Shining Light on the Scotogenic model

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Motivation

Despite its success, the Standard Model (SM) fails to explain several appearant problems which calls for an extension of the SM by new physics models. There is a huge variety to address these open questions, which are for instance:

- The non vanishing neutrino masses
- The nature of Dark Matter (DM)
- The origin of the matter-antimatter asymmetry
- and many more...

A straightforward extension is to add right handed neutrinos (e.g. νMSM [1]) but X-ray measurements put increasing bounds on these minimal models. This enforces us to look for more complicated new physics models.

The Scotogenic Model

In the Scotogenic model framework [3] the SM is extended with 3 right handed neutrinos N_k and an additional scalar doublet Σ. An exact $\mathbb{Z}_2$ symmetry is imposed under which all new particles are odd while SM particles are even.
The following table summarizes the particle content:

	$SU(2)_L$	$U(1)_Y$	$\mathbb{Z}_2$
Σ	2	1/2	-
N_k	1	0	-
Φ	2	1/2	+
L_i	2	-1/2	+

Table 1: Relevant particle spectrum of the Scotogenic model.

The $\mathbb{Z}_2$ symmetries has phenomenological consequences:

- The new doublet gains no vev
- Decays $N_k \to \gamma \nu_i$ are not allowed
- Radiative generation of neutrino masses
- The lightest right handed neutrino N_1 is a stable DM candidate

The Scotogenic Lagrangian is:

$$\mathcal{L} \subset y_{ki} \overline{N}_k \tilde{\Sigma}^\dagger L_i - \frac{1}{2} \overline{N}_k^c M_k N_k + V(\Phi, \Sigma) + \text{h.c.}, \tag{1}$$

where the scalar potential is given as

$$\begin{aligned} V(\Phi,\Sigma) =& \mu_1^2 \Phi^\dagger \Phi + \mu_2^2 \Sigma^\dagger \Sigma + \frac{\lambda_1}{2}\left(\Phi^\dagger\Phi\right)^2 + \frac{\lambda_2}{2}\left(\Sigma^\dagger\Sigma\right)^2 + \lambda_3\left(\Phi^\dagger\Phi\right)\left(\Sigma^\dagger\Sigma\right) \\ &+ \lambda_4\left(\Phi^\dagger\Sigma\right)\left(\Sigma^\dagger\Phi\right) + \frac{\lambda_5}{2}\left(\left(\Phi^\dagger\Sigma\right)^2\right). \end{aligned} \tag{2}$$

The masses of the four new scalars are:

$$m_\pm^2 = \mu_2^2 + \frac{\lambda_3 v^2}{2}, \quad m_A^2 = m_\pm^2 + \frac{(\lambda_4 - \lambda_5)\, v^2}{2}, \quad m_S^2 = m_A^2 + \lambda_5 v^2 \tag{3}$$

The Yukawa matrix can be parameterized using Casas-Ibarra parameterization:

$$y = \sqrt{\Lambda^{-1}} R \sqrt{m_\nu} U^\dagger_{\text{PMNS}} \tag{4}$$

For our project we arranged the mass spectrum in the following way:

$$M_1 = \mathcal{O}(\text{keV}) << M_{2,3} = \mathcal{O}(100\,\text{GeV}) < m_\pm = \mathcal{O}(100\text{s GeV}). \tag{5}$$

This specific choice will lead to a dominant production of keV DM via a Freeze-In (decays of scalars) and a subdominant decay production of the heavier neutrinos whose abundance is set by a Freeze-Out process.

Testing the model

In a previous paper [2], some of us have already shown that the Scotogenic model is able to tackle several open questions with new degrees of freedom below the TeV scale. Therefore it's an interesting question to search and discuss possible collider signatures.
Testing the model is tricky, because it only interacts weakly with the SM ("scotos" (greek) = Darkness). However, some analysis had already been done:

- Mono-Higgs: 1811.00490
- Mono-Lepton: 1710.03824
- Di-Lepton: 1611.09540

But the parameter range covered in these analysis is not large.
In our analysis we focussed on potential signatures in the channel

$$p\,p \to \sigma^\pm \sigma^\mp \to \ell_i^\pm \ell_j^\mp + N_k\, N_l, \tag{6}$$

where ℓ_i can be either electrons and muons or taus.

ATLAS results

The ATLAS collaboration presents results for the Di-Tau + MET (1708.07875) and the Di-Lepton + MET (1803.02762) channel, using Run-2 data with an integrated luminosity of $36\,\text{fb}^{-1}$. Various signal regions are defined by implementing several cuts to suppress SM background. The limits for new physics cross sections are summarized in the following table:

SR	N_{obs}	N_{exp}	σ^{95}_{vis} [fb]
SR-lowMass	10	14 ± 6	0.26
SR-highMass	5	3.7 ± 1.4	0.20

Table 2: 95% exclusion limits for non SM cross sections based on the Di-Tau analysis.

