

Right Handed Neutrinos, TeV Scale BSM Neutral Higgs and FIMP Dark Matter in EFT Framework

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- 3 DM phenomenology
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Motivation

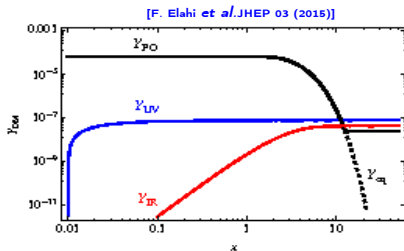
Evidence of Dark Matter: CMB power spectrum, rotation curves of galaxies...

- most popular WIMP paradigm \Rightarrow strong constraint from direct detection experiments
- Another paradigm: Feebly Interacting Massive Particle(FIMP)

FIMP

[L. J. Hall et al. JHEP 03 (2010)]

- feeble interaction explains null results from direct detection
 - negligible initial abundance, thermally decoupled
 - relic density grows with coupling strength
 - IR (renormalisable operators) and UV (non-renormalisable operators) freez-in
- Effective operator: $\frac{C}{\Lambda} DMDM\phi\phi$
 - naturally suppressed coupling



(see talk by S. Bhattacharya)

Theory framework

BSM fields: RHNs ($N_{1,2}$) + DM (N_3) + real singlet scalar (χ) \rightarrow all odd under \mathbb{Z}_2

New gauge-invariant interactions (upto dim=5) :

$$\mathcal{L}_{eff} = M_{Bij} N_i^T C^{-1} N_j + \frac{Y_{ij}}{\Lambda} \bar{L}_i \tilde{\Phi} N_j \chi + \frac{C_{ij}}{\Lambda} N_i^T C^{-1} N_j \chi^2 + \frac{C'_{ij}}{\Lambda} N_i^T C^{-1} N_j \Phi^\dagger \Phi + H.C$$

$$Y = \begin{pmatrix} Y_\nu^{11} & Y_\nu^{12} & \epsilon (= 0) \\ Y_\nu^{21} & Y_\nu^{22} & \epsilon \\ Y_\nu^{31} & Y_\nu^{32} & \epsilon \end{pmatrix} \rightarrow \text{Stability of DM}$$

Scalar Potential: $V(\chi, \Phi) = M_\Phi^2 \Phi^\dagger \Phi + m_\chi^2 \chi^2 + \lambda_1 (\Phi^\dagger \Phi)^2 + \lambda_2 \chi^4 + \lambda_3 (\Phi^\dagger \Phi) \chi^2$

$$\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} \phi \\ \chi \end{pmatrix}, \quad \tan 2\theta = \frac{\lambda_3 v_\chi v_\Phi}{(\lambda_2 v_\chi^2 - \lambda_1 v_\Phi^2)}$$

Scenario-I,II

Scenario-I: $\mathcal{L}_I = \frac{c_{ij}}{\Lambda} N_i^T C^{-1} N_j \chi^2 + \frac{Y_{ij}}{\Lambda} \bar{L}_i \tilde{\Phi} N_j \chi + \text{h.c.}$

Scenario-II: $\mathcal{L}_{II} = \mathcal{L}_I + \frac{c'_{ij}}{\Lambda} N_i^T C^{-1} N_j \phi^\dagger \phi$

- $(M_D)_{\gamma\alpha} = \frac{Y_{\gamma\alpha}}{\Lambda} v_\phi v_\chi$, $(M_R)_{\alpha\beta} = \frac{c_{\alpha\beta}}{\Lambda} v_\chi^2 + \frac{c'_{\alpha\beta}}{\Lambda} v_\phi^2$ ($\alpha, \beta = 1, 2$ & $\gamma = 1, 2, 3$)
- *Seesaw Mechanism* $\Rightarrow m_\nu = -M_D M_R^{-1} M_D^T$, $M_N \sim M_R$

- $M_{N_3} = \frac{c_{33}}{\Lambda} v_\chi^2 + \frac{c'_{33}}{\Lambda} v_\phi^2 \Rightarrow \text{Mass of DM}$

- **DM coupling with scalars:**

$$\lambda_{H_1 N_3 N_3} : -\frac{2v_\chi c_{33}}{\Lambda} \sin \theta + \frac{2v_\phi c'_{33}}{\Lambda} \cos \theta; \lambda_{H_2 N_3 N_3} : \frac{2v_\chi c_{33}}{\Lambda} \cos \theta + \frac{2v_\phi c'_{33}}{\Lambda} \sin \theta$$

Decay contribution $\Rightarrow \Omega_{N_3} h^2 = \frac{2.18 \times 10^{27}}{g_s \sqrt{g_\rho}} M_{N_3} \sum_{i=1}^2 \frac{g_{H_i} \Gamma_{H_i \rightarrow N_3 N_3}}{M_{H_i}^2}$

