Phenomenology of top-flavoured dark matter

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Why flavoured dark matter?

Unknown DM properties

- coupling to SM particles?
- single particle or entire sector?
- analogy to ordinary SM matter

➢ **flavoured?**

Assumption:

dark matter carries flavour and comes in multiple copies
➢ *enough to save the WIMP?*

➢ **New coupling to quarks:**

$$\lambda^{ij}\bar{q}_i\chi_j\phi$$

q_i	SM quarks
χ_j	DM fermion, flavoured
ϕ	coloured scalar mediator
λ	coupling matrix

The idea is not new. . .

Early studies of flavoured DM

- Flavoured Dark Matter in Direct Detection Experiments and at LHC
  J. Kile, A. Soni (April 2011)
- Dark Matter from Minimal Flavor Violation
  B. Batell, J. Pradler, M. Spannowsky (May 2011)
- Discovering Dark Matter Through Flavor Violation at the LHC
  J. F. Kamenik, J. Zupan (July 2011)
- Flavored Dark Matter, and Its Implications for Direct Detection and Colliders
  P. Agrawal, S. Blanchet, Z. Chacko, C. Kilic (Sep. 2011)
- Top-flavored dark matter and the forward-backward asymmetry
  A. Kumar, S. Tulin (Mar. 2013)
- Flavored Dark Matter and R-Parity Violation
  B. Batell, T. Lin, L.-T. Wang (Sep. 2013)
- . . .

➢ **common to most studies: Minimal Flavour Violation**

Going beyond MFV

MFV

➢ HARMLESS

But not very exciting.

Going beyond MFV

MFV

➢ HARMLESS

But not very exciting.

non-MFV

➢ DANGEROUS

But interesting if you know how to handle it!

Model building 101

- DM introduced as Dirac fermion χ that carries no gauge quantum numbers, but transforms as $U(3)_\chi$ flavour triplet
- coupling to SM quarks via scalar mediator ϕ, carrying the gauge quantum numbers of the respective quark
- phenomenologically: lightest χ flavour (stable, DM) couples dominantly to third generation

***b*-flavoured:** $\lambda_{ij}\,\phi\,\bar{d}^i_R\,\chi^j$	Agrawal, MB, Gemmler (2014)
***t*-flavoured:** $\lambda_{ij}\,\phi\,\bar{u}^i_R\,\chi^j$	MB, Kast (2017)
***bt*-flavoured:** $\lambda_{ij}\,\phi\,\bar{q}^i_L\,\chi^j$	MB, Das, Kast (2017)

➢ **each (simplified) model has distinct phenomenology**

A simplified model of top-flavoured dark matter

Flavoured Dirac-fermionic DM χ_j and couples to right-handed up-type quarks via a coloured scalar mediator MB, Kast (2017)

$$\mathcal{L}_{\rm NP} = i\bar\chi\partial\!\!\!/\chi - m_\chi\bar\chi\chi + (D_\mu\phi)^\dagger(D^\mu\phi) - m_\phi^2\phi^\dagger\phi - \lambda^{ij}\bar{u_{Ri}}\chi_j\phi$$
$$+\lambda_{H\phi}\,\phi^\dagger\phi\,H^\dagger H + \lambda_{\phi\phi}\,\phi^\dagger\phi\,\phi^\dagger\phi$$

Assumptions:

- Dark Minimal Flavour Violation (DMFV):
  λ constitutes *the only* new source of flavour violation
- DM is top-flavoured:[1] $m_{\chi_t} < m_{\chi_u}, m_{\chi_c}$

[1] see Jubb, Kirk, Lenz (2017) for charm-flavoured dark matter

Consequences of DMFV

Dark matter mass

Agrawal, MB, Gemmler (2014)

- $U(3)_\chi$ symmetry ensures equal mass for all flavours to leading order
- special form of mass splitting at higher order (c. f. MFV)

$$m_{\chi_i} = m_\chi(\mathbb{1} + \eta\,\lambda^\dagger\lambda + \dots)_{ii}$$

Dark matter stability

- DM stability is guaranteed if DMFV is exact (unbroken $\mathbb{Z}_3$ symmetry)

