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

Based on arXiv: 2104.04373 [hep-ph]

co-authors: G. Bélanger, S. Khan, M. Mitra, S. Shil

Rojalin Padhan, IOPB
email: rojalin.p@iopb.res.in

PHENO 2021, University of Pittsburgh
May 24-26,2021

Motivation

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

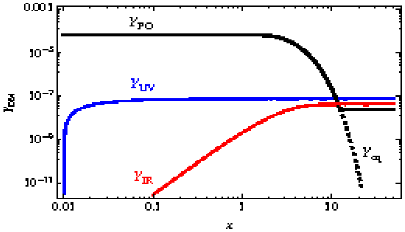
- Null results at direct detection experiments ⇒ strong constraints on most popular WIMP paradigm
- other theories: FIMP, SIMP, ELDER, Axion,ALPs etc

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

- feeble interaction explains null results from direct detection
- negligible initial abundance, thermaly 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

[F. Elahi *et al.*JHEP 03 (2015)]



Theory framework

Particle contents: SM + RHNs ($N_{1,2}$)+ DM (N_3)+real singlet scalar (χ)

New gauge-invariant interactions :

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

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

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

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

Scenario-I,II

$$\mathcal{L}_{eff} = \frac{c_{ij}}{\Lambda} N_i^T C^{-1} N_j \chi^2 + \frac{Y_{ij}}{\Lambda} \bar{L}_i \tilde{\Phi} N_j \chi + \frac{c'_{ij}}{\Lambda} N_i^T C^{-1} N_j \Phi^\dagger \Phi + \mathrm{h.c.}$$

($c'_{ij} = 0$ for scenario-I)

- $(M_D)_{\gamma\alpha} = \frac{Y_{\gamma\alpha}}{\Lambda} v_\Phi v_\chi, \quad (M_R)_{\alpha\beta} = \frac{c_{\alpha\beta}}{\Lambda} v_\chi^2 + \frac{c'_{\alpha\beta}}{\Lambda} v_\Phi^2 \quad (\alpha, \beta = 1, 2 \& \gamma = 1, 2, 3)$
- Seesaw Mechanism $\Rightarrow m_\nu = -M_D M_R^{-1} M_D^T, \; M_N \sim M_R$
- $\boxed{M_{N_3} = \frac{c_{33}}{\Lambda} v_\chi^2 + \frac{c'_{33}}{\Lambda} v_\Phi^2}$ $\Rightarrow$ Mass of DM

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

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

DM coupling with scalars:

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

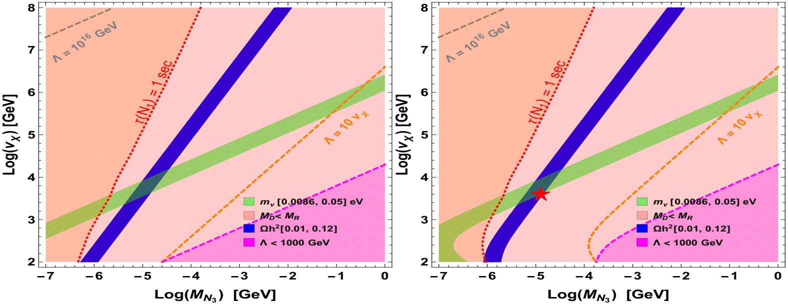


Figure: Scenario-I(Left), Scenario-II(Right)

	M_{H_2}	sin θ	y	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

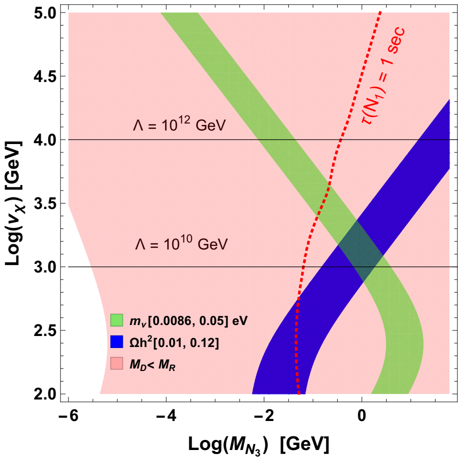
Scenario-III

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

- $\lambda_{H_1 N_3 N_3}$ and $\lambda_{H_2 N_3 N_3}$ same as Scenario-II
- The mass matrix of $N_{1,2}$, $(M_R)_{\alpha\beta} = \frac{c_{\alpha\beta} v_\chi^2}{\Lambda} + \frac{c'_{\alpha\beta} v_\phi^2}{\Lambda} + (M_B)_{\alpha\beta} \quad (\alpha, \beta = 1, 2)$
- DM mass, primarily be governed by bare mass term

