Towards a Comprehensive Exploration of Flavored Dark Matter Models

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credit to Lena for many of the slides!

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Particle Physics Phenomenology after the Higgs Discovery

Beyond Flavour Physics – Siegen, 23 June 2025

What is flavored dark matter?

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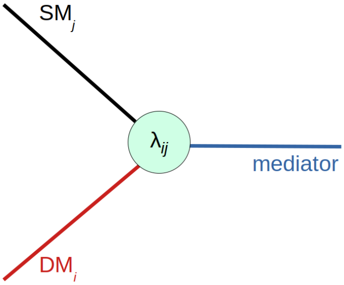
Basic assumptions

- 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 previous 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

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

- 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]	✗	✗	✗	✗

Towards efficient study of the flavored DM model space

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

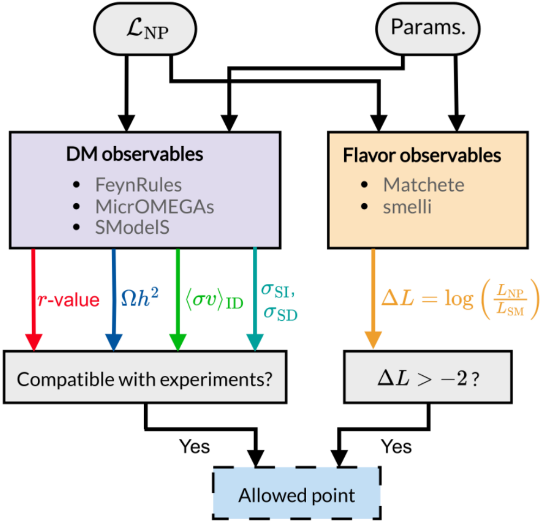
TO DO: analyse constraints on parameter space from

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

Goal

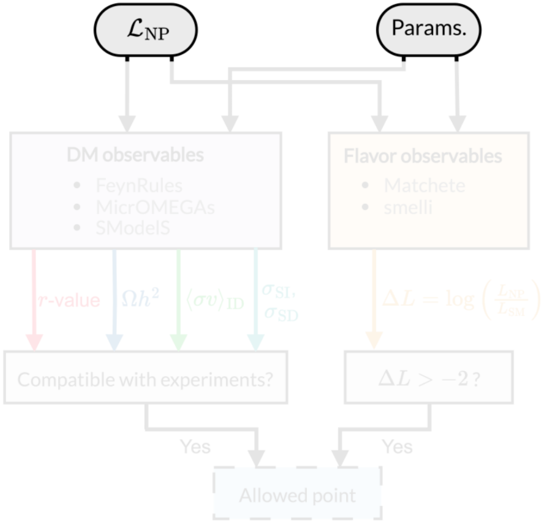
- create a **tool-chain** that connects available tools to explore different contstaints on flavored DM models in a (semi-)automatic manner
- use to efficiently identify viable parameter space and make model-specific predictions

The tool-chain setup



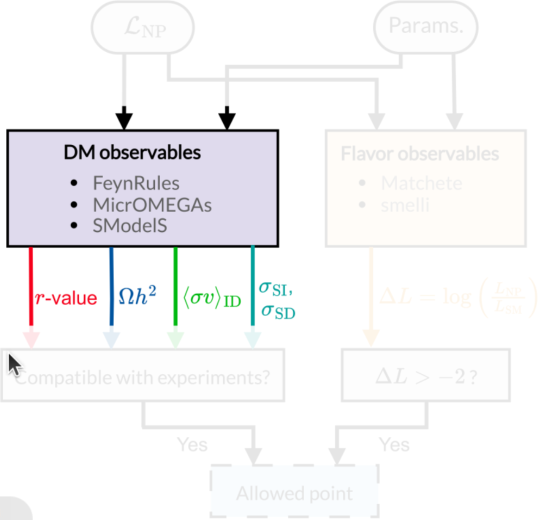
The tool-chain setup

- Lagrangian $\mathscr{L}_{\mathrm{NP}}$ describing all new physics (NP) interactions of DM model
- Values for masses M_{X_i} and M_Y
- Values for couplings to SM particles



