

Dark matter and lepton flavour phenomenology within a singlet-doublet scotogenic model

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LAPTh, Annecy



Overview

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 The T1-2A model

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Introduction



The T1-2A model



Results



Summary

Open questions of the Standard Model

The Standard Model has open questions :

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

Introduction to the scotogenic model

scotogenic = *scoto* + *genic*
 dark generate

The first scotogenic model was developed by Ma [[arXiv:0601225](#)].
SM is extended by 3 majorana fermions + 1 scalar field.
The scotogenic models are classified in Restrepo, Yaguna, Zapata
[[arXiv:1308.3655](#)]

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Details of the T1-2A model

Esch, Klasen, Yaguna [arXiv:1804.0338]

The SM is extended by :

Fermions

- a singlet F
 - a Dirac doublet Ψ

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

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

and Scalars

- a singlet S
 - a doublet Φ

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

Details of the T1-2A model

	Ψ_1	Ψ_2	F	Φ	S	H
$SU(2)_L$	2	2	1	2	1	2
$U(1)_Y$	-1	1	0	1	0	1
\mathbb{Z}_2	-1	-1	-1	-1	-1	+1

Table: Additional field content of the model T1-2A.

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.

The scalar sector

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

The scalar sector after EWSB

$$H = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}[v + h^0 + iG^0] \end{pmatrix}, \quad S, \quad \Phi = \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}[\phi^0 + iA^0] \end{pmatrix} \quad (2)$$

$$\mathcal{M}_\phi^2 = \begin{pmatrix} \mu_S^2 + \frac{1}{2}v^2\lambda_S & vT \\ vT & \mu_\Phi^2 + \frac{1}{2}v^2[\lambda_\Phi + \lambda'_\Phi + \lambda''_\Phi] \end{pmatrix} \quad (3)$$

Diagonalization according to

$$\begin{pmatrix} \phi_1^0 \\ \phi_2^0 \end{pmatrix} = U_\phi \begin{pmatrix} S \\ \phi^0 \end{pmatrix} \quad (4)$$

The fermion sector

$$\begin{aligned} -\mathcal{L}_{\text{fermion}} = & -\frac{i}{2} \left(\bar{\Psi}_1 \sigma^\mu D_\mu \Psi_1 + \bar{\Psi}_2 \sigma^\mu D_\mu \Psi_2 \right) \\ & + \frac{1}{2} M_F F^2 + M_\Psi \Psi_1 \Psi_2 + y_1 \Psi_1 H F + y_2 \bar{\Psi}_2 H \bar{F} + \text{h.c.} \end{aligned} \tag{5}$$

The fermion sector after EWSB

$$F, \quad \Psi_1 = \begin{pmatrix} \Psi_1^0 \\ \Psi_1^- \end{pmatrix}, \quad \Psi_2 = \begin{pmatrix} -(\Psi_2^-)^\dagger \\ (\Psi_2^0)^\dagger \end{pmatrix} \quad (6)$$

$$\mathcal{M}_{\chi^0} = \begin{pmatrix} M_F & \frac{v}{\sqrt{2}}y_1 & \frac{v}{\sqrt{2}}y_2 \\ \frac{v}{\sqrt{2}}y_1 & 0 & M_\Psi \\ \frac{v}{\sqrt{2}}y_2 & M_\Psi & 0 \end{pmatrix} \quad (7)$$

$$\begin{pmatrix} \chi_1^0 \\ \chi_2^0 \\ \chi_3^0 \end{pmatrix} = U_\chi \begin{pmatrix} F \\ \Psi_1^0 \\ (\Psi_2^0)^\dagger \end{pmatrix} \quad (8)$$

The masses are the eigenvalues of the mass matrix \mathcal{M}_{χ^0} .

