extend the SM with an $SU(2)_L$ scalar doublet Φ_2 and an vector-like $SU(2)$ triplet fermion N with $Y = 1$.

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:

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

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

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

Physical masses of the particles

The physical scalar masses after electroweak symmetry breaking are:

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

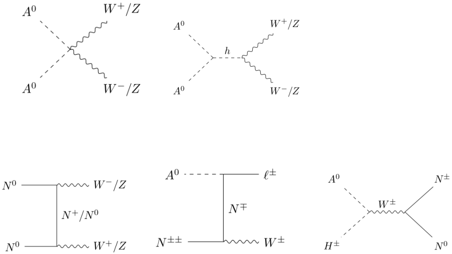
where, $\lambda_{L/S} = \lambda_3 + \lambda_4 \pm 2\lambda_5$.

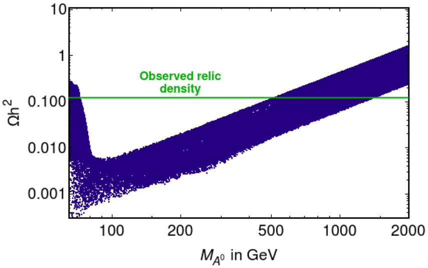
- Masses of each components of N are degenerate at the tree level, and they are equal to M_N.
- At one-loop level, mass splitting occurs as: $\Delta M_{N^\pm N^0} \sim 500\,\mathrm{MeV}, \quad \Delta M_{N^{\pm\pm} N^0} \sim 1.4\,\mathrm{GeV}$

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

Dark Matter Relic Density

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

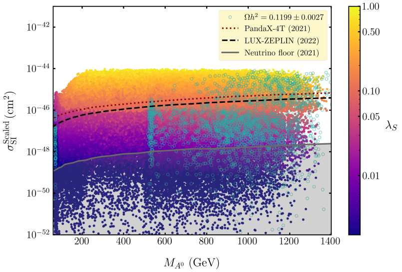




- The observed relic of $\Omega h^2 = 0.1199 \pm 0.0027$.
- A lower mass region satisfying relic around 70 GeV is due to the annihilation via s-channel Higgs boson exchange.
- Masses above 1.4 TeV are ruled out being overabundant.

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

Dark Matter Direct Detection



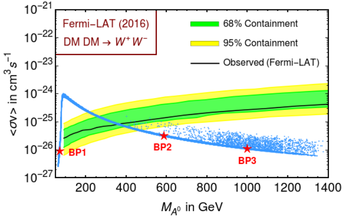
- Spin-independent scattering cross-section depends on the Higgs portal coupling as

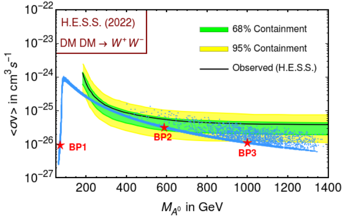
$$\sigma_{\rm SI} \simeq \frac{\lambda_S^2 f_n^2}{4\pi M_h^4} \frac{M_n^4}{(M_n + M_{A^0})^2}.$$

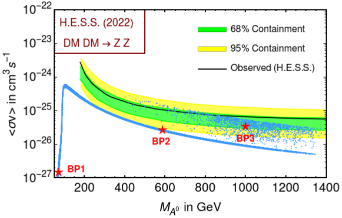
- The most stringent upper bound on Higgs portal coupling is from LUX-ZEPLIN experiment, excludes $|\lambda_S| \geq 0.5$ for $M_{A^0} > 500$ GeV.
- $|\lambda_S| \leq 0.01$ is excluded by neutrino floor bound.

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.

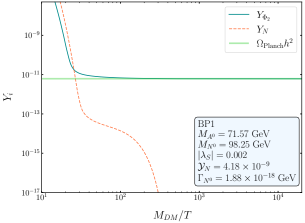
H.E.S.S. collaboration, Phys. Rev. Lett. 129 (2022) 111101
MAGIC, Fermi-LAT collaboration, JCAP 02 (2016) 039

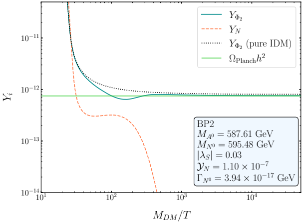
Benchmark Points

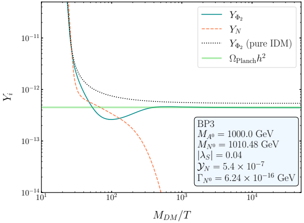
BP	M_{A^0} (GeV)	M_{H^0} (GeV)	$M_{H^\pm}$ (GeV)	M_{N^0} (GeV)	M_{N^-} (GeV)	$M_{N^{--}}$ (GeV)	$\mathcal{Y}_N$
BP1	71.57	117.16	84.76	98.25	98.61	99.28	4.2×10^{-9}
BP2	587.6	589.4	588.2	595.5	595.9	596.8	1.1×10^{-7}
BP3	1000.0	1010.5	1001.0	1010.5	1011.0	1011.9	5.4×10^{-7}