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

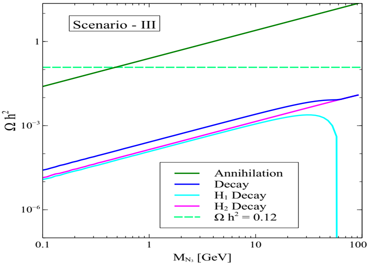
M_{H_2}	$\sin\theta$	y	$c_{33}\ (= c'_{33})$	$M_{N_3} - M_{B_3}$	M_{N_1}
250 GeV	0.1	1	10^{-4}	10^{-8} GeV	$4M_{N_3}$

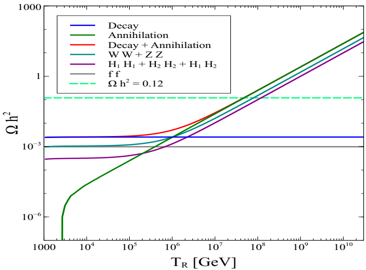


- presence of bare mass relaxes the strong correlation
- relic density and the neutrino mass constraints : $M_{N_3} \sim \mathcal{O}(\text{GeV})$ and $v_\chi \sim \mathcal{O}(\text{TeV}) \Rightarrow \lambda_2 \sim 1$ for $M_{H_2} \sim \mathcal{O}(100)$ GeV

high reheating temperature (T_R)

- decay channels: $H_i \to N_3 N_3$
- annihilation: $WW/ZZ \to N_3 N_3$, $H_i H_j \to N_3 N_3$ and $f\bar{f} \to N_3 N_3$

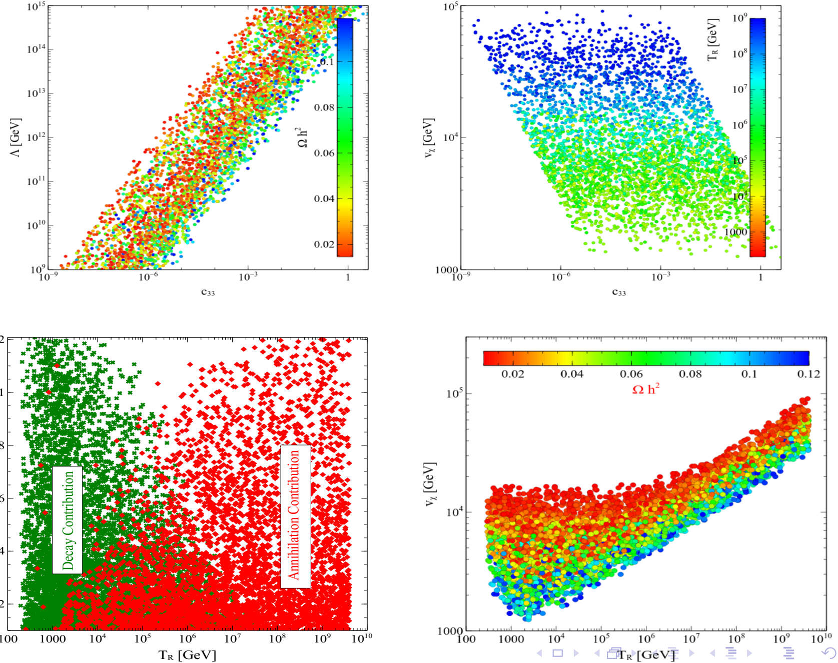




For scatter plot:

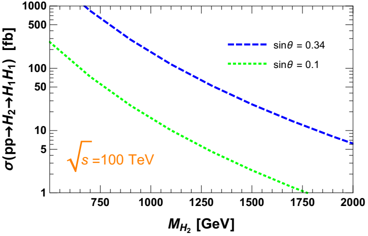
$$
\begin{array}{rcccl}
200 \text{ GeV} & < & M_{H_2} & < & 3000 \text{ GeV} \\
10 \text{ GeV} & < & M_{N_3} & < & 100 \text{ GeV} \\
10^{-3} & < & \theta & < & 10^{-1} \\
1000 \text{ GeV} & < & v_\chi & < & 10000 \text{ GeV} \\
200 \text{ GeV} & < & T_R & < & 10^{9} \text{ GeV} \\
10^{9} \text{ GeV} & < & \Lambda & < & 10^{14} \text{ GeV}\,.
\end{array}
\qquad (1)
$$

