Tasting Flavoured Majorana Dark Matter

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Outline

1. Dark Minimal Flavour Violation (DMFV)
2. Phenomenology
3. Summary and Outlook

Outline

The DMFV Framework

- new fields: DM flavour triplet χ_i and a mediator ϕ
- flavour symmetry extends to

$$U(3)_Q \times U(3)_u \times U(3)_d \times U(3)_L \times U(3)_e \times \mathcal{G}(3)_\chi \,,$$

  with $\mathcal{G}(3)_\chi$ depending on χ's particle nature
- new flavour and CP violating interaction

$$\lambda_{ij} \bar{f}_i \chi_j \phi \,,$$

  governed by coupling matrix λ

DMFV Hypothesis

λ constitutes the only new source of flavour and CP violation

Flavoured Majorana DM

Dirac fermionic DMFV models were already studied for

- right-handed down-type quarks — Agrawal, Blanke, Gemmler in [1405.6709]
- right-handed up-type quarks — Blanke, Kast in [1702.08457]
- left-handed quarks — Blanke, Das, Kast in [1711.10493]

We consider flavoured Majorana fermionic DM $\chi = (\chi_L, i\sigma_2\ \chi_L^*)^T$ coupling to right-handed up-type quarks via a scalar $(\mathbf{3},\mathbf{1})_{2/3}$ mediator ϕ:

$$\mathcal{L} = \mathcal{L}_{\mathsf{SM}} + \frac{1}{2}\left(i\bar{\chi}\partial\!\!\!/\chi - M_\chi\bar{\chi}\chi\right) - \left(\lambda_{ij}\,\bar{u}_{Ri}\chi_j\,\phi + h.c.\right) + (D_\mu\phi)^\dagger(D^\mu\phi)$$
$$- m_\phi^2\,\phi^\dagger\phi + \lambda_{H\phi}\,\phi^\dagger\phi\,H^\dagger H + \lambda_{\phi\phi}\left(\phi^\dagger\phi\right)^2 ,$$

with

$$\lambda = \mathbf{U}(\theta_{ij},\delta_{ij})\mathbf{D}(D_i)\mathbf{O}(\phi_{ij})\mathbf{d}(\gamma_i)\,.$$

Outline

LHC Constraints

Relevant LHC processes are

$$pp \to \chi_i \chi_j q_k \bar{q}_l \,, \quad pp \to \chi_i \chi_j q_k q_l \,, \quad pp \to \chi_i \chi_j \bar{q}_k \bar{q}_l \,,$$

giving rise to the signatures tops $+ \not{E}$ and $jj + \not{E}$.

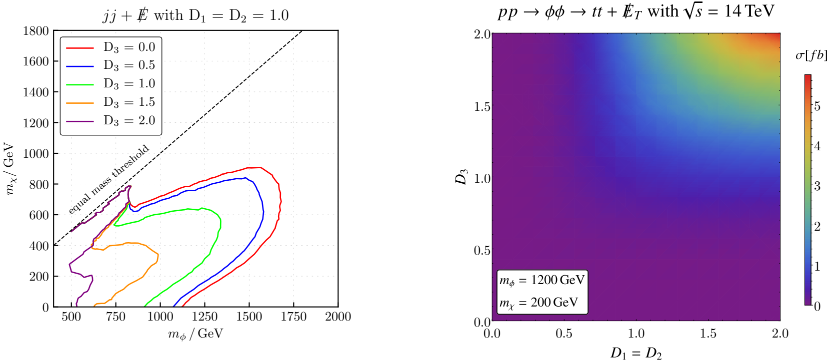

Fig. 1: Left: Constraints of LHC searches for $jj + \not{E}$ from [1908.04722] on the $m_\phi - m_\chi$ plane. Right: LO cross section of the $tt + \not{E}_T$ signature in $14\,\text{TeV}$ collisions.

$D^0 - \bar{D}^0$ Mixing Constraints

Majorana nature of χ yields additional mixing diagram:

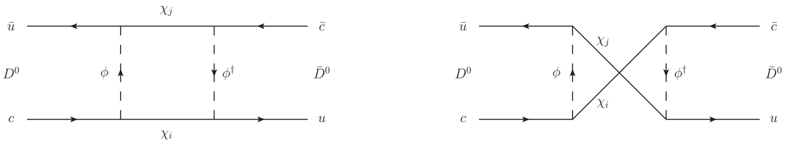

Fig. 2: Feynman diagrams of the $D^0 - \bar{D}^0$ mixing process.