Particle content in the mass basis

To summarize, the particle content in their physical states are :

fermion content

- three neutral particles :
 $\chi_1^0, \chi_2^0, \chi_3^0,$
- a charged fermion : $\chi^\pm.$

scalar content

- two neutral scalar and one neutral pseudo-scalar :
 $\phi_1^0, \phi_2^0, A^0,$
- a charged scalar $\phi^\pm.$

Three candidates for dark matter : $\chi_1^0, \phi_1^0, A^0.$

Interaction terms and neutrino masses

$$L_i = \begin{pmatrix} \nu_i \\ e_i^- \end{pmatrix} \quad (9)$$

Interaction terms

$$-\mathcal{L} \supset g_\Psi^i \Psi_2 L_i S + g_F^i \Phi L_i F + g_R^i L_{Ri}^c \Phi^\dagger \Psi_1 \quad (10)$$

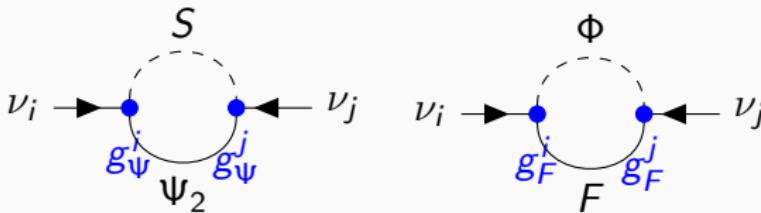
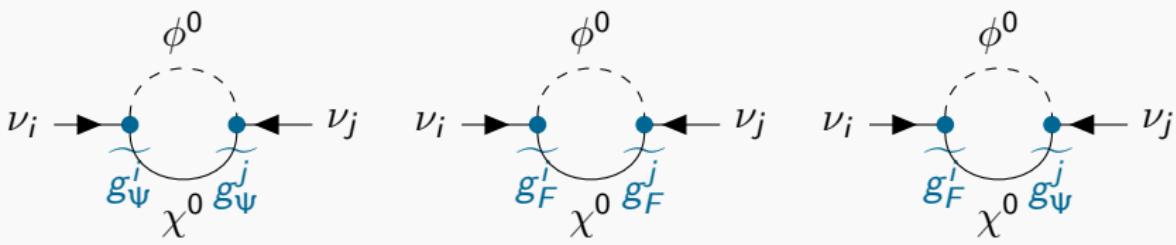


Figure: Generation of neutrino masses at the one-loop level in the model T1-2A. The diagrams show the contributions in the interaction basis.

Computation of the neutrino masses

$$-\mathcal{L} \supset g_{\Psi}^i \Psi_2 L_i S + g_F^i \Phi L_i F + g_R^i L_{Ri}^c \Phi^\dagger \Psi_1$$



$$\nu_i \rightarrow \overset{\phi^0}{\text{---}} \overset{\chi^0}{\text{---}} \overset{\widetilde{g}_i}{\text{---}} \overset{\widetilde{g}_j}{\text{---}} \nu_j \equiv \overline{\nu_j^c} \underbrace{\frac{M_{\chi^0}}{16\pi^2} B_0(0, M_{\chi^0}^2, M_{\phi^0}^2) \widetilde{g}_i}_{(M_\nu)_{ij}} \nu_i \quad (11)$$

$$M_\nu = \mathcal{G}^t M_L \mathcal{G} \quad (12) \quad 15/38$$

Computation of the neutrino masses

$$M_\nu = \begin{pmatrix} g_\Psi^1 & g_F^1 & 0 \\ g_\Psi^2 & g_F^2 & 0 \\ g_\Psi^3 & g_F^3 & 0 \end{pmatrix} \begin{pmatrix} M_{11} & M_{12} & 0 \\ M_{21} & M_{22} & 0 \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} g_\Psi^1 & g_\Psi^2 & g_\Psi^3 \\ g_F^1 & g_F^2 & g_F^3 \\ 0 & 0 & 0 \end{pmatrix} \quad (13)$$

Parameter	Interval in [GeV]
Δm_{12}^2	$[7.0; 7.84] \cdot 10^{-23}$
m_{ν_2}	$[8.367; 8.854] \cdot 10^{-12}$
Δm_{13}^2	$[2.47; 2.57] \cdot 10^{-21}$
m_{ν_3}	$[4.96; 5.07] \cdot 10^{-11}$

Parameter	Interval in degrees
θ_{12}	[31.90; 34.98]
θ_{13}	[8.33; 8.81]
θ_{23}	[46.8; 51.6]
δ_{CP}	[143; 251]

Neutrino masses and mixing parameters extracted from global fits of experimental neutrino data [NuFit2020](#).

