t-channel models: a SMEFT study of Dark Matter

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Outline

What is included:

1. t-channel models, build it.
2. SMEFT in the Warsaw basis.
3. DM computation.
4. Final plots.

What is not included (future work):

1. Phenomenology at colliders.

Motivations

Viable parameter space of t-channel models from Garny,Ibarra et al. [1] :

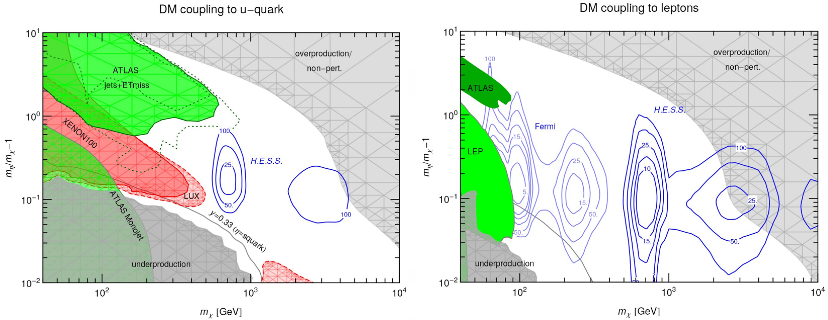


Figure: Left (Right):Collider and direct searches constraints for coupling to quark (leptons) .

Direct searches push m_χ towards bigger values $\longrightarrow$Indirect effect in EFT!

Following [2] we focus on leptophilic models (wide parameter space).

t-channel models

t-channel models: simplified, renormalizable lagrangians. A $\mathbb{Z}_2$ symmetry is included to stabilize the dark sector. The DM field and the mediator are both odd under the latter. Our choice: a fermionic dark matter χ and a scalar mediator η.

$$\mathcal{L}_{UV} = \mathcal{L}_{SM} + \mathcal{L}_{\eta} + \mathcal{L}_{\chi} + \mathcal{L}_{int}\,.$$

- S1M: $\chi \sim (\mathbf{1}, \mathbf{1}, 0), \quad \eta \sim (\mathbf{1}, \mathbf{1}, \mathbf{1})$:

$$\mathcal{L}_{int} \supset -(y)_{pr}\, \eta^p\, \bar{\chi}\, P_R\, e^r\, - (y)_{pr}\, \eta^{p\dagger}\, \bar{e}^r\, P_L \chi\, - (\lambda_3)_{pr}\, \eta^{p\dagger} \eta^r \phi^\dagger \phi\ ,$$

- S2M: $\chi \sim (\mathbf{1}, \mathbf{1}, 0), \quad \eta \sim (\mathbf{1}, \mathbf{2}, \mathbf{1})$:

$$\mathcal{L}_{int} \supset -\,(y)_{pr}\, \bar{\chi} P_L\, (\ell_p\, i\sigma_2 \eta_r)\, - (y)_{pr}\, (\eta_p^\dagger\, i\sigma_2 \bar{\ell}_r)\, P_R \chi\, - (\lambda_3)_{pr}\, (\eta_p^\dagger\, \eta_r)(\phi^\dagger\, \phi)\,.$$

Other free parameters: $m_\chi\,, \quad m_\eta\,$, s.t. $\quad \delta m = \frac{m_\eta - m_\chi}{m_\chi}\,, \ (0 < \delta m < 1)\,.$

Flavor

η is a triplet in flavor space: $G_{flavor} = U(3)^5 \otimes U(3)^{(\eta)}$. To reproduce a minimal amount of flavor violation we assume diagonal and universal coupling matrices [3]:

$$y \to (y)_{pr} = y\,\delta_{pr}\,, \quad \lambda_3 \to (\lambda_3)_{pr} = \lambda_3\delta_{pr}\,,$$

Coherent with the flavor assumption in SMEFT: $G_{flavor}^{(SMEFT)} = U(3)^{(5)}$.

- S1M: $\chi \sim (\mathbf{1},\mathbf{1},0), \quad \eta \sim (\mathbf{1},\mathbf{1},\mathbf{1})$:

$$\mathcal{L}_{int} \supset -y\,\delta_{pr}\;\eta^p\,\bar{\chi}\,P_R\,e^r\; - y\,\delta_{pr}\;\eta^{p\dagger}\,\bar{e^r}\,P_L\chi\; - \lambda_3\,\delta_{pr}\,\eta^{p\dagger}\eta^r\phi^\dagger\phi\;,$$