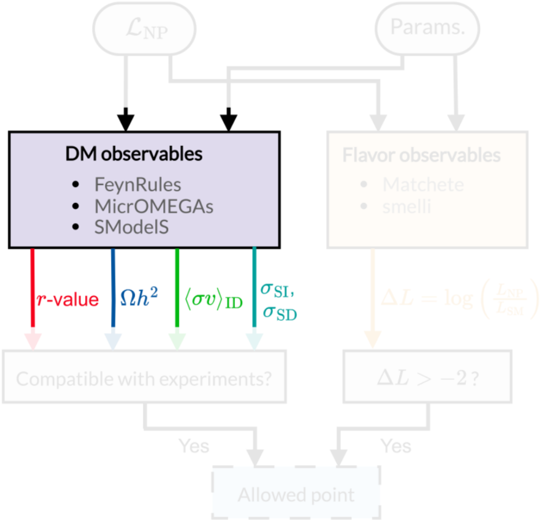
The tool-chain setup

- Implemented all models in FeynRules
- All FeynRules, CalcHEP and UFO model files available on GitHub in lena-ra/Flavored-Dark-Matter
- CalcHEP files used for implementation in MicrOMEGAs



The tool-chain setup

- MICROMEGAS computes DM properties:
  - Relic abundance Ωh^2 including coannihilation effects
  - Annihilation cross section $\langle \sigma v \rangle$ for every annihilation channel for indirect detection
  - Spin (in)dependent DM-nucleon cross section $\sigma_{\mathrm{SI/SD}}$

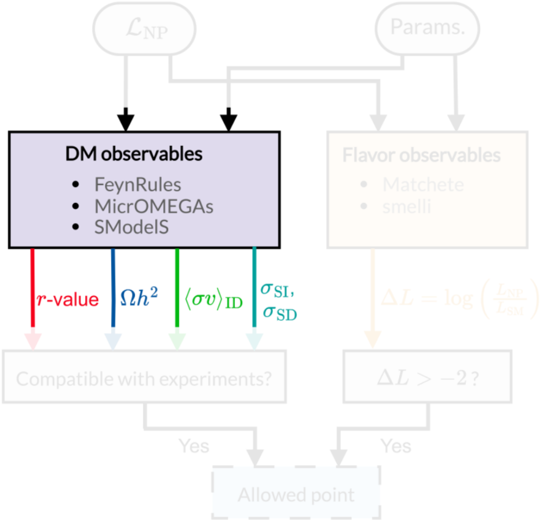


The tool-chain setup

- SModelS computes constraints from colliders by decomposing signatures of model into simplified model components
- Signatures tested against database of ATLAS and CMS searches
- Returns

$$r\text{-value} = \frac{\text{signal cross section}}{\text{experimental upper limit}}$$

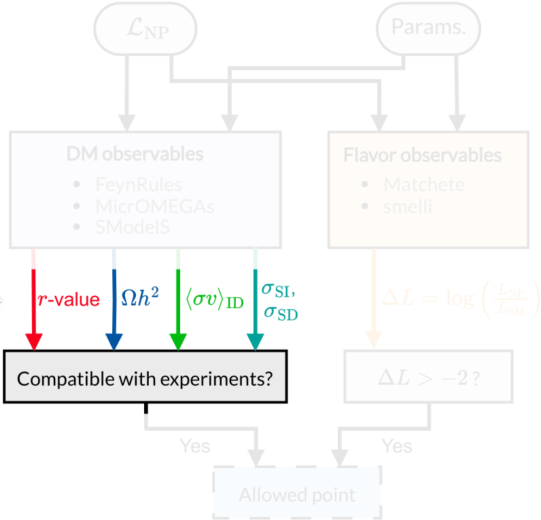
- Can identify missing topologies



The tool-chain setup

- Exclude parameter point if one of the following is true:
  - r-value ≥ 1
  - Ωh^2 not within [0.11, 0.13]
  - $\langle \sigma v \rangle_{\mathrm{ID}}$ > experimental limit from γ-ray, $\bar{p}$, e^+ and ν data, treatment of limit for mixes final states AB:

    $$\langle \sigma v \rangle_{AB} = \frac{1}{2}\left(\langle \sigma v \rangle_{AA} + \langle \sigma v \rangle_{BB}\right)$$
  - σ_{SI} or σ_{SD} > experimental limits from CRESST-III, LZ, XENON1T, DarkSide-50, PICO-60

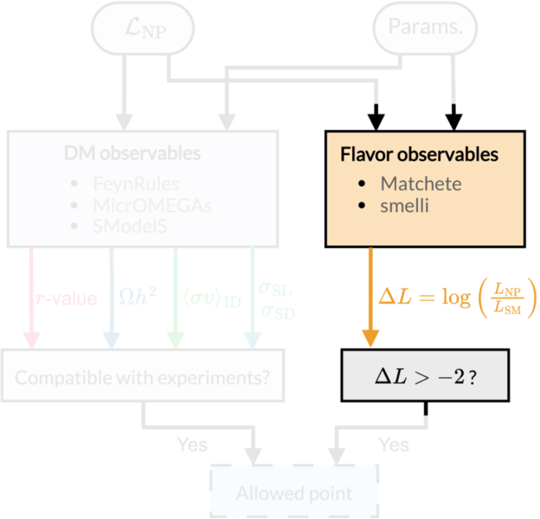


The tool-chain setup

- MATCHETE computes matching of DM model to SM Effective Field Theory
- SMELLI evolves SMEFT Wilson coefficients from high energy scale to low energy scale where flavor observables are measured
- Computes flavor observables
- Provides log-likelihood ratio

