Dark matter and Leptogenesis within a singlet-doublet scotogenic model

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LAPTh, Annecy

Overview

Table of Contents

Open questions of the Standard Model

The Standard Model has open questions :

- gravity
- hierarchy problem
- matter-antimatter asymmetry
- dark matter
- neutrino masses
- ...

Table of Contents

Details of the particle content of the model

B.Herrmann, J.Bernigaud, M.S [hep-ph/2107.04613v3]

	Ψ_1	Ψ_2	F_i	Φ	S	L	H
$SU(2)_L$	**2**	**2**	**1**	**2**	**1**	**2**	**2**
$U(1)_Y$	-1	1	0	1	0	-1	1
$\mathbb{Z}_2$	-1	-1	-1	-1	-1	+1	+1
lepton number	**+1**	**+1**	**0**	**0**	**0**	**+1**	**0**

Table: Additional field content of the model

The new particles are odd under a $\mathbb{Z}_2$ symmetry whereas the particles from the SM are even.
The lightest particle will be stable and will provide a DM candidate.

Interaction terms and neutrino masses

Interaction terms

$$-\mathcal{L} \supset y_{1i}\Psi_1 F_i H + y_{2i}\overline{\Psi_2}F_i H + g_{\Psi}^{\alpha}\Psi_2 L_\alpha S + g_{F_i}^{\alpha}\Phi L_\alpha F_i + g_R^{\alpha} e^c_{\mathrm{R}\alpha}\Phi^\dagger \Psi_1$$

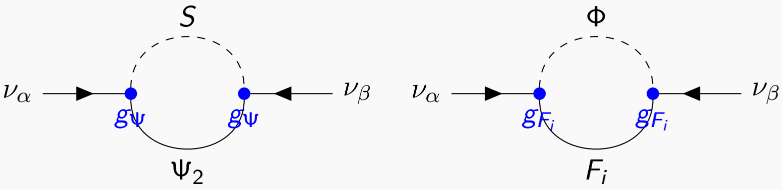


Figure: Generation of neutrino masses at the one-loop level in the model.

Sakharov conditions for Leptogenesis

Matter-antimatter asymmetry is given by

$$\eta_B = \frac{n_B - n_{\overline{B}}}{n_\gamma} = (6.15 \pm 0.25) \cdot 10^{-10} \,. \tag{1}$$

Sakharov conditions:

- Violation of lepton number $\implies$ couplings g_Ψ, g_{F_i}, g_R, and y_{1i}, y_{2i},
- Out-of-equilibrium decay of at least one of the F_i
- C and CP violation $\implies$ need a complex phase in one of the couplings g_Ψ, g_{F_i}, g_R, and y_{1i}, y_{2i}.

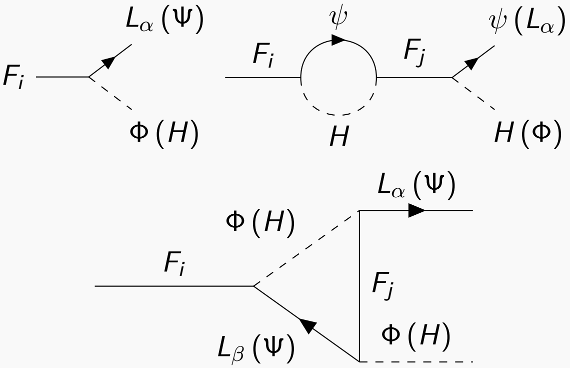
Leptogenesis is driven by the decay of F_i:

$$F_i \to L_\alpha \Phi \,,$$
$$F_i \to \Psi_j H \,.$$

Lepton asymmetry

The *CP* asymmetry is denoted by ϵ_α:

$$\boxed{\epsilon_\alpha \; = \; \frac{\Gamma_\alpha - \Gamma_{\overline{\alpha}}}{\Gamma_{\text{tot}}}}, \qquad (2)$$



Boltzmann equations (BE)