- S2M: $\chi \sim (\mathbf{1},\mathbf{1},0), \quad \eta \sim (\mathbf{1},\mathbf{2},\mathbf{1})$:

$$\mathcal{L}_{int} \supset -\,y\,\delta_{pr}\,\bar{\chi}P_L\,(\ell_p\,i\sigma_2\eta_r)\; - y\,\delta_{pr}\,(\eta_p^\dagger\,i\sigma_2\bar{\ell}_r)\,P_R\chi$$
$$-\,\lambda_3\,\delta_{pr}\,(\eta_p^\dagger\,\eta_r)(\phi^\dagger\,\phi)\,.$$

SMEFT

Take the low-energy limit in the SMEFT framework: $\mathcal{L}_{SMEFT} \to \mathcal{L}_{Warsaw}$.

$$\mathcal{L} = \mathcal{L}^{(4)} + \mathcal{L}^{(6)} + \ldots = \sum_d \sum_i \frac{C_i^{(d)}}{\Lambda^{d-4}} O_i^{(d)}, \quad C_i^{(d)} = \sum_{l \geq 1} \frac{C_i^{(d)}}{(4\pi)^{2l}}$$

The model $\mathbb{Z}_2$ symmetry induces **one-loop generated WC**.
Automation through: Matchete package [4].

MATCHETE v0.2.0

by Javier Fuentes-Martín, Matthias König, Julie Pagès, Anders Eller Thomsen, and Felix Wilsch
Reference: arXiv:2212.04510
Website: https://gitlab.com/matchete/matchete

Carry out low-E limit of our model.

Disclaimer: currently Matchete does not map automatically the effective lagrangian in the Warsaw basis, a reduction by hand was required applying carefully:

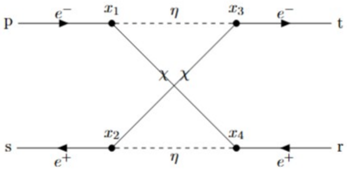
- Equations of motions ($C_{H\Box}$).
- Fiertz identities either in Lorentz space and internal spaces i.e. $SU(N)$ (C_{ee}, C_{ll}).

Focus: C_{ee}

Non-trivial mapping to Warsaw in S1M model (analogous procedure in S2M) .
For $\chi^C = \chi$:

$$\tilde{C}_{ee}\tilde{\mathcal{O}}_{e\,e} = \frac{1}{(4\pi)^2 m_\eta^2}\left(-\frac{g_1^4}{20} + \frac{y^4}{4}\mathcal{F}_1\left(\frac{m_\chi}{m_\eta}\right) - \frac{g_1^2 y^2}{6}\mathcal{F}_2\left(\frac{m_\chi}{m_\eta}\right)\right)\underbrace{\delta^{ps}\delta^{rt}\left(\bar{e}^s\gamma_\mu P_R e^p\right)\left(\bar{e}^t\gamma^\mu P_R e^r\right)}_{C_{ee}}$$

$$+\frac{y^4\delta^{ps}\delta^{rt}}{2(4\pi)^2 m_\eta^2}\mathcal{F}_3\left(\frac{m_\chi}{m_\eta}\right)\left(\bar{e}^s C P_L \bar{e}^{tT}\right)\left(e^{rT} C P_R e^p\right)$$



For $\chi^C \neq \chi$ the term proportional to $\mathcal{F}_3$ vanishes:

$$C_{ee}\mathcal{O}_{e\,e} = \frac{1}{(4\pi)^2 m_\eta^2}\left(-\frac{g_1^4}{20} + \frac{y^4}{4}\mathcal{F}_1\left(\frac{m_\chi}{m_\eta}\right) - \frac{g_1^2 y^2}{6}\mathcal{F}_2\left(\frac{m_\chi}{m_\eta}\right)\right)\delta^{ps}\delta^{rt}\left(\bar{e}^s\gamma_\mu P_R e^p\right)\left(\bar{e}^t\gamma^\mu P_R e^r\right) .$$

Global fits

Note: a negligible mass splitting δm between χ and η allows us to perform only 1-matching procedure (single NP scale). We require that the values of our WCs lie within the intervals defined by Bartocci et al. [5].

A global analysis of the SMEFT under the minimal MFV assumption

Riccardo Bartocci, Anke Biekötter, Tobias Hurth

PRISMA+ Cluster of Excellence & Institute of Physics (THEP) & Mainz Institute for Theoretical Physics, Johannes Gutenberg University, D-55099 Mainz, Germany

Adopt intervals including NLO+RGE effects.

Constraints are valid at a fixed scale $\Lambda = 4$TeV, but our NP scale varies.

$$C(\mu) = U(\mu, \Lambda) C(\Lambda) \,, \quad \mu < \Lambda \,, \quad \mu \in [0.5, 4]\text{TeV} \,.$$

RGE in SMEFT: We make use of `DSixTools` software [6] .