- 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

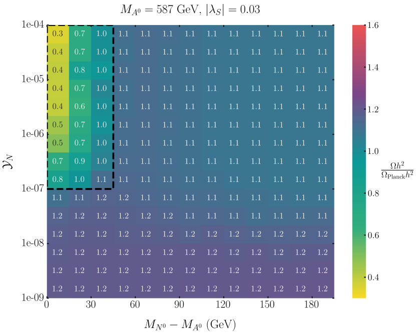


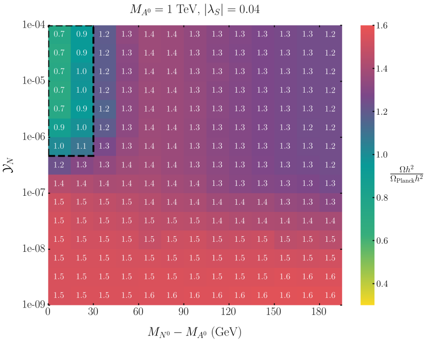




- For BP1, decay effects of N is almost negligible and A^0 decouples with higher yield compared to N, and A^0 provides the correct relic density.
- As mass increases from BP1 to BP3, N decouples with higher yield.
- For BP2 and BP3, yield of A^0 suffers a dip for more co-annihilation due to compressed spectra.
- Number density of A^0 increases when N decays off completely.
- Pure Inert doublet scalar shows overabundant for BP2 and BP3, 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



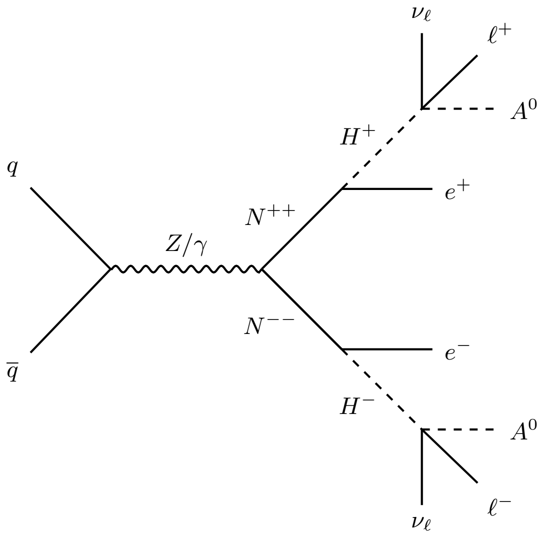


- Lower the Yukawa couplings: less co-annihilation + very late decay of the fermions.
- Higher the mass splitting: less phase space for co-annihilation.

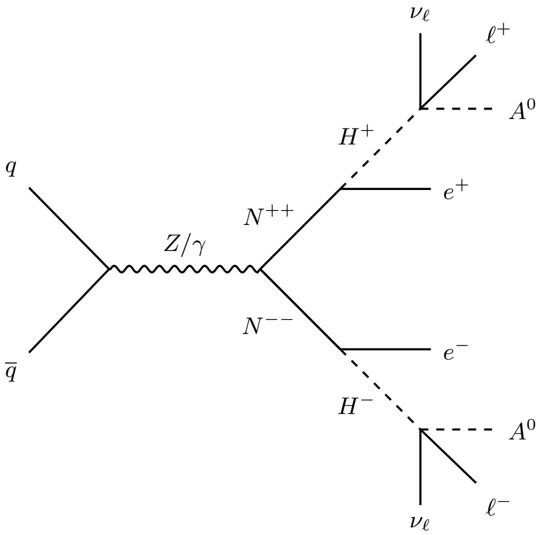
$\Longrightarrow$ enhancement of dark matter number density leads to overabundance.

- 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.