BE to track the evolution of the particle density, and the of the asymmetry density of $B - L$:

$$\frac{\mathrm{d}n_{F_i}}{\mathrm{d}x} = (D+S)(n_{F_i} - n_{F_i}^{\mathrm{eq}}) \implies \text{out-of-eq decays of } F_i \,, \quad (3)$$

$$\frac{\mathrm{d}n_{B-L}}{\mathrm{d}x} = \underbrace{-\epsilon_\alpha D(n_{F_i} - n_{F_i}^{\mathrm{eq}})}_{\textit{asymmetry}} - \underbrace{W n_{B-L}}_{\textit{washout}} \,. \quad (4)$$

Table of Contents

Results on the baryon asymmetry

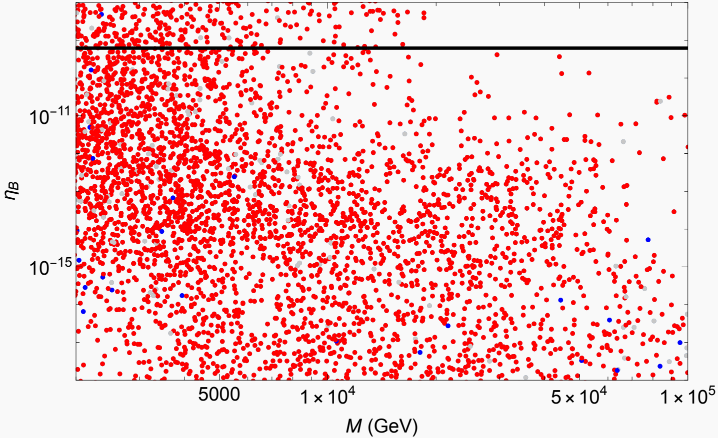


Figure: Preliminary results from a MCMC scan. The baryon asymmetry η_B can be reached in this model. The horizontal black line represents the observed baryon asymmetry $\eta_B = 6 \cdot 10^{-10}$.

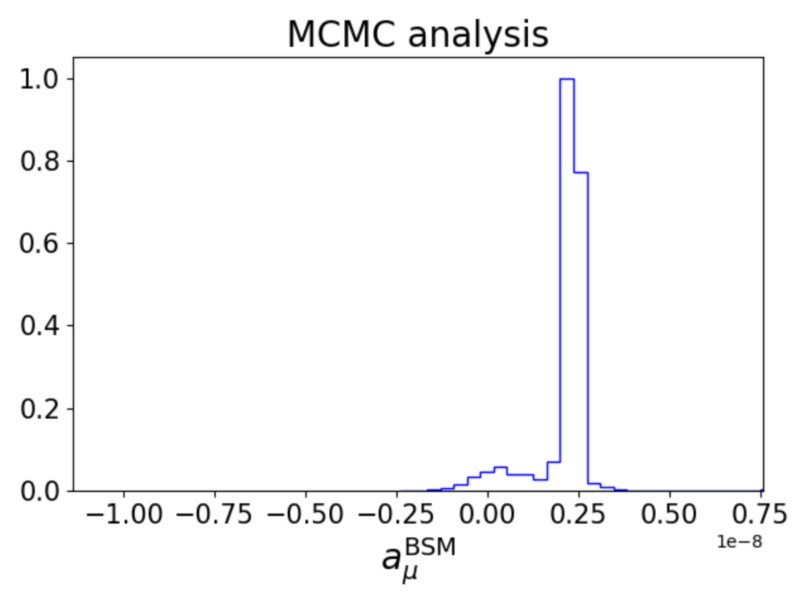
Conclusion

- Dark matter, neutrino masses and LFV constraints are accommodated
- Preliminary work gives promising results: baryon asymmetry can be generated in this scenario
- $(g-2)$ is possible to achieve, while obtaining the baryon asymmetry, the correct neutrino masses, dark matter, and satisfying LFV constraints.

Thank you

Thank you for your attention !