SR	N_{obs}	N_{exp}	σ^{95}_{vis} [fb]
DF-100	78	14 ± 6	0.26
DF-150	11	11.5 ± 3.1	0.32
DF-200	6	2.1 ± 1.9	0.33
DF-300	2	0.6 ± 0.6	0.18
SF-loose	153	133 ± 22	2.02
SF-high	9	9.8 ± 2.9	0.29

Table 3: 95% exclusion limits for non SM cross sections based on the Di-Lepton analysis.

We set up our own analysis pipeline and cross checked with the given model parameterization. A grid parameter space where we varied the masses of the scalars and the right handed neutrinos were performed, but it turned out that the current sensitivity is not strong enough to test a significant parameter region. The best benchmark point gives:

$$\begin{aligned} \text{Di} - \text{Tau}: &\quad \text{SR} - \text{high} \to \sigma = (0.15 \pm 0.06)\,\text{fb} \\ \text{Di} - \text{Lepton}: &\quad \text{DF} - 100 \to \sigma = (0.91 \pm 0.16)\,\text{fb}, \end{aligned} \tag{7}$$

which is only slightly in reach of the present data.

Going beyond

In the approaching future we will see the start of the HL-LHC project, which will deliver up to $4000\,\text{fb}^{-1}$ at a center of mass energy of $14\,\text{TeV}$. This will lead to a significant increase of event rates and enables us to reach lower sensitivities which will probe interesting regions of parameter space for our model.
Our approach is based on the pre existing searches but makes use of the larger luminosities. We estimated sensitivies by calculating signal over background

$$\mathcal{S} = \frac{S}{\sqrt{S+B}}. \tag{8}$$

Compared to the current analysis the production cross section is increased by $\approx 20\%$ and the luminosity increase gives a factor 10.5.
Taking the mass of N_2 and N_3 to be equal we derived the potential exclusion and discovery regions:

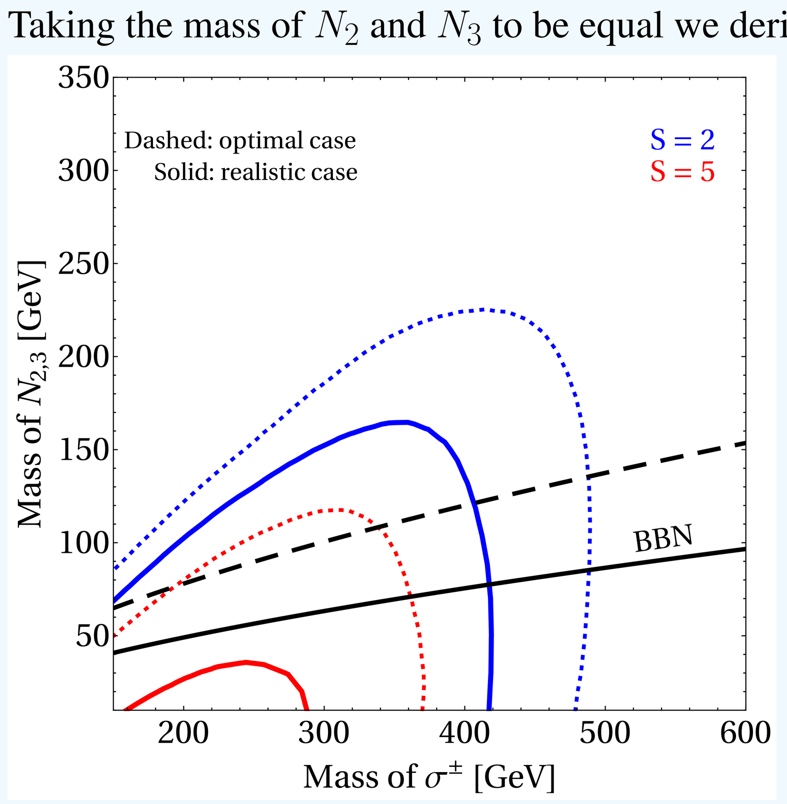


Figure 1: Projected sensitivities for a Di-Tau search at HL-LHC.