NP contribution reads

$$M_{12}^{D,\,\text{NP}} = \frac{\eta_D m_D f_D^2 \hat{B}_D}{384\pi^2 m_\phi^2} \left[\xi_f \cdot f(x) - 2\,\xi_g \cdot g(x) \right],$$

$$\xi_f = \left(\lambda\lambda^\dagger\right)^2_{cu}, \quad \xi_g = \left(\lambda\lambda^T\right)_{cc} \left(\lambda\lambda^T\right)^*_{uu}.$$

We constrain the model using

$$x_{12}^D = 2\,\tau_{D^0}\,|M_{12}^D| \quad \phi_{12}^D = \text{Arg}(M_{12}^D)$$

$$x_{12}^{D,\text{SM}} \in [-3\%, 3\%] \quad \phi_{12}^{D,\,\text{SM}} = 0$$

Numerical Values and Limits	
$\hat{B}_D$	0.75 ± 0.02
f_D	$209.0 \pm 2.4\,\text{MeV}$
η_D	0.772
m_{D0}	$1864.83 \pm 0.05\,\text{MeV}$
τ_{D0}	$410.1 \pm 1.5\,\text{fs}$
x_{12}^D	$[0.21\%, 0.63\%]$
ϕ_{12}^D	$[-2.8^\circ, 1.7^\circ]$

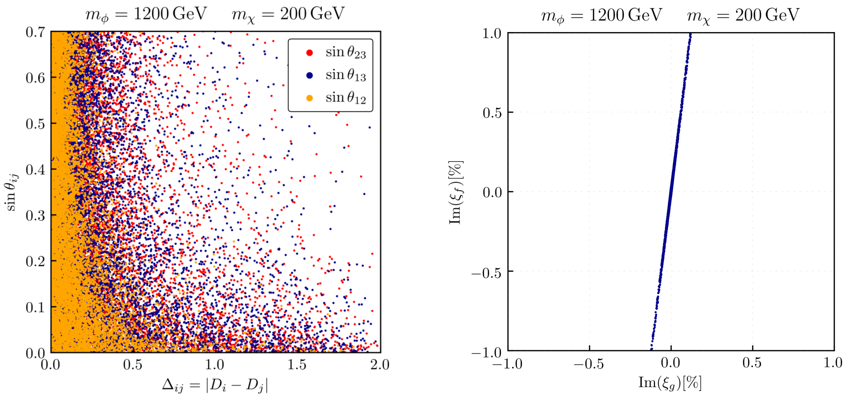

Fig. 3: Allowed mixing angles θ_{ij} (left) and couplings $\mathrm{Im}(\xi_i)$ (right).

Cosmology Constraints

DM mass splittings are parametrized as

$$M_{\chi,ij} = m_\chi \left\{ \mathbb{1} + \frac{\eta}{2}\left(\lambda^\dagger\lambda + \lambda^T\lambda^*\right) + \mathcal{O}(\lambda^4) \right\}_{ij} ,$$

yielding $\tilde{\lambda} = \lambda W^T$ after diagonalization.

We consider two freeze-out scenarios:

- Quasi-Degenerate Freeze-Out (QDF): mass splitting is below 1%, we choose $\eta = -0.01$
- Single-Flavour Freeze-Out (SFF): mass splitting is above 10%, we choose $\eta = -0.0575$

Low-velocity expansion:

$$\langle \sigma v \rangle = a + b\,\langle v^2 \rangle\,,\ \text{with}\ \langle v^2 \rangle = 6\,T_f/m_\chi \approx 0.3\,.$$

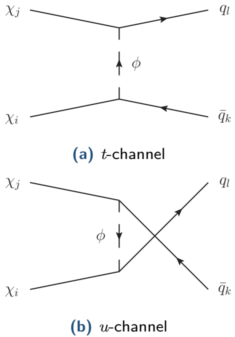

Fig. 4: Feynman diagrams of the annihilation process.