$(g-2)_\mu$


MCMC analysis
1.0
0.8
0.6
0.4
0.2
0.0
−1.00 −0.75 −0.50 −0.25 0.00 0.25 0.50 0.75
1e−8
a_μ^{BSM}

Baryon asymmetry with $(g-2)_\mu$

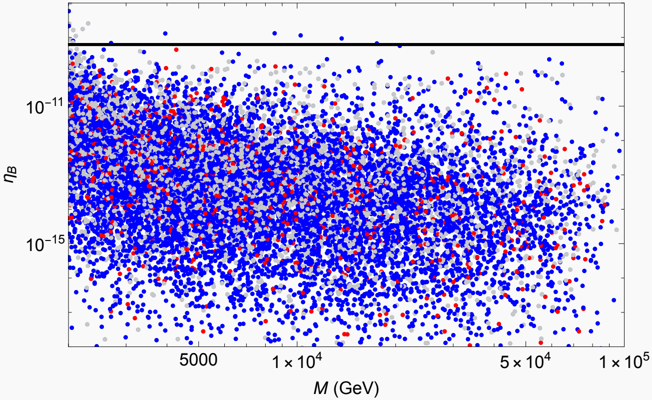


Figure: The baryon asymmetry η_B plotted against the mass of F_i driving Leptogenesis. Parameters fit constraints from LFV decays and accommodate the $(g-2)_\mu$ anomaly. Points in red satisfy DM relic density, points in blue are where DM is under-produced and points in gray are overproduced DM.

couplings

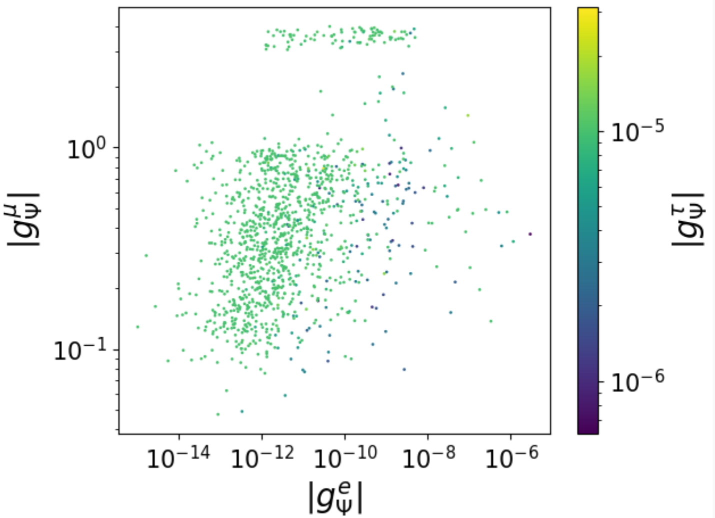
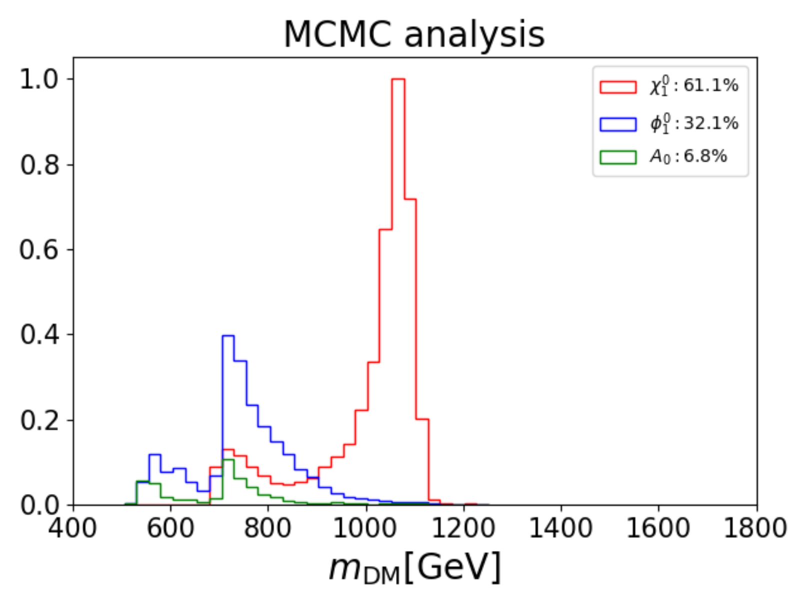
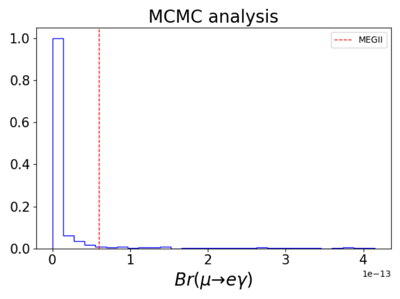