The intervals are restrictive → difficult from random couplings to obtain the experimental values

Casas Ibarra parametrization

[hep-ph/0103065]

From this equation :

$$\mathcal{M}_\nu = \mathcal{G}^t M_L \mathcal{G}$$

we can isolate the \mathcal{G} matrix :

Casas Ibarra parametrization

$$\mathcal{G} = \underbrace{U_L D_M^{-1/2}}_{(14)} R \underbrace{D_\nu^{1/2} V_{PMNS}^*}_{(14)}$$

D_ν is the diagonal matrix which contains the neutrino masses.
Thanks to this parametrization, the couplings g_Ψ and g_F are a function of the neutrino masses.

The numerical strategy

The numerical strategy

- *SARAH* [[arXiv:1309.7223](#)] → a *Mathematica* package to code our model
- *SPheno* [[arXiv:1104.1573](#)] → to generate the model spectrum and the two-body decays
- *micrOMEGAS* [[arXiv:1801.0350](#)] → code to compute the relic density and the direct detection within our model
- We used a Markov Chain Monte Carlo (MCMC) technique to efficiently scan the parameter space

Constraints

Observable	Interval
m_H	125.1 ± 3.0 GeV
$\text{BR}(\mu^- \rightarrow e^- \gamma)$	$< 4.2 \cdot 10^{-13}$
$\text{BR}(\tau^- \rightarrow e^- \gamma)$	$< 3.3 \cdot 10^{-8}$
$\text{BR}(\tau^- \rightarrow \mu^- \gamma)$	$< 4.4 \cdot 10^{-8}$
$\text{BR}(\mu^- \rightarrow e^- e^+ e^-)$	$< 1.0 \cdot 10^{-12}$
$\text{BR}(\tau^- \rightarrow e^- e^+ e^-)$	$< 2.7 \cdot 10^{-8}$
$\text{BR}(\tau^- \rightarrow \mu^- \mu^+ \mu^-)$	$< 2.1 \cdot 10^{-8}$
$\text{BR}(\tau^- \rightarrow \mu^+ e^- e^-)$	$< 1.5 \cdot 10^{-8}$
$\text{BR}(\tau^- \rightarrow \mu^- e^+ e^-)$	$< 2.1 \cdot 10^{-8}$
$\text{BR}(\tau^- \rightarrow e^+ \mu^- \mu^-)$	$< 1.7 \cdot 10^{-8}$
$\text{BR}(\tau^- \rightarrow e^- \mu^+ \mu^-)$	$< 2.7 \cdot 10^{-8}$
$\text{CR}_{\mu \rightarrow e}(\text{Ti})$	$< 4.3 \cdot 10^{-12}$
$\text{CR}_{\mu \rightarrow e}(\text{Pb})$	$< 4.6 \cdot 10^{-11}$
$\text{CR}_{\mu \rightarrow e}(\text{Au})$	$< 7.0 \cdot 10^{-13}$

$\text{BR}(Z^0 \rightarrow e^\pm \mu^\mp)$	$< 7.5 \cdot 10^{-7}$
$\text{BR}(Z^0 \rightarrow e^\pm \tau^\mp)$	$< 9.8 \cdot 10^{-6}$
$\text{BR}(Z^0 \rightarrow \mu^\pm \tau^\mp)$	$< 1.2 \cdot 10^{-5}$
$\text{BR}(\tau^- \rightarrow e^- \pi^0)$	$< 8.0 \cdot 10^{-8}$
$\text{BR}(\tau^- \rightarrow \mu^- \pi^0)$	$< 1.1 \cdot 10^{-7}$
$\text{BR}(\tau^- \rightarrow e^- \eta)$	$< 9.3 \cdot 10^{-8}$
$\text{BR}(\tau^- \rightarrow e^- \eta')$	$< 1.6 \cdot 10^{-7}$
$\text{BR}(\tau^- \rightarrow \mu^- \eta)$	$< 6.5 \cdot 10^{-8}$
$\text{BR}(\tau^- \rightarrow \mu^- \eta')$	$< 1.3 \cdot 10^{-7}$
$\Omega_{\text{CDM}} h^2$	0.1198 ± 0.0042
Direct detection	XENON1T