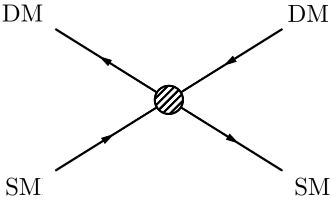
Parametrisation of DM-quark coupling

- $U(3)_\chi$ symmetry helps to remove 9 parameters

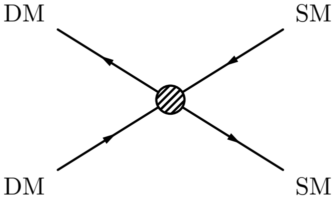
$$\lambda = U_\lambda D_\lambda$$

U_λ unitary matrix, 3 mixing angles θ_{12}, θ_{13}, θ_{23} and 3 phases
D_λ real diagonal matrix w/ positive entries

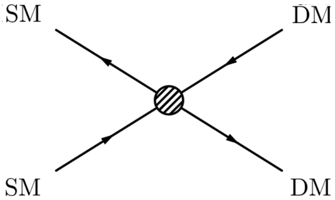
Signatures of flavoured dark matter



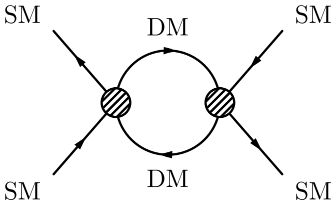
direct detection



indirect detection



collider searches

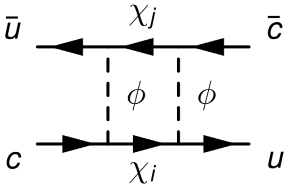


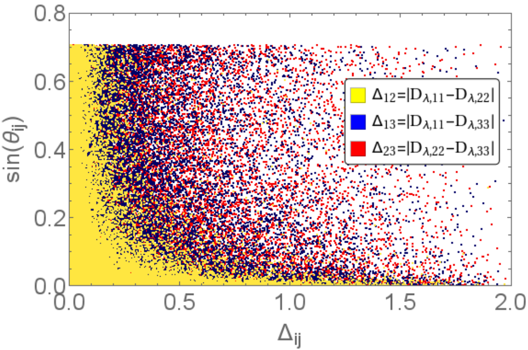
precision flavour data

Flavour constraints

MB, Kast (2017)

- no impact on K and B meson decays
- contribution to $D^0 - \bar{D}^0$ mixing





large 12-mixing only for quasi-degenerate $\chi_{u,c}$:

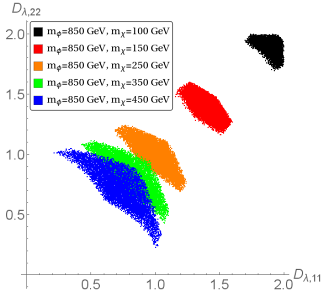
$$\Delta_{12} \ll 1 \quad \text{or} \quad \theta_{12} \sim 0$$

Constraint from observed relic abundance

MB, Kast (2017)

- assume DM to be relic of thermal freeze-out
- different freeze-out scenarios
  - **quasi-degenerate freeze-out (QDF)** $\Delta m_\chi \lesssim 1\%$
  - **single-flavour freeze out (SFF)** $\Delta m_\chi \gtrsim 10\%$
- annihilation cross-section relates mediator mass m_ϕ, DM mass m_χ, and DM couplings $D_{\lambda,ii}$

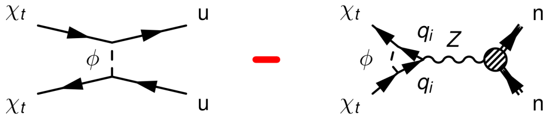
➢ **for fixed mediator mass, smaller DM mass implies larger couplings**



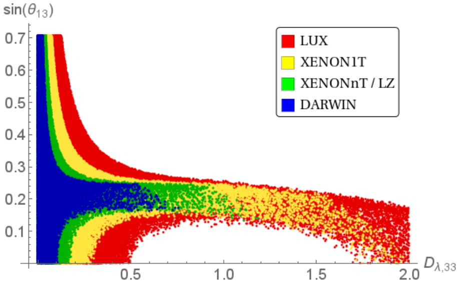
QDF scenario

Constraints from direct detection experiments

- for top-flavoured DM, Z-penguin contribution becomes relevant



➢ realisation of xenophobic DM scenario FENG, KUMAR, SANFORD (2013)



- cancellation between tree-level and Z-penguin contribution requires non-zero mixing angle θ_{13}
- for future experiments, cancellation not sufficiently effective for all xenon isotopes
  - ➢ **upper bound on coupling**

MB, KAST (2017)

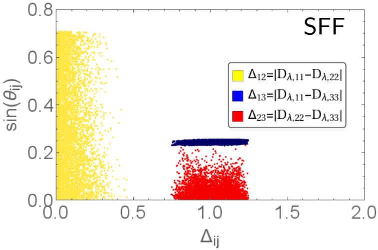
Phenomenological sweet-spots

MB, Kast (2017)