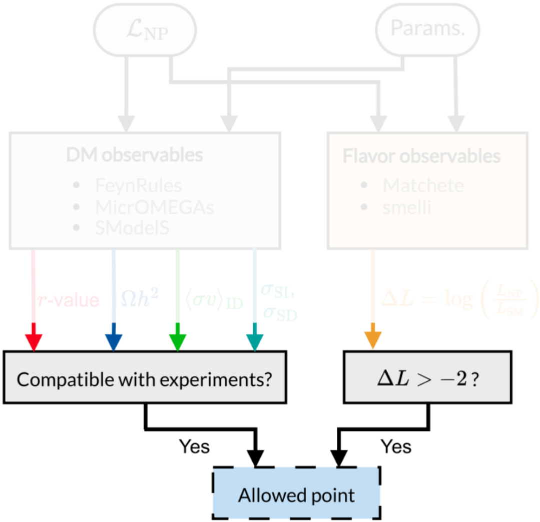
$$\Delta L = \log\left(\frac{L_{\mathrm{NP}}}{L_{\mathrm{SM}}}\right)$$

- Keep point if $\Delta L > -2$



The tool-chain setup

- Perform random parameter scan
- Keep point if not excluded by any observable (first check DM observables, then flavor observables)
- Obtain viable parameter space for any of the flavored DM models



Application: Majorana DM coupled to right-handed leptons

	u_R	d_R	q_L	e_R	ℓ_L
Real scalar DM	✗	✗	✗	✗	✗
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The model

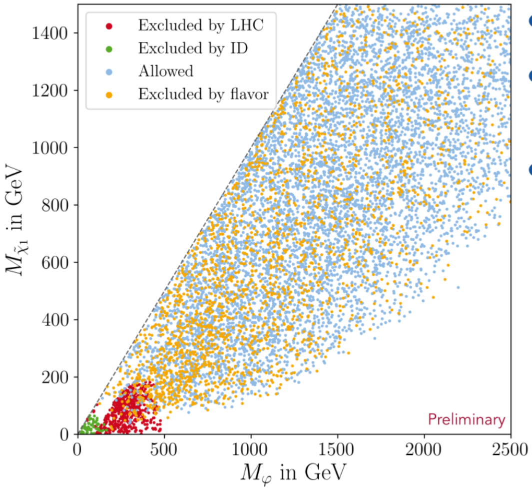
- Dark matter flavor triplet $\tilde{\chi}$, mediator φ
- New physics contribution with flavour and CP violating interaction:

$$\mathcal{L}_{\mathrm{NP}} \supset \frac{1}{2}\bar{\tilde{\chi}}(i\partial\!\!\!/ - M_{\tilde{\chi}})\tilde{\chi} + (D_\mu\varphi)^\dagger(D^\mu\varphi) - m_\varphi^2\varphi^\dagger\varphi + (\lambda_{ij}\,\bar{e}_{R,i}\,\tilde{\chi}_j\,\varphi + \mathrm{h.c.})$$
$$+\lambda_{\varphi\varphi}(\varphi^\dagger\varphi)^2 + \lambda_{\varphi H}(\varphi^\dagger\varphi)(H^\dagger H)$$

- Mass matrix cannot be generic → expand mass matrix in powers of λ:

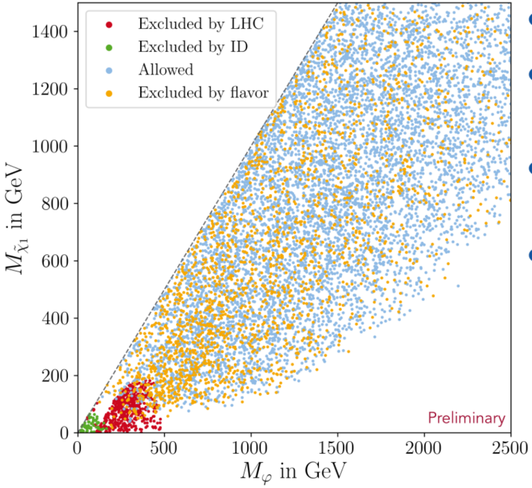
$$M_{\tilde{\chi}} = m_{\tilde{\chi}}\left[\mathbf{1} + \frac{\eta}{2}(\lambda^\dagger\lambda + \lambda^T\lambda^*) + \mathcal{O}(\lambda^4)\right] \xrightarrow{\text{Diagonalize}} M_{\tilde{\chi}}^D = \mathrm{diag}(M_{\tilde{\chi}_1}, M_{\tilde{\chi}_2}, M_{\tilde{\chi}_3})$$