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Results on dark matter

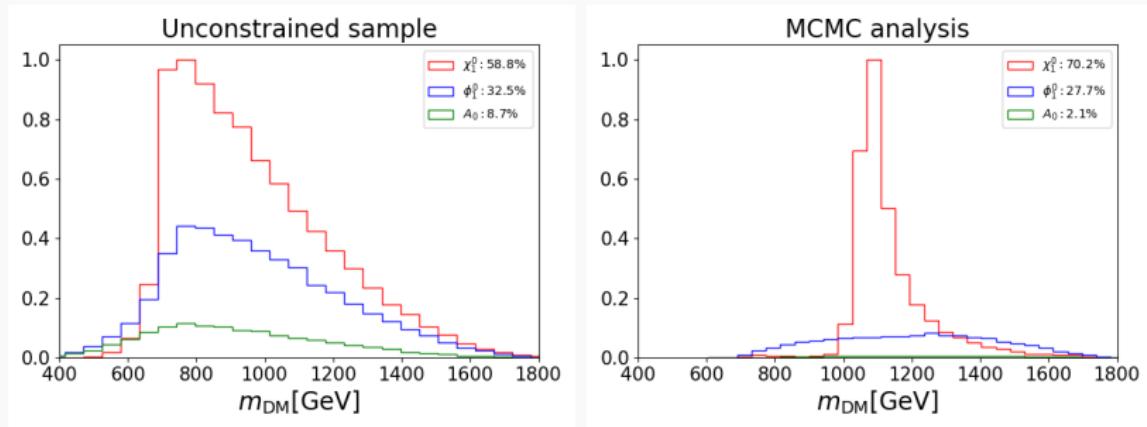


Figure: Histogram of the dark matter mass in a scan without constraints (left), and in the MCMC scan (right).

Dark matter (co-)annihilation

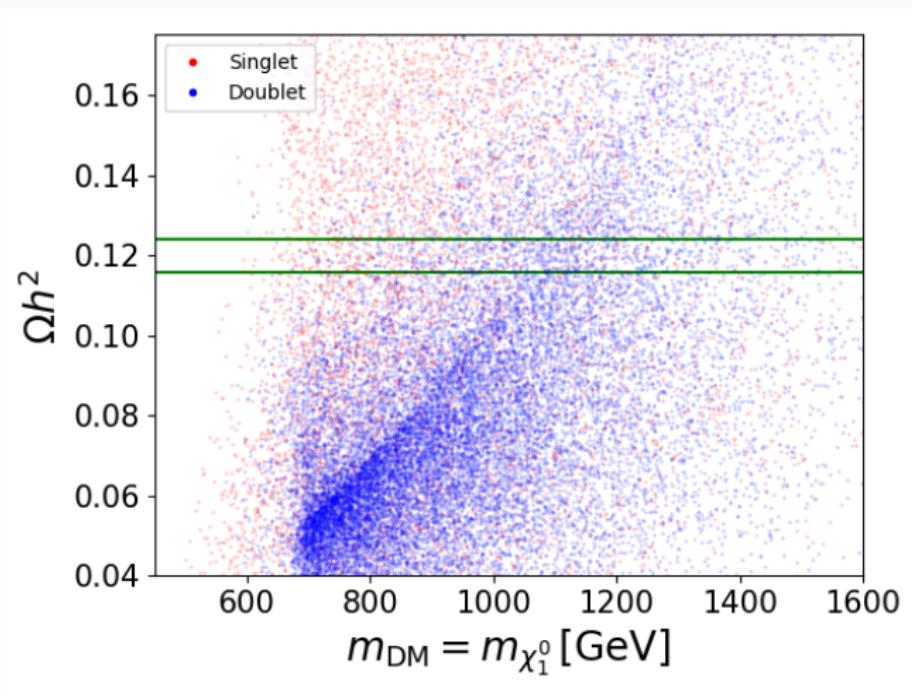


Figure: The points are from a scan without constraints, and they were selected in order to have a fermionic DM.