Negligible RGE effects: color singlet model has RGE effects mostly the Higgs sector, sizeable effect only for diagonal entries in Higgs sector(C_H, C_{HB}).

DM

For the dark matter freeze-out, $\delta m < 1$ implies that we need to take into account the co-annihilating regime [7].
Effective cross section for $\chi^C = \chi$ DM reads:

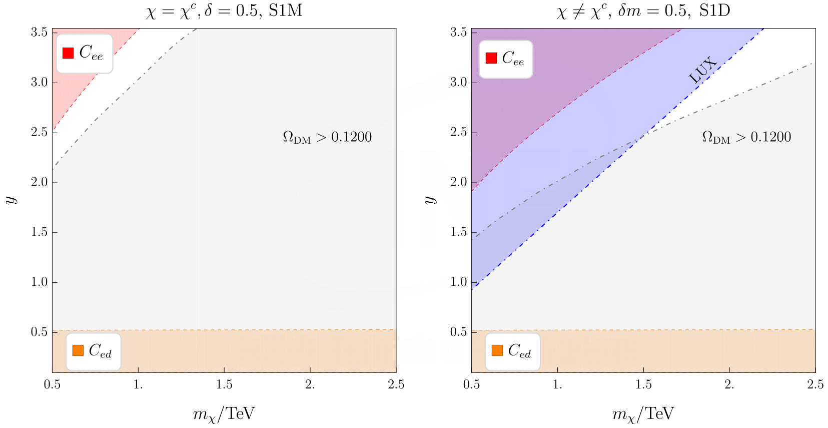
$$\sigma_{\rm eff} v_{\rm rel} = \Bigg[\sigma_{\chi\chi} v_{\rm rel} + \frac{4 g_\eta}{g_\chi} e^{-\delta m \frac{m_\chi}{T}} (1+\delta m)^{\frac{3}{2}} \sigma_{\chi\eta^\dagger} v_{\rm rel} + \frac{2 g_\eta^2}{g_\chi^2} e^{-2\delta m \frac{m_\chi}{T}} (1+\delta m)^3 \left(\sigma_{\eta\eta} v_{\rm rel} + \sigma_{\eta\eta^\dagger} v_{\rm rel} \right) \Bigg] \frac{1}{\left[1 + 2\frac{g_\eta}{g_\chi} e^{-\delta m \frac{m_\chi}{T}} (1+\delta m)^{\frac{3}{2}}\right]^2}$$

SMEFT: $\delta m < 1$ allows to integrate out η, χ simultaneously. Larger splitting breaks SMEFT expansion.

Dark Matter: small δm requires co-annihilation channel to be considered, larger δm simplify $\sigma_{eff} v_{\rm rel}$.

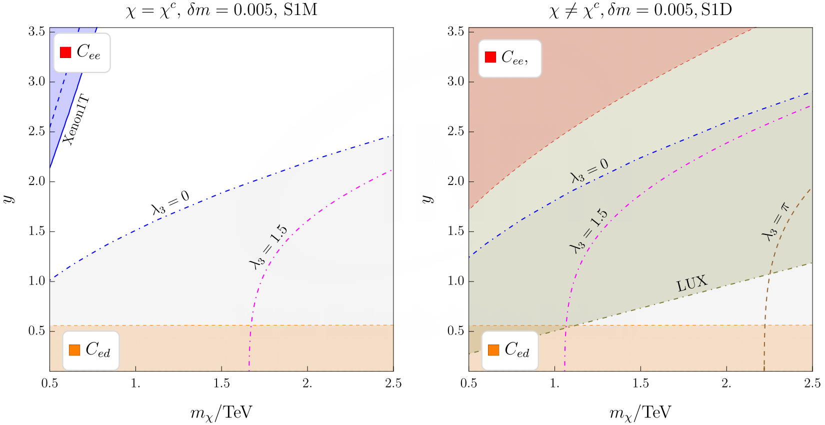
Note that $\chi^C \neq \chi$ does not allow $\sigma_{\eta\eta}$.