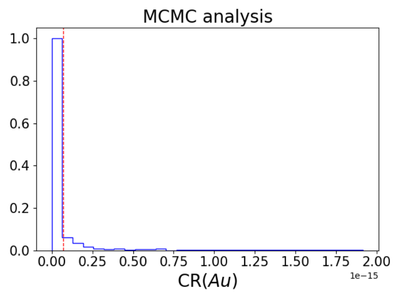
Figure: Hierarchy needed to obtain the correct $(g-2)_\mu$

Dark matter phenomenology



LFV


MCMC analysis
MEGII
1.0
0.8
0.6
0.4
0.2
0.0
0
1
2
3
4
1e−13
$Br(\mu\to e\gamma)$


MCMC analysis
1.0
0.8
0.6
0.4
0.2
0.0
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
1e−15
CR(Au)

The parameter space

- Markov Chain Monte Carlos analysis
- constraints from LFV, dark matter, experimental observations such as the Higgs mass and neutrino masses

Washout processes

$$W = W_{ID} + W_{\Delta L=1} + W_{\Delta L=2} \,. \tag{5}$$

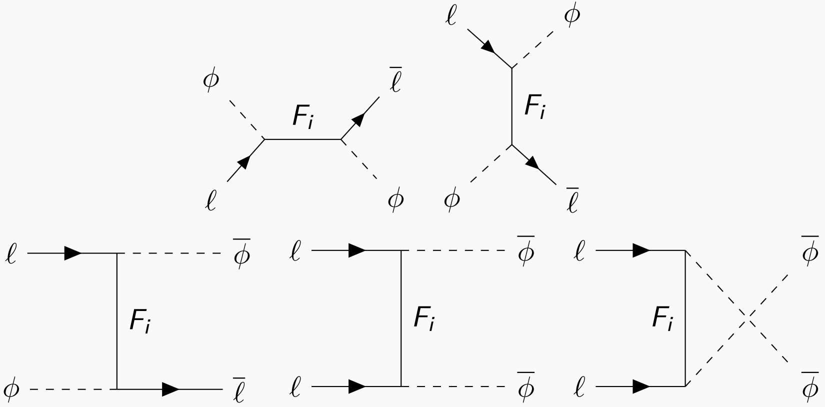


Figure: Washout processes $\Delta L = 2$

Strong washout process

The washout erases the lepton asymmetry, and thus decrease the amount of baryon asymmetry.
In this specific scenario we are in the strong washout regime.
Decay parameter K is above four.
$\Gamma_{ID} \propto |g|^2/M_{F_i} \sim 10^{-12}/M_{F_i}$, with $M_{Pl} \approx 1.22 \times 10^{19}$,
the Hubble parameter $H \propto M_{F_i}^2 \cdot 10^{-19}$.
So $K \propto 10^7/M_{F_i}$ and we know that M_{F_i} is of the order of few TeV
$\Longrightarrow$ strong washout regime

Vertex correction

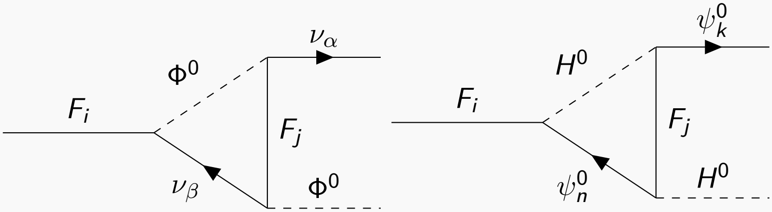


Figure: Vertex correction diagrams involving the other Majorana fermion in the loop. In the right triangle, the Yukawa couplings y_{ij} take an important role. The indices $k, n = \{1, 2\}$, $i, j = \{A, B\}$, and $\alpha, \beta = \{e, \mu, \tau\}$.