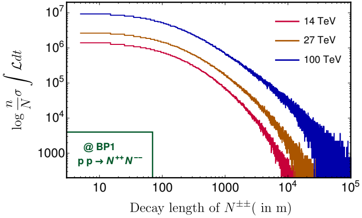
Displaced decay length distribution of $N^{\pm\pm}$

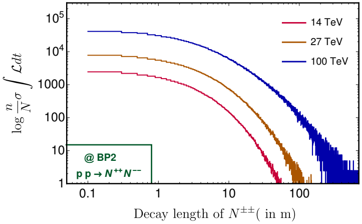
	BP1 $\mathcal{Y}_N = 4.2 \times 10^{-9}$		BP2 $\mathcal{Y}_N = 1.1 \times 10^{-7}$		BP3 $\mathcal{Y}_N = 5.4 \times 10^{-7}$	
$N^{\pm\pm}$	$\Gamma_{\rm tot}$ (GeV)	$c\tau_0$ (m)	$\Gamma_{\rm tot}$ (GeV)	$c\tau_0$ (m)	$\Gamma_{\rm tot}$ (GeV)	$c\tau_0$ (m)
	1.27×10^{-18}	155.42	5.92×10^{-17}	3.33	1.34×10^{-15}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

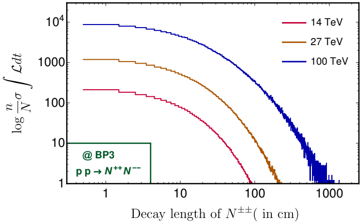
- Boost effect can enhance the decay length as,

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

- τ gives the distribution, boost effect comes from $\frac{p}{m}$.







Events at CMS, ATLAS

- The electrons, produced displaced, can be identified by reconstructing the tracker hits at CMS/ATLAS ECal.
- The events are shown for BP1 for with the integrated luminosity of 300 fb^{-1}.
- Corresponding decay channel is: $p\,p \to N^{++}N^{--} \to (H^{+}e^{+})\,(H^{-}e^{-}) \to (A^{0}\boldsymbol{\ell}^{+}\boldsymbol{e}^{+})\,(A^{0}\boldsymbol{\ell}^{-}\boldsymbol{e}^{-})$

4 displaced leptons at E_{CM} =				
14 TeV		27 TeV		100 TeV
CMS	ATLAS	CMS	ATLAS	FCC-hh detector
14.8	37.0	16.8	33.6	1096.2

Events at MATHUSLA

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

$$\begin{aligned} \text{Co-ordinates: } & 60 < x < 85\,\mathrm{m} \\ & -50 < y < 50\,\mathrm{m} \\ & 68 < z < 168\,\mathrm{m} \end{aligned}$$

- Since MATHUSLA is proposed to be situated above CMS and at one of the hemispheres, one can not observe pair production processes there.

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

	2 displaced leptons at $E_{\mathrm{CM}} =$		
Production mode	14 TeV	27 TeV	100 TeV
$p\,p \to N^{++}N^{--}$	249.1	507.7	1690.6

Conclusions

- We study the interplay between the $\mathbb{Z}_2$ odd Higgs doublet scalar and the $SU(2)$ triplet vector like lepton.
- The parameter space is highly constrained from Plank data, direct and indirect detection experiments.
- 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 vertex signatures at the colliders, which can be studied in CMS, ATLAS, and MATHUSLA.


Thank you

Backup Slides

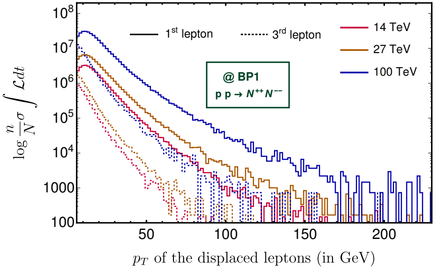
Boltzmann equations

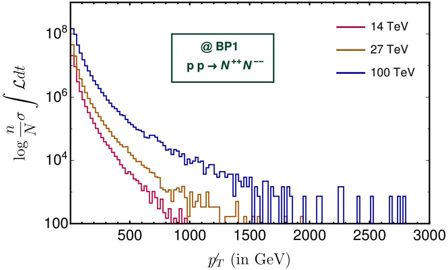
$$\begin{aligned}\frac{dY_{A^0}}{dx} = &-\frac{1}{x^2}\frac{s(M_{A^0})}{H(M_{A^0})}\Bigg[\langle\sigma v\rangle_{1100}\left(Y_{A^0}^2-(Y_{A^0}^{eq})^2\right)+\langle\sigma v\rangle_{1122}\left(Y_{A^0}^2-Y_{N^0}^2\frac{(Y_{A^0}^{eq})^2}{(Y_{N^0}^{eq})^2}\right)\\ &+\langle\sigma v\rangle_{1200}\left(Y_{A^0}Y_{N^0}-Y_{A^0}^{eq}Y_{N^0}^{eq}\right)\Bigg]+\frac{x\Gam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

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

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.

p_T and $\not{p}_T$ distribution of leptons





- Leptons are very soft due to compressed mass spectrum.