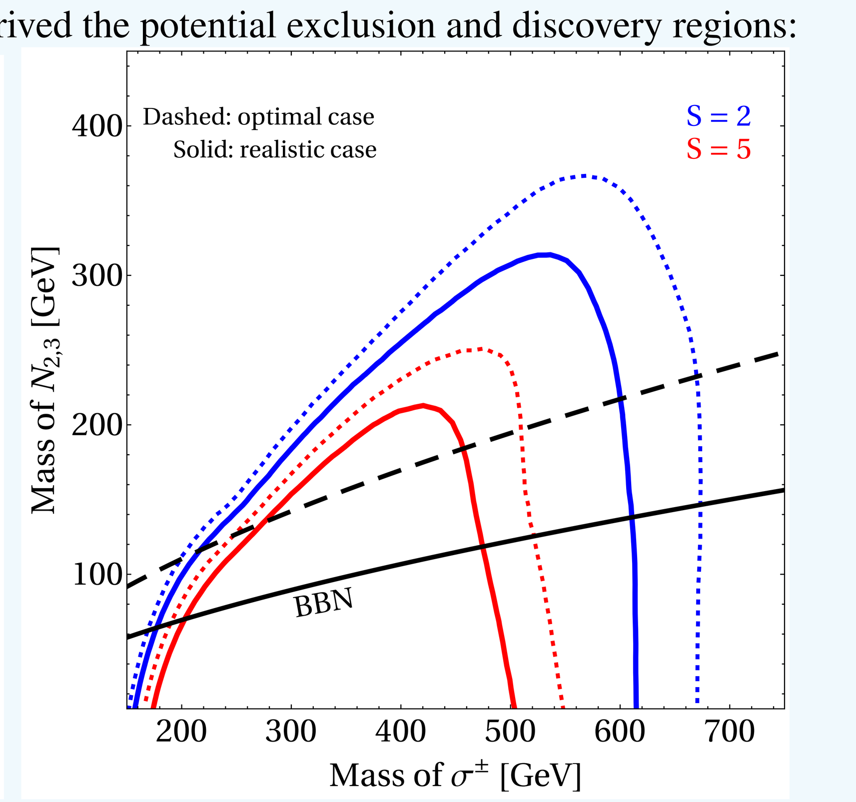


Figure 2: Projected sensitivities for a Di-Lepton search at HL-LHC.

Optimization of cross sections:
The production cross section is given by the production

$$\sigma(p\,p \to \ell^\pm \ell^\mp N_k\, N_l) = \sigma(p\,p \to \sigma^\pm \sigma^\mp) \times \text{BR}(\sigma^\pm \to \ell_i^\pm N_k)^2. \tag{9}$$

In fact, the branching ratios BR(...) are not fixed but can be varied using free parameters available when using Casas-Ibarra parameterization. In principle we can have four free parameters

	w	ξ	δ	α_2	$\text{BR}(\sigma^\pm \to \tau^\pm N_k)[\%]$
NH	1.72	> 1	2π	π	38.27
IH	1.31	> 1	π	$-\pi$	27.32

Table 4: Optimization of the respective BR for the Di-Tau search.

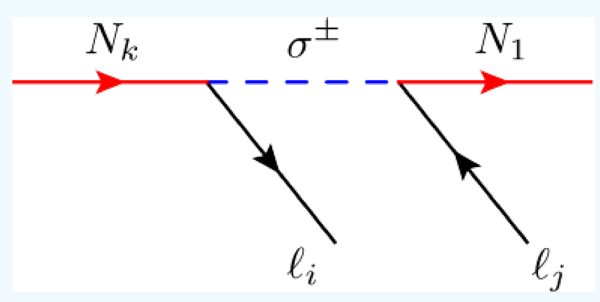
	w	ξ	δ	α_2	$\text{BR}(\sigma^\pm \to \ell^\pm N_k)[\%]$
NH	0.42	< -2	2π	π	86.44
IH	2.35	< -2	π	$-\pi$	99.74

Table 5: Optimization of the respective BR for the Di-Lepton search. Realizing IH will give an effective zero-two matrix.

The limits in fig. 1 and fig. 2 are estimated for a NH scenario.

Cosmological implications

BBN Constraints:



- $\Gamma(N_k \to \ell_i^\pm \ell_j^\mp N_1) = \frac{M_k^5}{6144\pi^3 m_\pm^4}\left(|y_{1i}|^2|y_{kj}|^2 + |y_{1j}|^2|y_{ki}|^2\right)$
- Freeze-In of DM N_1 requires very small couplings y_{1i}
- Mass splitting between scalars and neutrinos

$\Rightarrow$ Late time decays of $N_{2,3}$ possible which can spoil BBN.
$\Rightarrow$ For significantly abundant particles one imposes normally $\tau \lesssim 1\,\text{sec}$ (for leptons less stringent)