Dark matter (co-)annihilation

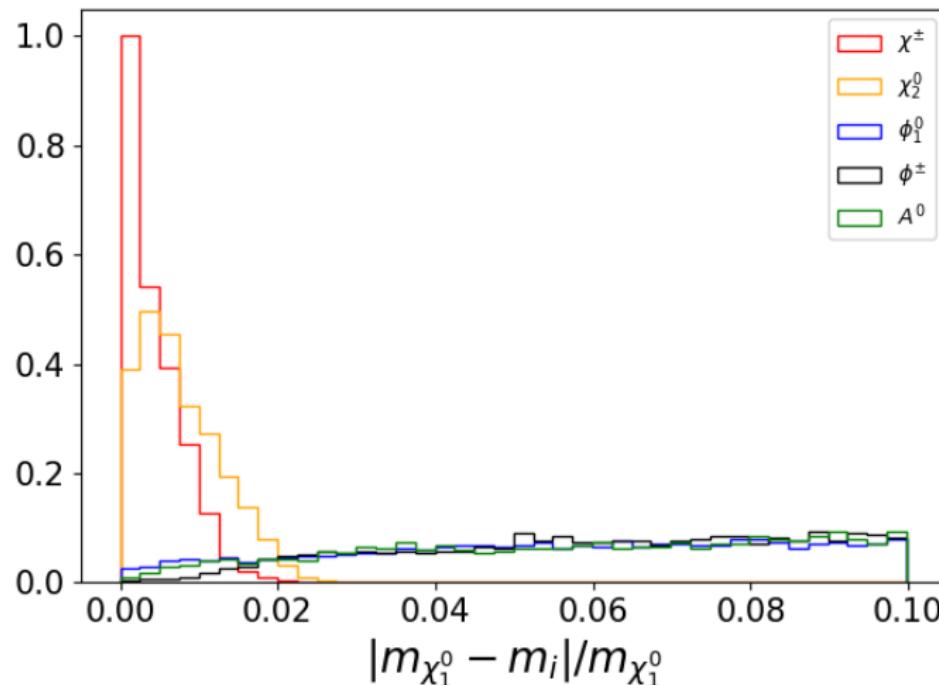


Figure: Coannihilation processes in the case of a fermionic DM.

Dark matter (co-)annihilation

The most important coannihilation processes for a fermionic DM χ_1^0 :

- $\chi_1^0 \chi_2^0 \rightarrow q_i \bar{q}_i$
 - $\chi_1^0 \chi^\pm \rightarrow d_i \bar{u}_i$
 - $\chi^\pm \chi^\mp \rightarrow q_i \bar{q}_i$

Dark matter (co-)annihilation

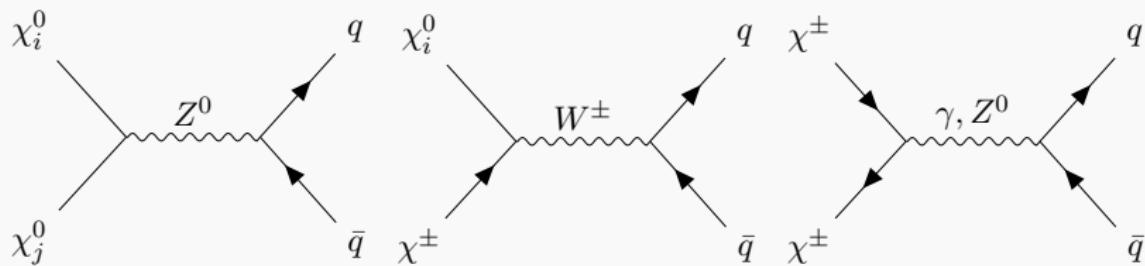


Figure: Dominant co-annihilation processes for the case of doublet-dominated fermionic dark matter. The indices $i, j = 1, 2$ run over the different neutral fermion states involved in the co-annihilation.