Experimental constraints from

- flavour physics
- DM relic abundance
- DM direct detection

place **stringent limits** on the model



➢ identification of phenomenologically viable sweet-spots in parameter space then to be used as **benchmark scenarios for an in-depth analysis of LHC signatures**

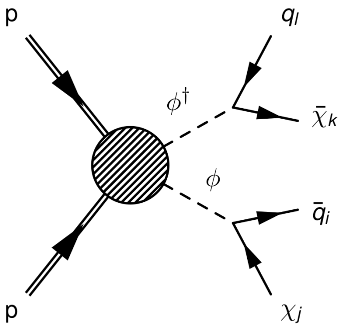
Benchmark scenarios for LHC studies

	DM mass	couplings	mixing angles
RH-SFF	200 GeV	$D_{\lambda,11} = D_{\lambda,22}$	$\sin\theta_{13} = 0.25$
		$D_{\lambda,33} = D_{\lambda,11} + 1.0$	$\theta_{12} = \theta_{23} = 0$
RH-QDF	150 GeV	$D_{\lambda,11} = D_{\lambda,22}$	$\sin\theta_{13} = 0.2$
		$D_{\lambda,33} = D_{\lambda,11} + 0.2$	$\theta_{12} = \theta_{23} = 0$

- representative benchmarks describing different DM freeze-out scenarios
- **two free parameters** in each benchmark scenario: mediator mass m_ϕ, coupling $D_{\lambda,11}$
- CP phases δ_{ij} irrelevant for our study and hence set to 0

MB, Pani, Polesello, Rovedi (2020)

Top-flavoured dark matter at the LHC



- mediator pairs abundantly produced through QCD interactions and t-channel DM exchange
  ➢ most stringent constraints
- signatures similar to SUSY squarks

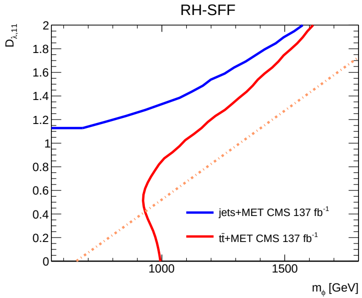
$$t\bar{t} + \not{E}_T \qquad jj + \not{E}_T$$

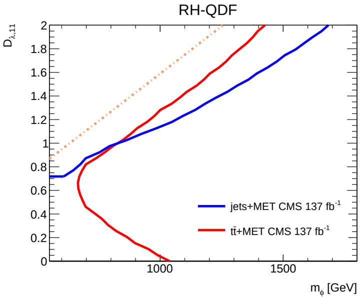
  ➢ recast existing LHC searches
- relative rates of different final states depend on DM flavour structure

MB, Kast (2017)
MB, Pani, Polesello, Rovedi (2020)

Recasting CMS $137\,\mathrm{fb}^{-1}$ search for multijet+$\not{E}_T$

MB, Pani, Polesello, Rovedi (2020)



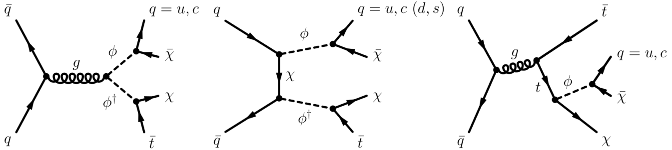


- sensitivity depends on overall coupling strength
- weaker limits in QDF scenario (approx. equal couplings)
- thermal relic scenario still viable in SFF scenario

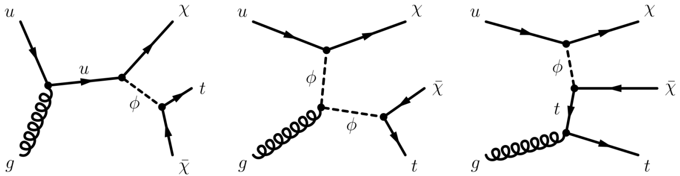
Single-top signatures of top-flavoured dark matter

Top-flavoured DM also induces **flavour-violating final states**:

- $t + j + \not{E}_T$ (dominated by mediator pair-production)