Planck 2018 result: $\Omega h^2 = 0.1199 \pm 0.0012$ at 68% C.L

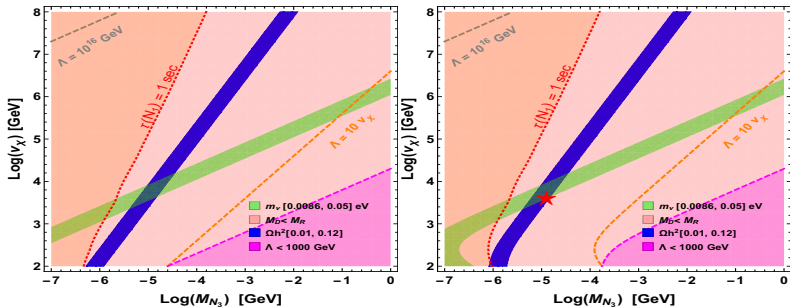


Figure: Scenario-I(Left), Scenario-II(Right)

	M_{H_2}	$\sin \theta$	γ	$c_{11} (c'_{11})$	$c_{33} (c'_{33})$	$M_{N_{1,2}}$
Scenario-I	250 GeV	0.1	10^{-4}	1 (0)	2.5×10^{-6} (0)	$4 \times 10^5 M_{N_3}$
Scenario-II	250 GeV	0.1	10^{-4}	1 (1)	2.5×10^{-6} (2.5×10^{-6})	$4 \times 10^5 M_{N_3}$

- strong correlation between DM mass and v_χ
- GeV scale DM satisfy relic abundance if $v_\chi > 10^8$ GeV $\Rightarrow \lambda_2 < 10^{-12}$ for $M_{H_2} \sim \mathcal{O}(100)$ GeV. (as $M_{H_2} \sim \sqrt{\lambda_2} v_\chi$)
- fine-tuning relaxes if $M_{N_3} \sim$ KeV for which $v_\chi \sim 10^3$ GeV

Scenario-III

$$\mathcal{L}_{\text{eff}} = M_{Bij} N_i^T C^{-1} N_j + \frac{c_{ij}}{\Lambda} N_i^T C^{-1} N_j \chi^2 + \frac{c'_{ij}}{\Lambda} N_i^T C^{-1} N_j \phi^\dagger \phi + \frac{Y_{ij}}{\Lambda} \bar{L}_i \tilde{\phi} N_j \chi + H.C$$

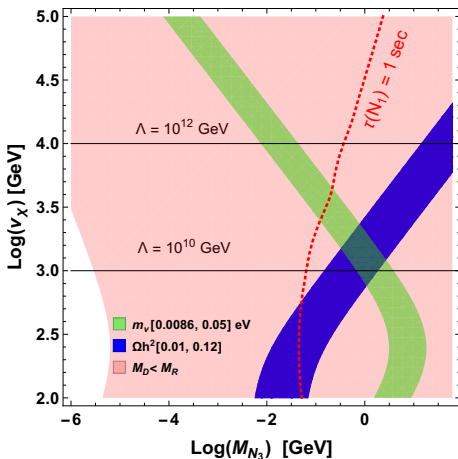
- DM couplings same as Scenario-II:

$$\lambda_{H_1 N_3 N_3} : -\frac{2v_\chi c_{33}}{\Lambda} \sin \theta + \frac{2v_\phi c'_{33}}{\Lambda} \cos \theta; \lambda_{H_2 N_3 N_3} : \frac{2v_\chi c_{33}}{\Lambda} \cos \theta + \frac{2v_\phi c'_{33}}{\Lambda} \sin \theta$$

- The mass matrix of $N_{1,2}$, $(M_R)_{\alpha\beta} = \frac{c_{\alpha\beta} v_\chi^2}{\Lambda} + \frac{c'_{\alpha\beta} v_\phi^2}{\Lambda} + (M_B)_{\alpha\beta}$ ($\alpha, \beta = 1, 2$)
- DM mass, (primarily governed by bare mass term)

$$M_{N_3} = \frac{c_{33} v_\chi^2}{\Lambda} + \frac{c'_{33} v_\phi^2}{\Lambda} + M_{B_3}$$