Without co-annihilation, the relic density would be higher.

Direct Detection

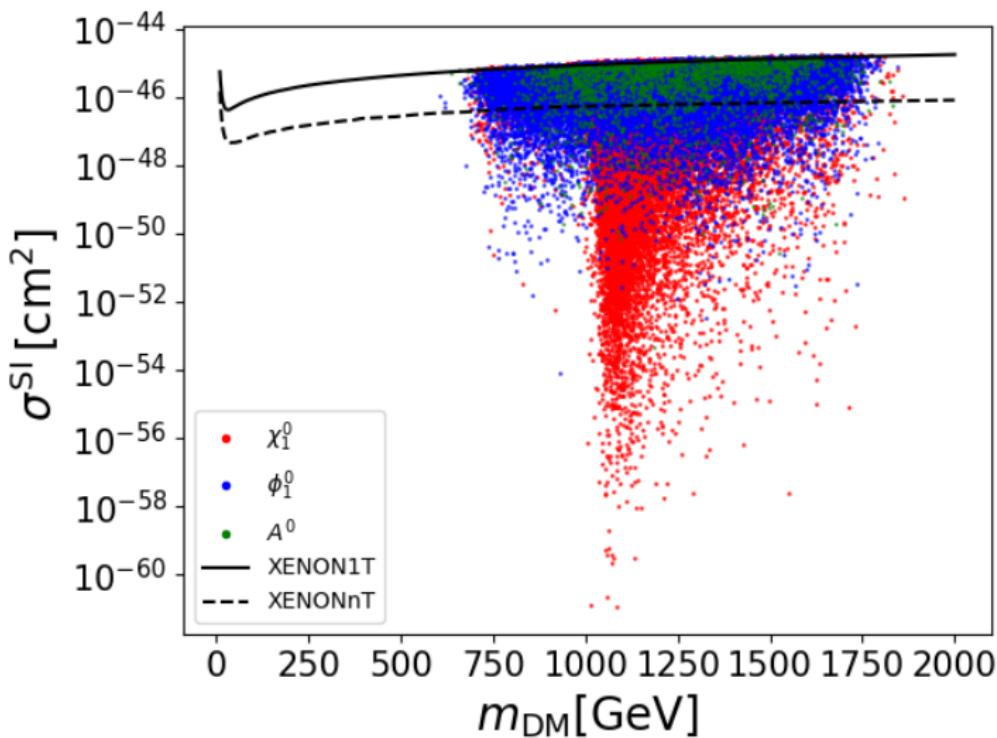


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Summary

- The SM was extended by two scalars (doublet and singlet) and two fermions (doublet and singlet).
- The T1-2A model provides two-non-zero neutrino masses and a viable candidate for DM. Large DM phenomenology : scalar, pseudo-scalar or fermionic.
- This model emphasizes a fermionic DM with a predictive mass range [1,1.2] TeV.
- The model survives to the projection of the XENONnT limit.

Outlooks

- Extensive study of the T1-2A model for leptogenesis to explain the matter-antimatter asymmetry.
 - Collider signatures for the long lived particles : 3-body decay of χ^+ , and LFV signature $pp \rightarrow l\bar{l} E_T$.

Thank you

Thank you for your attention !

Back up MCMC

$$\mathcal{L}_n \equiv \mathcal{L}(\vec{\theta}_n, \vec{O}) = \prod_i \mathcal{L}_i(\vec{\theta}_n, O_i). \quad (15)$$

$$\ln \mathcal{L}_i(\vec{\theta}_n, O_i) = \frac{-(O_i(\vec{\theta}_n) - O_i^{\text{exp}})^2}{2\sigma_i^2}, \quad (16)$$

$$p = \mathcal{L}^{n+1}/\mathcal{L}^n. \quad (17)$$

Back up Casas Ibarra parametrization

$$M_{11} = \sum_{k,n} f_{kn} (U_F^\dagger)_{3k}^2 (U_S^\dagger)_{1n}^2, \quad (18)$$