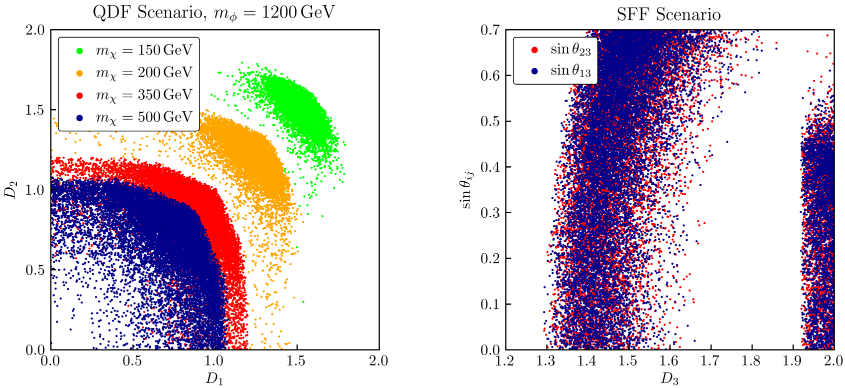

Fig. 5: Allowed couplings D_i (left) and mixing angles θ_{ij} (right) for top-flavoured DM with $m_\chi = 220\,\mathrm{GeV}$ and $m_\phi = 950\,\mathrm{GeV}$.

Direct Detection Constraints

Majorana: bilinears which are odd under charge parity vanish, i.e.

$$\bar{\chi}\gamma^{\mu}\chi = \bar{\chi}\sigma^{\mu\nu}\chi = 0\,.$$

WIMP-nucleon cross section is given by

$$\sigma^N_{\mathsf{SD}} = \frac{3}{16\pi}\mu_N^2 a_u^2 \Delta u^2\,, \qquad a_u \propto \frac{|\tilde{\lambda}|^2}{m_\phi^2 - (m_\chi + m_q)^2}\,,$$

$$\sigma^N_{\mathsf{SI}} = \frac{4}{\pi}\mu_N^2 f_N^2\,, \qquad f_N \propto \frac{|\tilde{\lambda}|^2}{\left(m_\phi^2 - (m_\chi + m_q)^2\right)^2}\,.$$

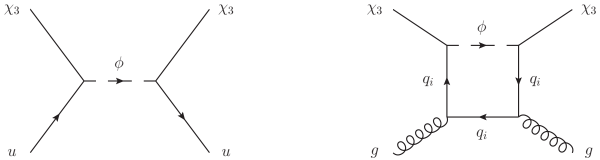

Fig. 6: Feynman diagrams of the tree-level (left) and one-loop scattering process (right).

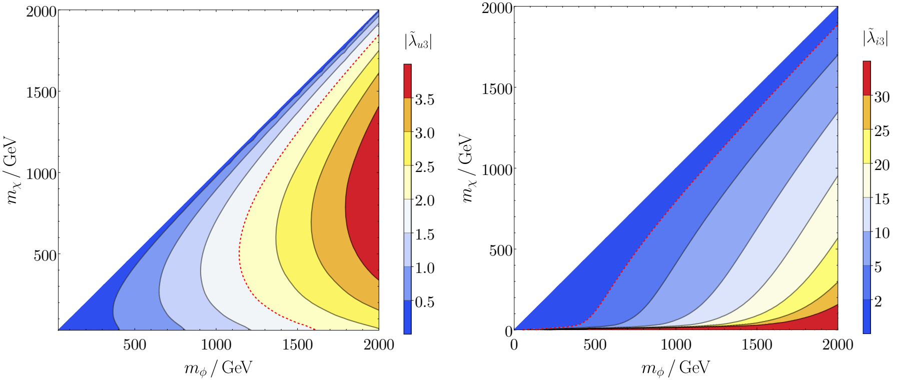

Fig. 7: Direct detection constraints on $\tilde{\lambda}$ from spin-dependent (left) and spin-independent (right) scattering. Limits were obtained from the PICO-60 [1902.04031] and XENON1T [1805.12562] experiments.

Combined Analysis

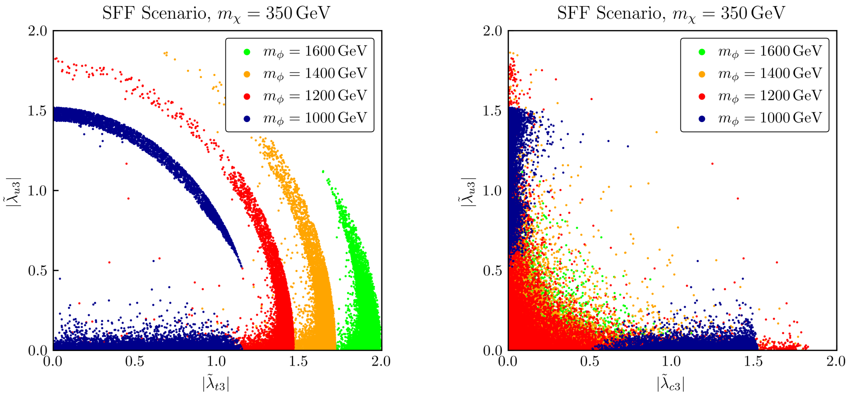

Fig. 8: Allowed coupling in the context of all constraints for the SFF scenario.