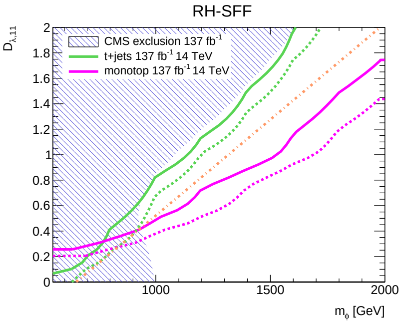


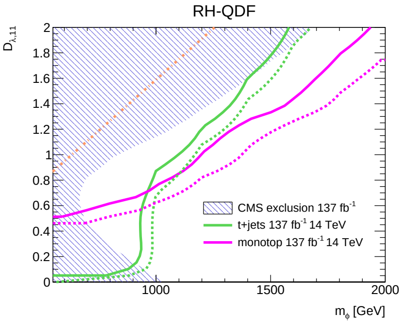
- "monotop" $t + \not{E}_T$



MB, Pani, Polesello, Rovedi (2020)

(HL-)LHC reach for single-top final states



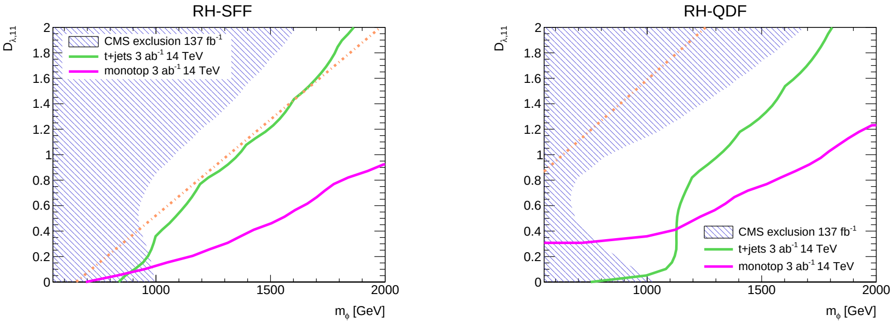


Dedicated single-top searches

MB, Pani, Polesello, Rovedi (2020)

- cover additional parameter space
- probe thermal freeze-out in SFF scenario

(HL-)LHC reach for single-top final states



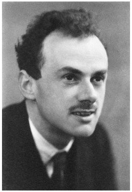
Dedicated single-top searches MB, Pani, Polesello, Rovedi (2020)

- cover additional parameter space
- probe thermal freeze-out in SFF scenario
- have significant discovery reach at the HL-LHC

Top-flavoured dark matter going Majorana

In our simplified model, DM flavour triplet is assumed to be a gauge singlet

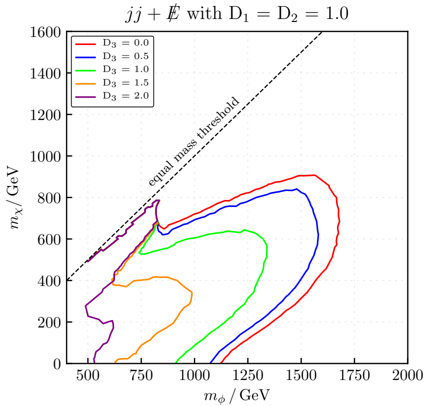
➢ Dirac or Majorana fermion? (analogy to RH neutrinos)

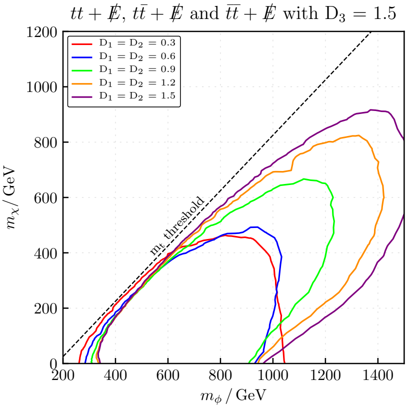


Switching from Dirac to Majorana DM:
"**That's one small step for a Lagrangian – one giant leap for phenomenology.**"

N. Armstrong (1969)

LHC constraints on top-flavoured Majorana DM





Observation

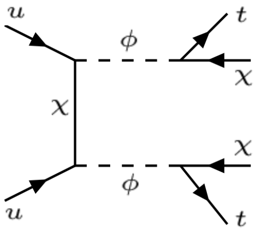
Acaroglu, MB (in prep.)

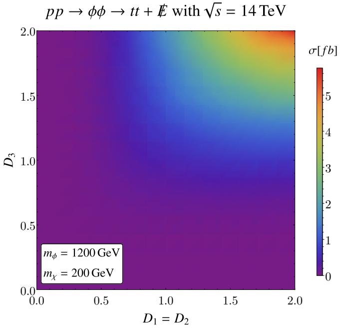
In contrast to SUSY and Dirac DM, bounds are strongest when $m_\chi \neq 0$!