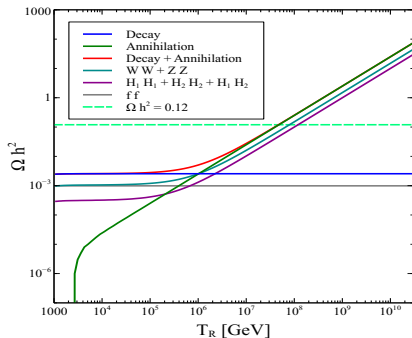
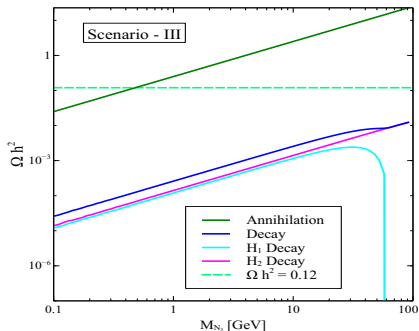
M_{H_2}	$\sin \theta$	y	$c_{33} (= c'_{33})$	$M_{N_3} - M_{B_3}$	M_{N_1}
250 GeV	0.1	1	10^{-4}	10^{-8} GeV	$4M_{N_3}$

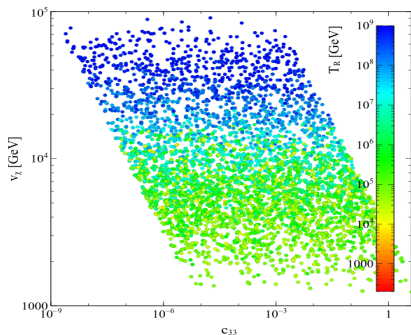
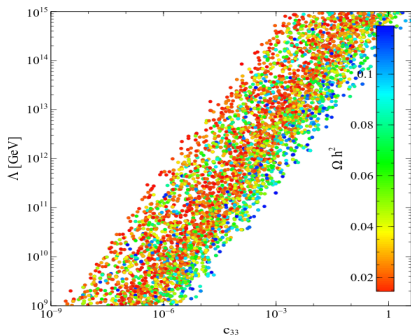


- bare mass relaxes the strong correlation between M_{N_3} and v_χ
- $M_{N_3} \sim \mathcal{O}(\text{GeV})$ and $v_\chi \sim \mathcal{O}(\text{TeV}) \Rightarrow \lambda_2 \sim 1$ for $M_{H_2} \sim \mathcal{O}(1)$ TeV

High reheating temperature (T_R)

- decay channels: $H_i \rightarrow N_3 N_3$ (Independent of T_R)
- annihilation: $WW/ZZ \rightarrow N_3 N_3, H_i H_j \rightarrow N_3 N_3$ ($\propto T_R$)
- numerical simulation: [micrOMEGAs5.0](#)



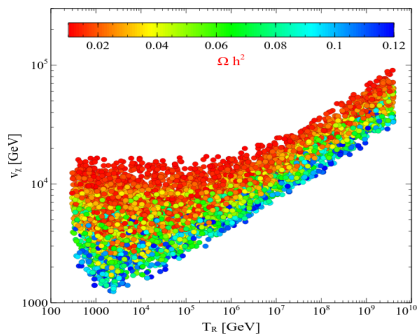
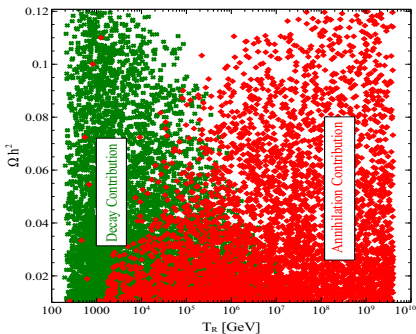


For scatter plot:

- 200 GeV < M_{H_2} < 3000 GeV
- 10 GeV < M_{N_3} < 100 GeV
- 10^{-3} < θ < 10^{-1}
- 1000 GeV < ν_χ < 10000 GeV
- 200 GeV < T_R < 10^9 GeV
- 10^9 GeV < Λ < 10^{14} GeV .

(1)

- N_3 contributes at least 10% of the total DM: $0.01 < \Omega h^2 < 0.1211$
- $c_{33} = \frac{\Lambda(M_{N_3} - M_{B_3})}{\nu_\chi^2 + \beta_3 \nu_\phi^2}$, ($\beta_3 = c'_{33}/c_{33} = 1$)
- $\Omega h^2 \propto T_R/\nu_\chi^2$ (annihilation)

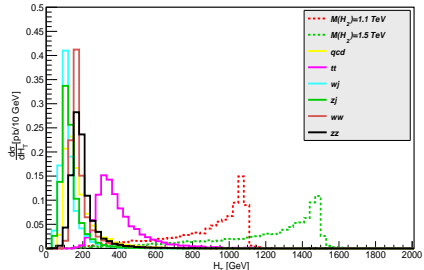
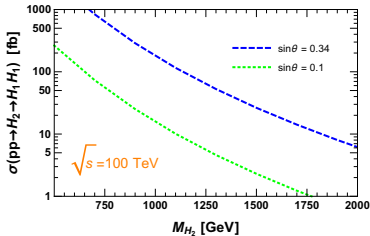