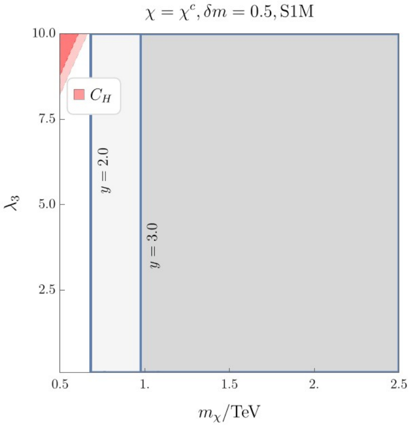
Plots S1 $\delta m = 0.5$

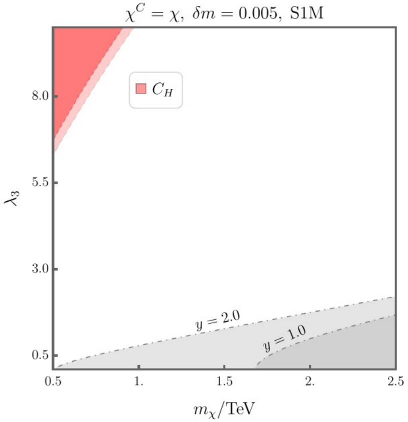


- Majorana DM viable region at low m_χ while Dirac DM allows for higher m_χ.

Plots S1 $\delta m = 0.005$




$\chi = \chi^c, \delta m = 0.5, \mathrm{S1M}$
10.0
7.5
5.0
2.5
λ_3
C_H
$y = 2.0$
$y = 3.0$
0.5
1.
1.5
2.
2.5
m_χ/TeV


$\chi^C = \chi,\ \delta m = 0.005,\ \mathrm{S1M}$
8.0
5.5
3.0
0.5
λ_3
C_H
$y = 2.0$
$y = 1.0$
0.5
1.
1.5
2.
2.5
m_χ/TeV

Conclusions & future directions:

Main points of this project:

1. The parameter space for t-channel leptophilic DM models has been analysed though complementary constraints (low-energy experiments, Direct Searches, Cosmology).
2. A complete SMEFT basis allows us not to overcount possible NP signals.
3. In the precision era the inclusion of RGE is necessary as it modify WC by $\mathcal{O}(10\%)$. Further research is needed to include errors from global fits.

Possible new directions:

1. study other t-channel models (colored, richer flavor structures etc.).
2. A phenomenological study in SMEFT is desirable.

Thank you!

Backup 1

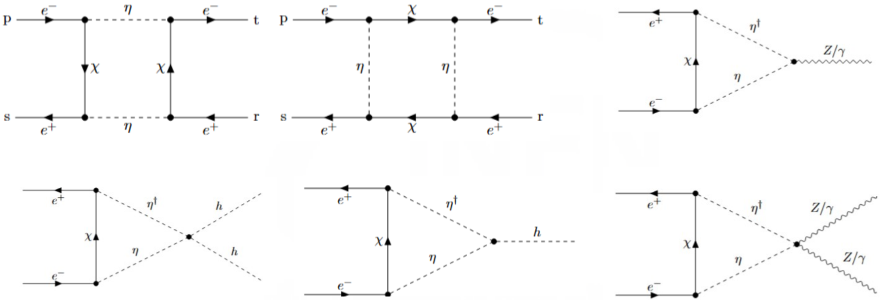
Explicitly writing down the model lagrangian:

$$\mathcal{L}_\chi = \frac{1}{2}\bar{\chi}(i\gamma^\mu\partial_\mu - m_\chi)\chi \,,$$
$$\mathcal{L}_\eta = (D_\mu\eta)^\dagger(D_\mu\eta) - m_\eta^2\eta^\dagger\eta - \lambda_2(\eta^\dagger\eta)^2 \,,$$
$$D_\mu\eta = (\partial_\mu - ig_1 Y_\eta B_\mu - ig_2 W_\mu^a\tau^a)\eta\,.$$

The complete interaction lagrangian for S2M reads (no flavor index):

$$\mathcal{L}_{int} = -y\,\bar{\chi}P_L\,(\ell\, i\sigma_2\eta) - y\,(\eta^\dagger\, i\sigma_2\bar{\ell})\,P_R\chi + \\ - \lambda_3(\eta^\dagger\eta)(\phi^\dagger\phi) - \lambda_4(\eta^\dagger\phi)(\phi^\dagger\eta) - \frac{\lambda_5}{2}\left[(\phi^\dagger\eta)^2 + (\eta^\dagger\phi)^2\right] \,.$$

Backup 2



Some UV diagrams from model S1M

Backup 3

- $\chi\chi \to e^+e^-$ for Majorana dark matter (leading p-wave)

$$\sigma v_{\rm rel} = y^4 \frac{m_\chi^2(m_\chi^4 + m_\eta^4)}{48\pi(m_\chi + m_\eta)^4} v_{\rm rel}^2$$

- s-wave contribution is helicity suppressed, $(m_e/m_\chi)^2 \simeq 10^{-5}$

- $\chi\bar{\chi} \to e^+e^-$ for Dirac dark matter (leading s-wave)

$$\sigma v_{\rm rel} = y^4 \frac{m_\chi^2}{128\pi(m_\chi^2 + m_\eta^2)^2}$$

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