$$M_{12} = \frac{1}{\sqrt{2}} \sum_{k,n} f_{kn} (U_F^\dagger)_{1k} (U_F^\dagger)_{3k} (U_S^\dagger)_{1n} (U_S^\dagger)_{2n}, \quad (19)$$

$$M_{22} = \frac{1}{2} \sum_{k,n} f_{kn} (U_F^\dagger)_{1k}^2 [(U_S^\dagger)_{2n}^2 - (U_S^\dagger)_{3n}^2], \quad (20)$$

$$f_{kn} = \frac{1}{16\pi^2} \frac{M_{\chi_k^0}}{M_{\Phi_n^0}^2 - M_{\chi_k^0}^2} \left[M_{\chi_k^0}^2 \log \left(\frac{M_{\chi_k^0}^2}{\mu^2} \right) - M_{\Phi_n^0}^2 \log \left(\frac{M_{\Phi_n^0}^2}{\mu^2} \right) \right]. \quad (21)$$

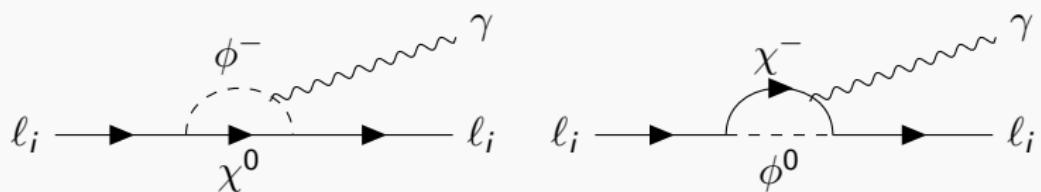
$(g - 2)$ 

Figure: Contribution to the $(g - 2)_\ell$ within the T1-2A

If the photon is emitted by the charged scalar as shown in the left diagram of the Figure 8, then the contribution to the $(g - 2)_\ell$ is negative [arXiv:2104.03691] and it cannot reach experimental data.

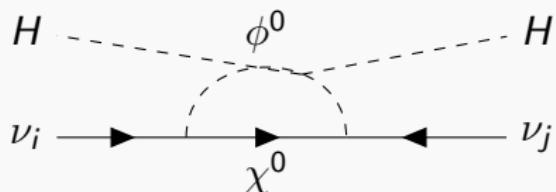
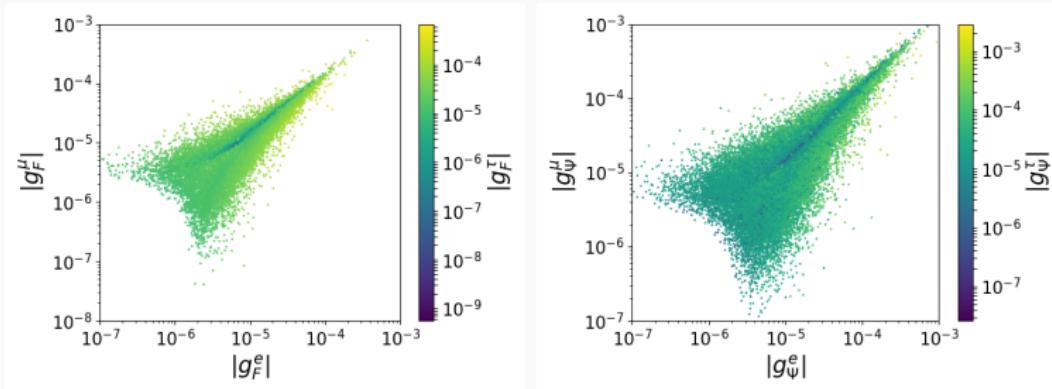
$(g - 2)$ 