The particle content

Esch, Klasen, Yaguna [arXiv:1804.0338]

The SM is extended by :

Fermions

- a singlet F
- a Dirac doublet Ψ

$$\Psi_1 = \begin{pmatrix} \Psi_1^0 \\ \Psi_1^- \end{pmatrix}$$

$$\Psi_2 = \begin{pmatrix} -\left(\Psi_2^-\right)^\dagger \\ \left(\Psi_2^0\right)^\dagger \end{pmatrix}$$

and Scalars

- a singlet S
- a doublet Φ

$$\Phi = \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}\left(\phi^0 + iA^0\right) \end{pmatrix}$$

The scalar sector

$$
\begin{aligned}
-\mathcal{L}_{\text{scalar}} &= M_H^2\left|H\right|^2 + \lambda_H\left|H\right|^4 + \frac{1}{2}M_S^2 S^2 + \frac{1}{2}\lambda_{4S}S^4 + M_\Phi^2\left|\Phi\right|^2 \\
&+ \lambda_{4\Phi}\left|\Phi\right|^4 + \frac{1}{2}\lambda_S S^2\left|H\right|^2 + \lambda_\Phi\left|\Phi\right|^2\left|H\right|^2 + \lambda'_\Phi\left|H\Phi^\dagger\right|^2 \\
&+ \frac{1}{2}\lambda''_\Phi\left\{\left(H\Phi^\dagger\right)^2 + \text{h.c.}\right\} + T\left\{SH\Phi^\dagger + \text{h.c.}\right\}
\end{aligned}
\tag{6}
$$

Back up MCMC

$$\mathcal{L}_n \;\equiv\; \mathcal{L}(\vec{\theta}_n, \vec{O}) \;=\; \prod_i \mathcal{L}_i(\vec{\theta}_n, O_i)\,. \tag{7}$$

$$\ln \mathcal{L}_i(\vec{\theta}_n, O_i) \;=\; \frac{-(O_i(\vec{\theta}_n) - O_i^{\mathrm{exp}})^2}{2\sigma_i^2}\,, \tag{8}$$

$$p \;=\; \mathcal{L}^{n+1}/\mathcal{L}^n\,. \tag{9}$$

Back up Casas Ibarra parametrization

$$\mathrm{M}_{11} = \sum_{k,n} f_{kn}(U_F^\dagger)^2_{3k}(U_S^\dagger)^2_{1n}\,, \tag{10}$$

$$\mathrm{M}_{12} = \frac{1}{\sqrt{2}}\sum_{k,n} f_{kn}(U_F^\dagger)_{1k}(U_F^\dagger)_{3k}(U_S^\dagger)_{1n}(U_S^\dagger)_{2n}\,, \tag{11}$$

$$\mathrm{M}_{22} = \frac{1}{2}\sum_{k,n} f_{kn}(U_F^\dagger)^2_{1k}\left[(U_S^\dagger)^2_{2n} - \left(U_S^\dagger\right)^2_{3n}\right], \tag{12}$$

$$f_{kn} = \frac{1}{16\pi^2}\frac{M_{\chi_k^0}}{M^2_{\Phi_n^0} - M^2_{\chi_k^0}}\left[M^2_{\chi_k^0}\log\left(\frac{M^2_{\chi_k^0}}{\mu^2}\right) - M^2_{\Phi_n^0}\log\left(\frac{M^2_{\Phi_n^0}}{\mu^2}\right)\right]. \tag{13}$$

$(g-2)$

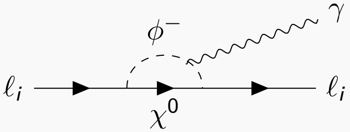


Figure: Contribution to the $(g-2)_\ell$ scotogenic models.

