Recent News from Flavored Dark Matter

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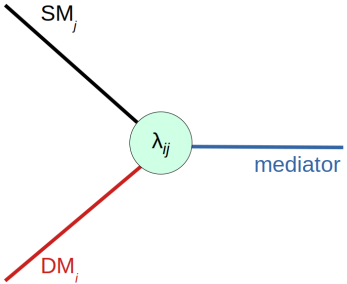
Particle Physics Phenomenology after the Higgs Discovery

Particle Physics Phenomenology after the Higgs Discovery – MITP, 16 October 2025

What is flavored dark matter?

Basic assumptions

- dark matter comes in three generations
- dark flavor triplet couples to SM flavor triplet via new mediator field
- new flavor-violating coupling matrix λ



The flavored DM model space

Model-building choices

- the nature of DM
  - scalar or fermion
  - real or complex representation

  ➢ 4 options
- the SM fermion portal
  - quarks or leptons
  - left- or right-handed...

  ➢ 5 options
- the flavor structure
  - Minimal Flavor Violation (MFV) or beyond

➢ **vast flavored DM model space!**

- not all options of DM nature and SM fermion have been explored
- many early studies were restricted to MFV

Minimal step beyond MFV

Dark Minimal Flavor Violation (DMFV)

- dark flavor symmetry $U(3)$ or $O(3)$
- broken only by new coupling matrix λ

Agrawal, MB, Gemmler (2014)

More on Dark Minimal Flavor Violation (DMFV)

DMFV principle AGRAWAL, MB, GEMMLER (2014)

- extend concept of Minimal Flavor Violation, where all flavor violation originates from SM Yukawas
- DMFV: one new source of flavor violation – coupling matrix λ
- other flavorful interactions can be expanded in powers of λ

$$\text{e.g.} \quad M_{\text{Dirac DM}} = m_{\text{DM}} \left[\mathbb{1} + \eta \lambda^\dagger \lambda + \mathcal{O}(\lambda^4) \right]$$

➢ reduced number of new physical parameters, yet interesting non-MFV phenomenology

Previously studied DMFV models

	u_R	d_R	q_L	e_R	ℓ_L
Real scalar DM	✗	✗	✗	✗	✗
Complex scalar DM	✗	✗	✗	[Acaroglu, Agrawal, Blanke 2022] [Acaroglu, Blanke, Tabet 2022] [Acaroglu, Agrawal, Blanke 2023]	[Acaroglu, Agrawal, Blanke 2022]
Dirac fermion DM	[Blanke, Kast 2017] [Jubb, Kirk, Lenz 2017] [Blanke et al. 2021]	[Agrawal, Blanke, Gemmler 2022] [Bensalem, Stolarski 2022]	[Blanke, Das, Kast 2018] [Blanke et al. 2021]	[Chen, Huang, Takhistov 2016]	✗
Majorana fermion DM	[Acaroglu, Blanke 2022] [Acaroglu, **LR** et al. 2024]	✗	✗	✗	✗

slide stolen from Lena Rathmann

Towards efficient study of the flavored DM model space

Analyzing models one-by-one "by hand" is an interesting phenomenology playground and a great exercise for PhD students, but is not very efficient!

TO DO: analyze constraints on parameter space from

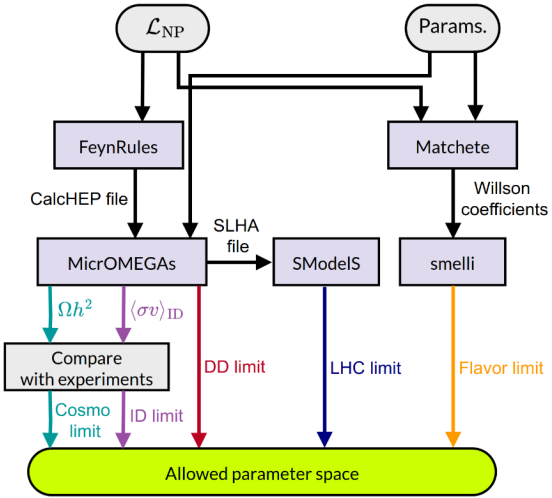
- DM relic abundance
- direct and indirect DM detection experiments
- flavor physics
- collider searches