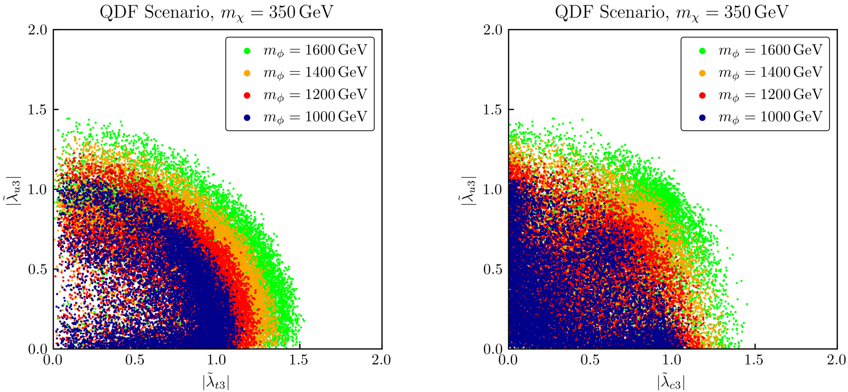

Fig. 9: Allowed coupling in the context of all constraints for the QDF scenario.

Direct CPV in Charm Decays

- LHCb measurement LHCb Collab. in [1905.05428]

$$\Delta A^{\text{dir}}_{\text{CP, LHCb}} = A_{\text{CP}}(D \to K^+K^-) - A_{\text{CP}}(D \to \pi^+\pi^-) = (-0.157 \pm 0.029)\%$$

- QCD light-cone sum-rule estimation Khodjamirian, Petrov in [1706.07780]

$$\Delta A^{\text{dir}}_{\text{CP, LCSR}} = (0.02 \pm 0.003)\%$$

- hint at NP in $\Delta A^{\text{dir}}_{\text{CP}}$?
- large effects were found in non-flavoured model

Altmannshofer et al. in [1202.2866]

- we use the same approach to estimate size of $\Delta A^{\text{dir}}_{\text{CP}}$

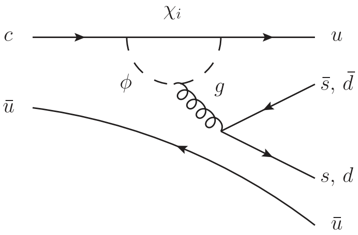

Fig. 10: Penguin diagram of NP D^0 decay.

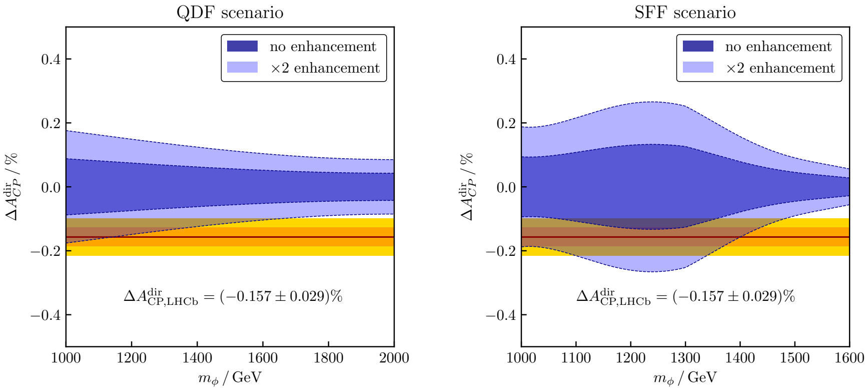

Fig. 11: $\Delta A^{\rm dir}_{\rm CP}$ in dependence of m_ϕ for the QDF scenario (left) and the SFF scenario (right). In both scenarios the DM mass is fixed to $m_\chi = 350\,\mathrm{GeV}$.

Outline

Summary and Outlook

Summary:

- DMFV models generally have a very rich phenomenology
- Majorana nature: new LHC signatures, additional mixing diagram and strongly loosened direct detection constraints
- both freeze-out scenarios are capable of enhancing $\Delta A^{\text{dir}}_{\text{CP, LHCb}}$ significantly

Outlook:

- more detailed analysis of LHC constraints via LLP searches
- dedicated collider study of this model's smoking-gun signature $tt + \not{E}$
- study of "intermediate" freeze-out scenarios

Thank you!