BE

Baryon asymmetry $\eta_B = (6.15 \pm 0.25) \cdot 10^{-10}$.

- initial conditions, $x_i = M_i/T$:

$$N_{F_i}(x_i \ll 1) \;=\; N_{F_i}^{\rm eq}\,. \tag{14}$$

$$N_L(x_i \ll 1) \;=\; 0\,. \tag{15}$$

- track $B-L$ number density by solving BE, When the temperatures drop:

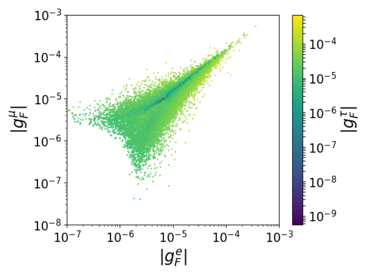
$$N_{B-L}^f \;=\; N_{B-L}(x_i \gg 1)\,. \tag{16}$$

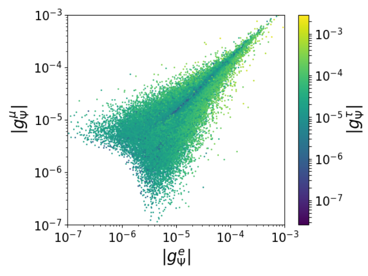
- through sphaleron processes, it is converted into baryon asymmetry η_B

$$\eta_B \;=\; \frac{3}{4}\,\frac{C}{f}\,N_{B-L}^f\,, \tag{17}$$

where $C = 28/79$, and $f = 2387/86$.

Couplings g_Ψ^i and g_F^i





Back up Setup of the g couplings

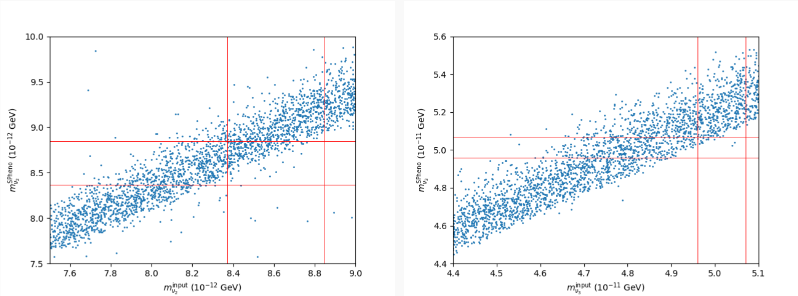
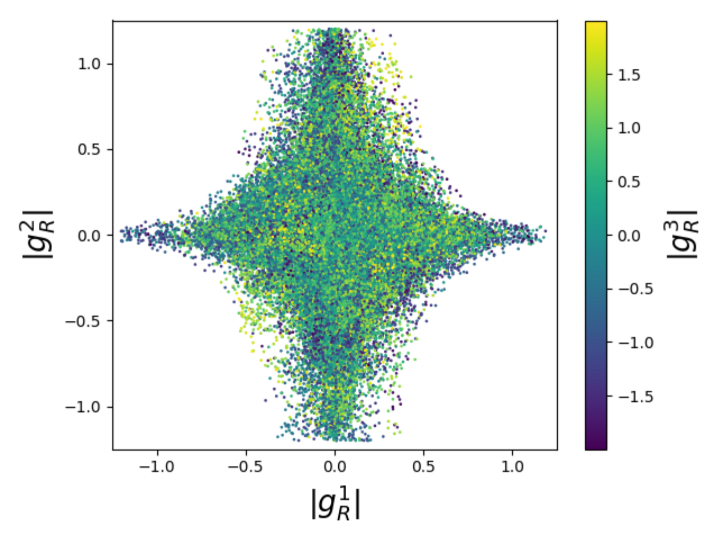


Figure: Impact of one-loop corrections to scalar and fermion masses on the neutrino masses.

The leading order masses are the ones entering in the Casas Ibarra parametrization. The NLO masses are the ones given by *SPheno*.

Couplings g_R



Relic density