Goal

Belfatto, MB, Heisig, Krämer, Rathmann, Wilsch – in preparation

- create a **tool-chain** that connects available tools to explore different constraints on flavored DM models in a (semi-)automatic manner
- use to efficiently identify viable parameter space and make model-specific predictions

The tool-chain setup



Tool-chain contains

- `FeynRules` implementation of all 20 models
- link to `MicrOMEGAs` via `CalcHEP`
  - relic abundance
  - direct and indirect detection
  - LHC constraints through `SModelS` interface
- matching to SMEFT with `Matchete`
  - flavor constraints from `smelli` (based on `flavio`)

Publicly available soon at

`https://github.com/lena-ra/Flavored-Dark-Matter`

Application to Majorana flavored DM

	u_R	d_R	q_L	e_R	ℓ_L
Real scalar DM	✗	✗	✗	✗	✗
Complex scalar DM	✗	✗	✗	[Acaroglu, Agrawal, Blanke 2022] [Acaroglu, Blanke, Tabet 2022] [Acaroglu, Agrawal, Blanke 2023]	[Acaroglu, Agrawal, Blanke 2022]
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Majorana fermion DM	[Acaroglu, Blanke 2022] [Acaroglu, **LR** et al. 2024]	see now! ✗	✗	see paper ✗	✗

Majorana flavored DM coupled to right-handed down quarks

The model

- dark Majorana flavor triplet $\tilde{\chi}$, scalar mediator φ
- coupling matrix λ violates flavor and CP

$$\begin{aligned}\mathcal{L} \supset & \frac{1}{2}\bar{\tilde{\chi}}(i\partial\!\!\!/ - M_{\tilde{\chi}})\tilde{\chi} + (D_\mu\varphi)^\dagger(D^\mu\varphi) - m_\varphi^2\varphi^\dagger\varphi + (\lambda_{ij}\bar{d}_i\tilde{\chi}_j\varphi + \text{h.c.}) \\ & + \lambda_{\varphi H,1}(\varphi^\dagger\varphi)(H^\dagger H) + \lambda_{\varphi\varphi}(\varphi^\dagger\varphi)^2\end{aligned}$$

- **DMFV ansatz:** DM mass matrix non-generic, spurion expansion in λ

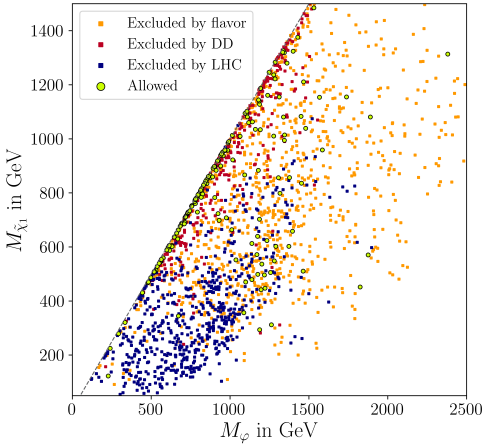
$$\tilde{M}_{\tilde{\chi}} = M_{\tilde{\chi}}\left[\mathbb{1} + \frac{\eta}{2}(\lambda^\dagger\lambda + \lambda^\intercal\lambda^*) + \mathcal{O}(\lambda^4)\right]$$

➢ mass eigenstates $\tilde{\chi}_1$ (DM), $\tilde{\chi}_2$, $\tilde{\chi}_3$

General parameter scan

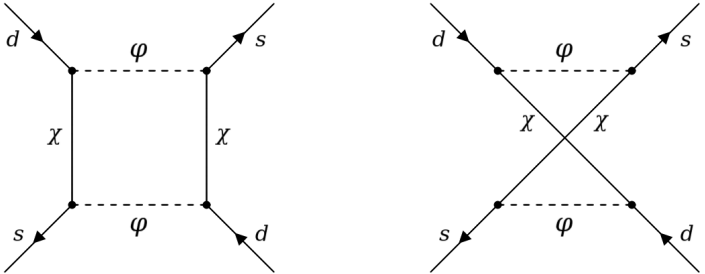
Results

- strong constraint from relic abundance, implies lower bound on $M_{\tilde{\chi}_1}$
- LHC: mediator pair-production rules out most of parameter space with $M_{\tilde{\chi}_1} \lesssim 400\,\text{GeV}$
- direct detection constraint most sensitive to near-degeneracy region
- flavor physics rules out large part of remaining parameter space
  (note: we sampled the flavor-relevant parameters with logarithmic prior!)