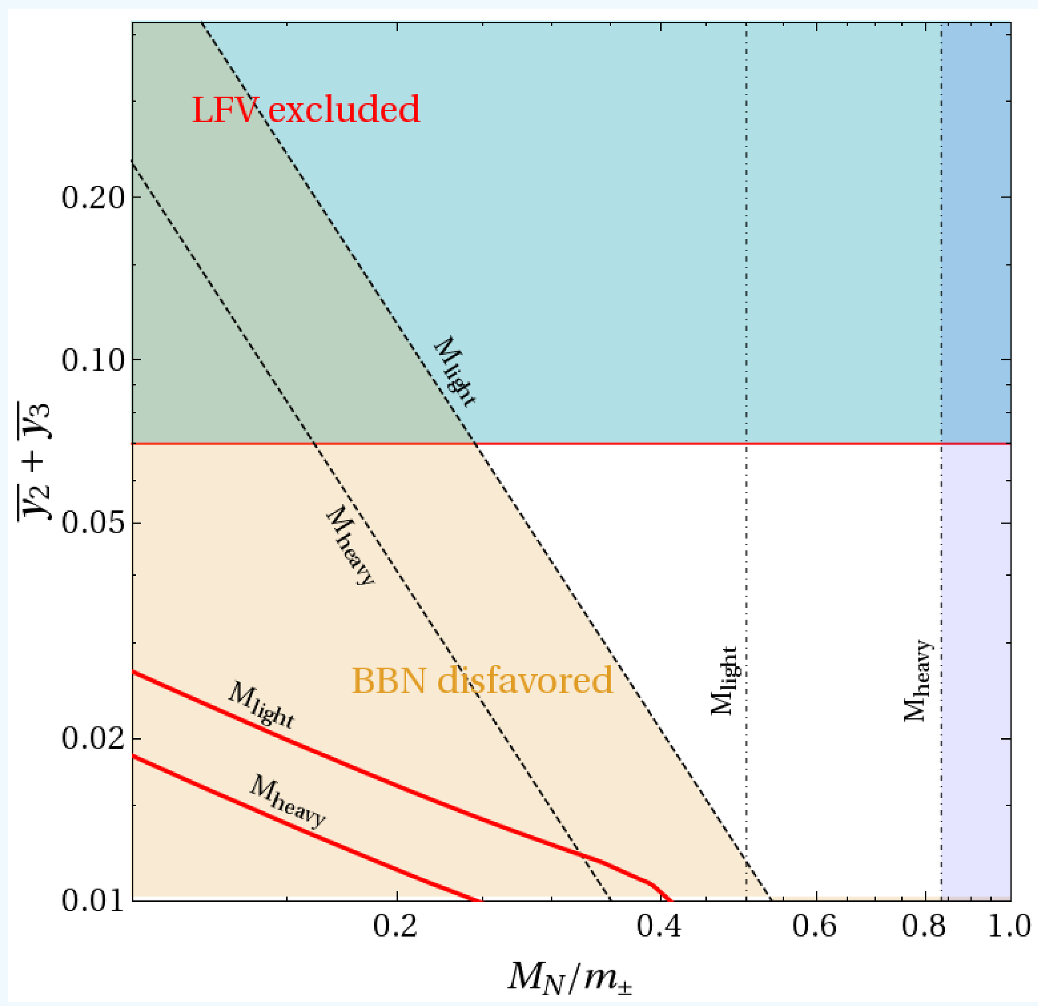


Figure 3: Constraints on the Yukawa strenght. The red shaded region is excluded by lepton flavor violation processes. The green region is disfavored by BBN because of too long life times. M_{light} corresponds to a charged scalar mass of 200 GeV and M_{heavy} to 600 GeV. The dashed dotted lines are representing a mass gap $m_\pm - M_N = 100\,\text{GeV}$ as needed by LHC. Finally, given in red solid lines are limits from DM productio due to $N_{2,3}$ decays: DM will be overproduced for parameter choices below the respective red lines.

Open work

- Constraints from structure formation seems to be negligible, but we need a more refined analysis
- Using an e^+e^- collider to test our model setup
- Projections for FCC-hh or similar collider $\to$ How to model background?

References

[1] Takehiko Asaka and Mikhail Shaposhnikov. The numSM, dark matter and baryon asymmetry of the universe. *Phys. Lett.*, B620:17–26, 2005.

[2] Sven Baumholzer, Vedran Brdar, and Pedro Schwaller. The New νMSM ($\nu\nu$MSM): Radiative Neutrino Masses, keV-Scale Dark Matter and Viable Leptogenesis with sub-TeV New Physics. *JHEP*, 08:067, 2018.

[3] Ernest Ma. Verifiable radiative seesaw mechanism of neutrino mass and dark matter. *Phys. Rev.*, D73:077301, 2006.