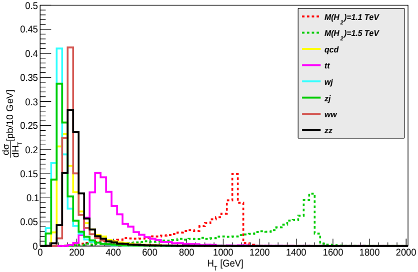
- numerical simulation: micrOMEGAs5.0
- $0.01 < \Omega h^2 < 0.1211$

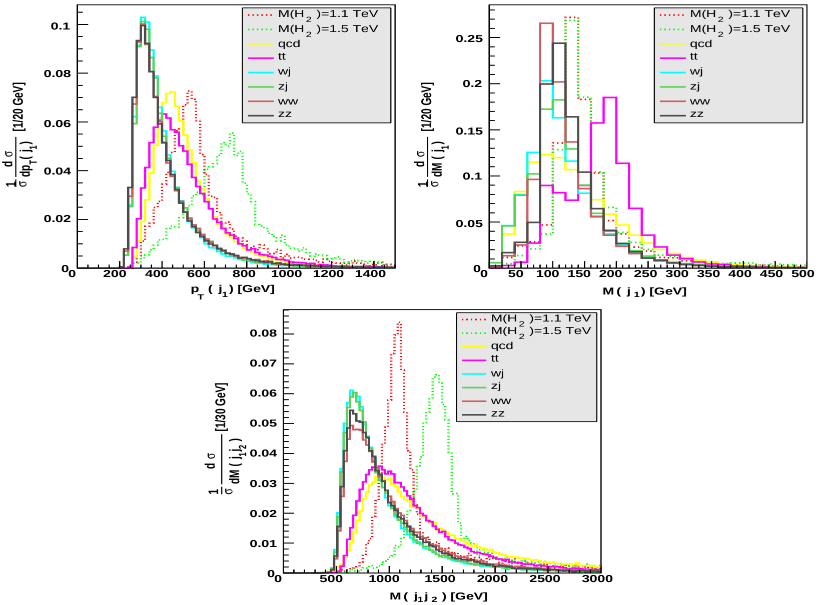

Λ [GeV]
c_{33}
Ωh^2
v_χ [GeV]
T_R [GeV]
Decay Contribution
Annihilation Contribution

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: $\mu_{H_1 \to xx} \sim \cos^2\theta = 1.17 \pm 0.1$ [arXiv:1809.10733 [hep-ex]].
- Signal : $pp \to H_2 \to H_1(\to b\bar{b})H_1(\to b\bar{b}) \to 2j_{\rm fat}$
  background: QCD, di-boson, di-top...






M(H 2)=1.1 TeV
M(H 2)=1.5 TeV
qcd
tt
wj
zj
ww
zz
p T (j1) [GeV]
M (j 1) [GeV]
M (j1j 2) [GeV]
[1/20 GeV]
[1/30 GeV]

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 subjets.
- c_7 : For the leading and sub-leading fatjets, each of the fatjets will contain two b-tagged subjets.

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
$\frac{\sigma^s\sqrt{\mathcal{L}}}{\sqrt{\sigma^s+\sigma^b}}$, $\mathcal{L} = 30$ ab^{-1}	3.05 (0.26)		2.26 (0.19)	

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

Summary

- Freez-in mechanism has been studied in a EFT frame work, where one among the 3 gauge singlet RHNs plays the role od FIMP, other two participate in light neutrino mass generation via seesaw mechanism.
- Another BSM particle,the gauge singlet scalar has sizable mixing with SM Higgs, which leads to possible detection of BSM Higgs at collider.
- DM relic density is set by decay of scalars and annihillation of gauage bosons, scalars and fermions. For low reheating temperature decay channels are dominant and for high value annihillation channels.
- We explore the collider signature of a TeV scale BSM Higgs at 100 TeV LHC in resonant di-higgs channel. Subsequent decay of SM Higgs to $b\bar{b}$ pair leads to di-fatjet signature.

Thank you for attention!