The issue with flavor

Strong constraints from neutral meson mixing (K^0, B_d^0, B_s^0)



- standard box diagram contribution suppressed for small off-diagonal terms in λ
- crossed box diagram governed by diagonal entries of λ ➢ hierarchy required!

A flavor structure for λ

- singular value decomposition of λ

$$\lambda = \text{quark-flavor rotation} \times \text{diagonal couplings} \times \text{dark-flavor rotation}$$

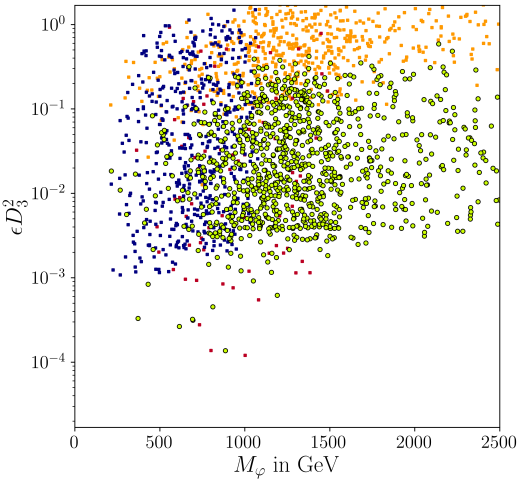
- analytic estimate suggests possible structure

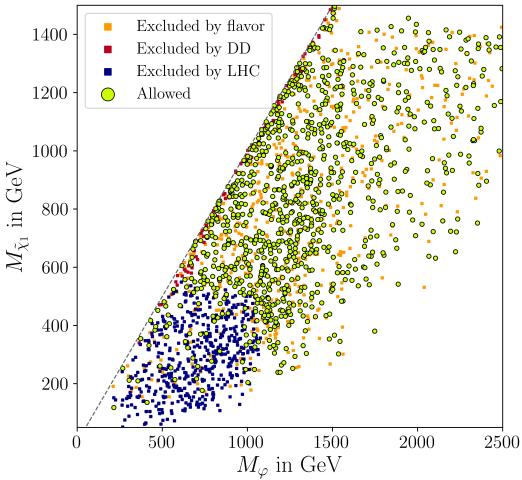
$$\lambda \propto \begin{pmatrix} 1 & \mathcal{O}(\epsilon) & \mathcal{O}(\epsilon^2) \\ \mathcal{O}(\epsilon) & 1 & \mathcal{O}(\epsilon) \\ \mathcal{O}(\epsilon^2) & \mathcal{O}(\epsilon) & 1 \end{pmatrix} \times \begin{pmatrix} \mathcal{O}(\epsilon^2) \times D_3 & & \\ & \mathcal{O}(\epsilon) \times D_3 & \\ & & D_3 \end{pmatrix} \times \begin{pmatrix} & \mathcal{O}(1) \text{ rot.} & \end{pmatrix}$$

with

$$\epsilon < 10^{-1} \frac{1}{D_3^2} \frac{M_\varphi}{1\,\text{TeV}}$$

Results of flavor-scenario scan





Conclusions and outlook

Flavored dark matter

- vast model- and parameter space already at the simplified model level which needs to be explored
- tool-chain allows for efficient determination of viable parameter space
- identification of possible flavor structures and interesting phenomenology

Publicly available soon at

`https://github.com/lena-ra/Flavored-Dark-Matter`

and on the arXiv!

Belfatto, MB, Heisig, Krämer, Rathmann, Wilsch