Figure: Contribution to the $(g - 2)_{\ell}$ within the T1-2A

Couplings g_ψ^i and g_F^i



Back up Setup of the g couplings

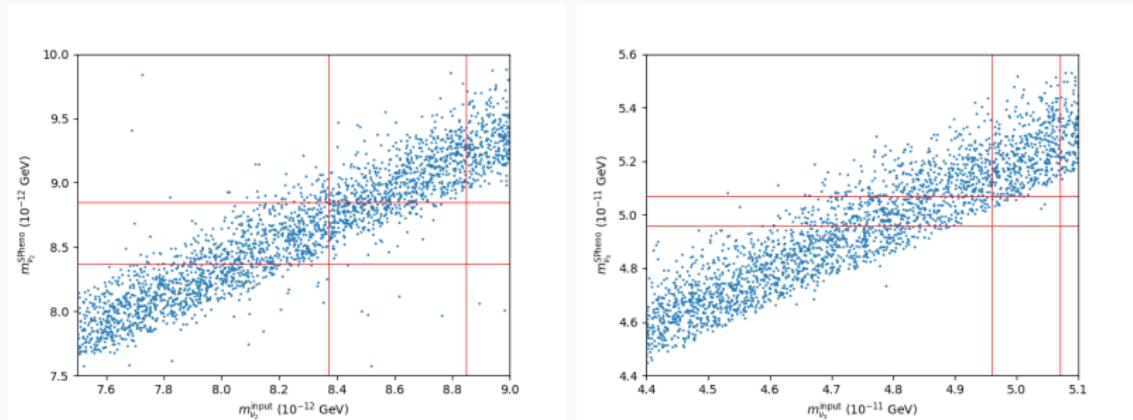
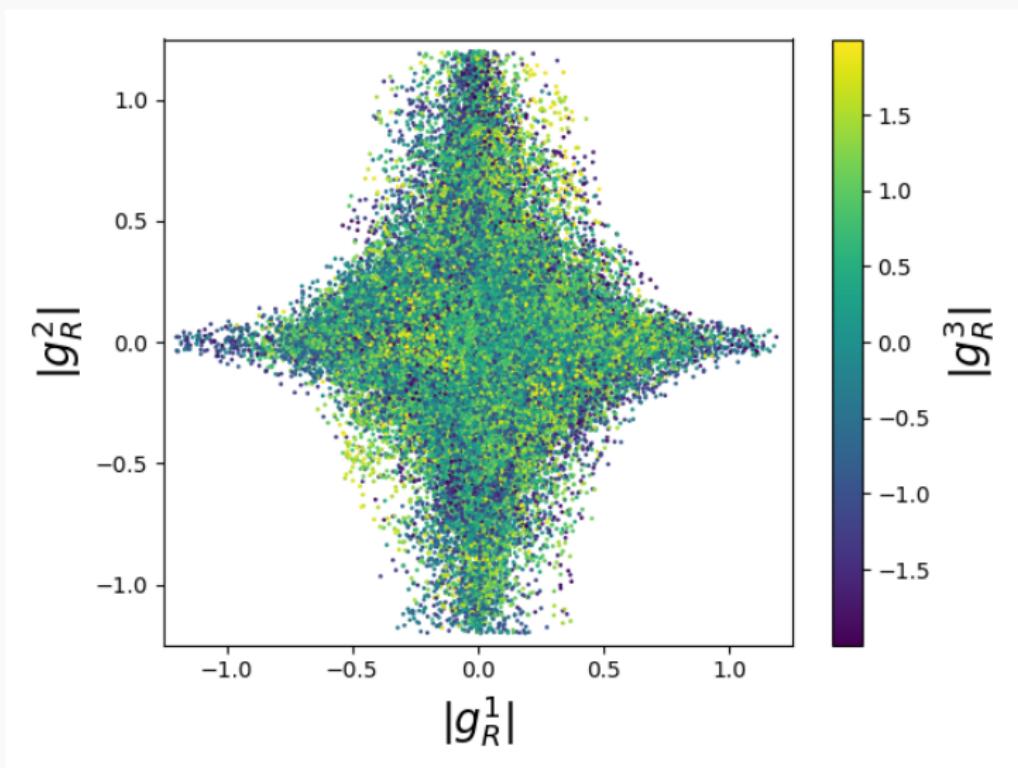


Figure: Impact of one-loop corrections to scalar and fermion masses on the neutrino masses.

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