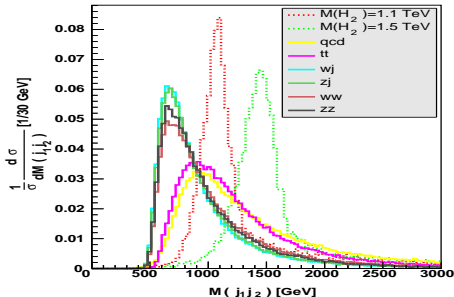
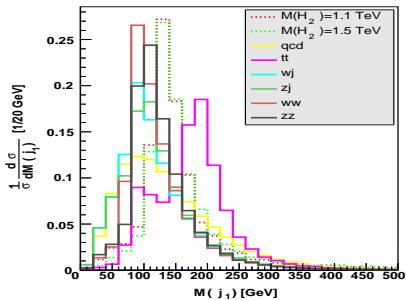
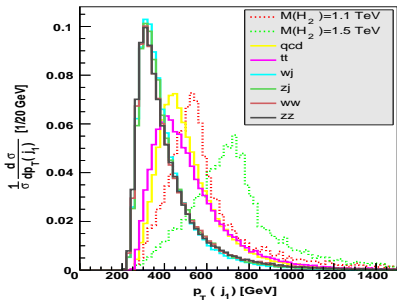
- Left plot: $T_R > 10^6 - 10^7$ GeV, the annihilation contribution dominate
- Right plot: $T_R > 10^6$ GeV, sharp linear relation between T_R and v_χ

$$\bullet \lambda_{H_2 N_3 N_3} = \frac{2(M_{N_3} - M_{B_3})(v_\chi \cos \theta + \beta_3 v_\phi \sin \theta)}{v_\chi^2 + \beta_3 v_\phi^2}$$

BSM Higgs (H_2) at $\sqrt{s} = 100$ TeV LHC

- Resonant di-Higgs production from BSM Higgs with mass $\sim \mathcal{O}$ (TeV) and mixing angle $\sin \theta = 0.1, 0.34$
- consistent with scalar resonance searches and Higgs signal strength measurement: $\mu_{H_1 \rightarrow xx} \sim \cos^2 \theta = 1.17 \pm 0.1$ [arXiv:1809.10733].
- **Signal** : $pp \rightarrow H_2 \rightarrow H_1(\rightarrow b\bar{b})H_1(\rightarrow b\bar{b}) \rightarrow 2j_{\text{fat}}$
background: QCD, di-boson, di-top





- **HEPTools:**
FeynRules, MadGraph5, Pythia8, Delphes
- **Jet clustering:**
Cambridge-Aachen, $R = 1.0$

set of cuts:

- c_1 : $N_j \geq 2$.
- c_2 : $p_T(j_1) \geq 250$ GeV and $p_T(j_2) \geq 250$ GeV.
- c_3 : $|M_{H_1} - M_{j_{1,2}}| \leq 20$ GeV.
- c_4 : $|M_{H_2} - M(j_1 j_2)| \leq 150$.
- c_5 : $|\Delta\eta(j_1 j_2)| \leq 1.5$.
- c_6 : leading and sub-leading fatjets must contain at least two subjects.
- c_7 : For the leading and sub-leading fatjets, each of the fatjets will contain two b -tagged subjects.

Results:

	$M_{H_2}=1.1$ TeV		$M_{H_2}=1.5$ TeV	
	σ^s [fb]	σ^b [fb]	σ^s [fb]	σ^b [fb]
before cut	36.22 (3.13)	4.17×10^7	8.64 (0.75)	4.17×10^7
after cut	0.745 (0.064)	1791.9	0.19 (0.016)	211.43
$\frac{\sigma^s \sqrt{\mathcal{L}}}{\sqrt{\sigma^s + \sigma^b}}, \mathcal{L} = 30 \text{ ab}^{-1}$	3.05 (0.26)		2.26 (0.19)	

* number with (without) bracket is for $\sin \theta = 0.34$ (0.1)

Summary

- **Freez-in mechanism** has been studied in a **EFT framework**, where one among the **3 gauge singlet RHNs** plays the role of FIMP DM, other two participate in light neutrino mass generation via seesaw mechanism.
- This framework can accommodate a GeV scale FIMP as DM and a TeV scale BSM Higgs. DM relic density is set by decay of scalars and annihilation of gauge bosons, scalars and fermions.
- **BSM Higgs** has sizable mixing with SM Higgs, which leads to its possible detection of at collider.
- We study the **di-fatjet signature** of the **TeV scale BSM Higgs at 100 TeV LHC** via **resonant di-higgs channel**.

Thank you for attention!