Viable mass ranges

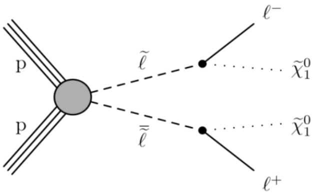


- Relic abundance most constraining
- Lower bound on DM mass because of upper limit on coupling
- ID constrains weak because of p-wave suppression of annihilation

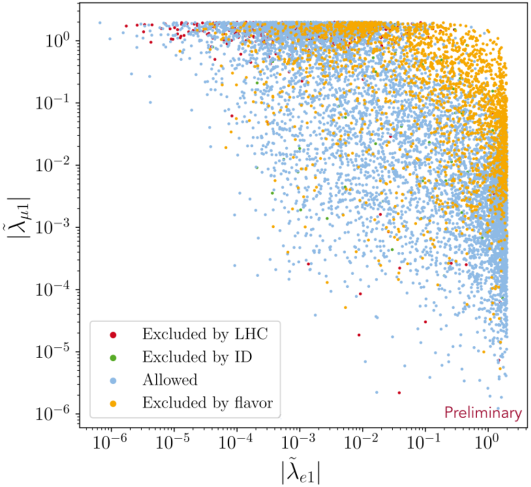
Viable mass ranges



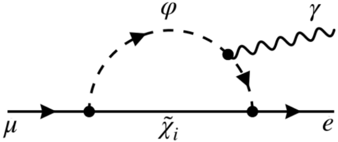
- Relic abundance most constraining
- Lower bound on DM mass because of upper limit on coupling
- ID constrains weak because of p-wave suppression of annihilation
- Drell-Yan production of mediator pair decaying into leptons + $\not{E}_T$ is dominant LHC signal



Viable coupling parameters



- Strong flavor constraints from lepton-flavor violating decays



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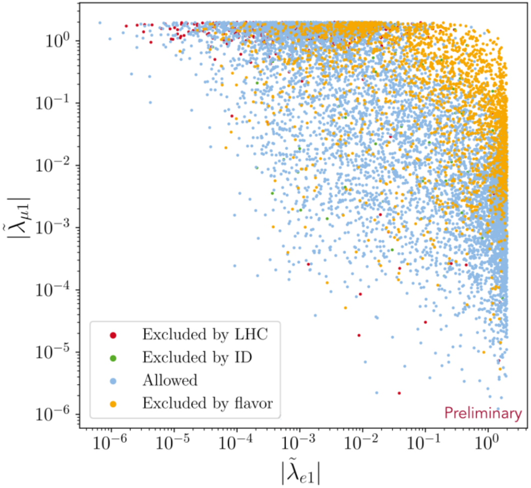

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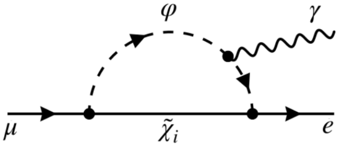
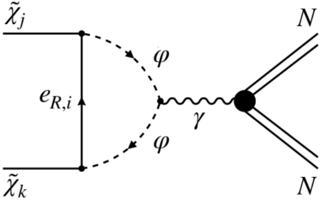


- DD constraints absent as only possible contribution is very suppressed



Current limitations of the setup

- parameter scan for concrete model may require "smart sampling" to efficiently target viable region
- relic abundance calculation currently only for canonical WIMP freeze-out, but can be extended to other scenarios available in MICROMEGAS
- indirect detection constraints on flavor-violating annihilation channels only approximated
- full one-loop contributions to direct detection not implemented in MICROMEGAS
- SMODELS database of LHC searches limited, may miss constraints if topology not exactly reproduced ➢ LHC sensitivity potentially underestimated
- EFT approach of MATCHETE, SMELLI not applicable for very light DM masses

Conclusions and outlook

- Flavored DM models have rich phenomenology but many models have not been studied
- Developed framework to study different flavored DM models including constraints from relic density, direct & indirect detection, collider and flavor observable
- Showed constraints on Majorana DM coupling to e_R
- Strongest constraints from correct relic abundance and lepton-flavor violating decays, collider and ID constraints only relevant for small DM masses
- Outlook: Study other missing models