LHC smoking gun: Same-sign di-tops+$\not{E}_T$

- Majorana mass term for χ allows for contributions from additional diagrams
- uu initial state enhanced by valence quark PDFs

➢ **final states with same-sign quarks**





- top charge-sign can be determined in semi-leptonic top decays
- essentially background-free
- $\mathcal{O}$(fb) cross-sections predicted for $tt + \not{E}_T$

➢ **dedicated search highly motivated**

Acaroglu, MB (in prep.)

...and new physics in charm?

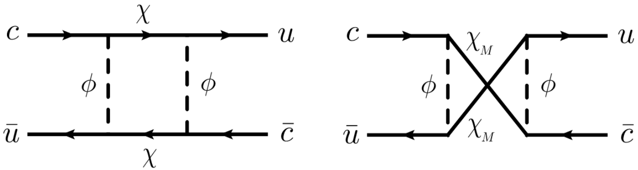
Dirac case: MB, Kast (2017)

experimental constraints on $D^0 - \bar{D}^0$ mixing exclude significant contributions to rare and CP-violating D decays

Majorana case: Acaroglu, MB (in prep.)

additional "crossed box" contributions lead to partial cancellation of NP contributions to $D^0 - \bar{D}^0$ mixing

➢ more space left for significant NP contributions in charm



see Altmannshofer, Primulando, Yu, Yu (2012)

ΔA_{CP} – CP violation in D decays

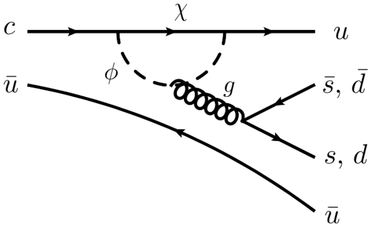
$$\Delta A_{\text{CP}} = A_{\text{CP}}(D \to K^+K^-) - A_{\text{CP}}(D \to \pi^+\pi^-)$$

- measures direct CP violation in D decays
- LHCb 2019: $\Delta A_{\text{CP}}^{\text{dir,exp}} = (-15.7 \pm 2.9) \cdot 10^{-4}$
  ➢ discovery of CP violation in charm
- SM prediction challenging due to hadronic long-distance effects
  ➢ naive estimate: $\Delta A_{\text{CP}}^{\text{dir,SM}} \sim \mathcal{O}[(\alpha_s/\pi)(V_{ub}V_{cb}^*)/(V_{us}V_{cs}^*)] \sim 10^{-4}$
  ➢ light-cone sum-rule prediction: $\Delta A_{\text{CP}}^{\text{dir,LCSR}} = (2.0 \pm 0.3) \cdot 10^{-4}$
  Khodjamirian, Petrov (2017)

➢ **New physics in $\Delta A_{\text{CP}}^{\text{dir}}$?**

Top-flavoured DM in $\Delta A_{\mathrm{CP}}^{\mathrm{dir}}$

top-flavoured DM contributes to $D \to K^+K^-, \pi^+\pi^-$ decays via gluon penguins



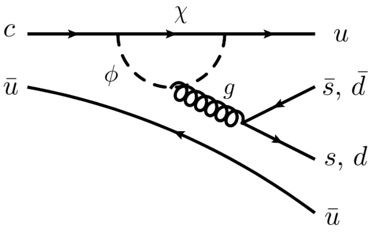
large effects found in a minimal Majorana+scalar model

Altmannshofer et al. (2012)

➢ **phenomenologically viable for top-flavoured DM?**

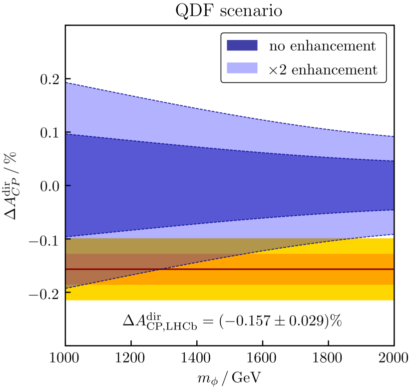
Top-flavoured DM in $\Delta A_{\mathrm{CP}}^{\mathrm{dir}}$

top-flavoured DM contributes to $D \to K^+K^-, \pi^+\pi^-$ decays via gluon penguins



large effects found in a minimal Majorana+scalar model

Altmannshofer et al. (2012)



Acaroglu, MB (in prep.)

Take-home messages

Top-flavoured dark matter

- can reconcile WIMP hypothesis thanks to non-trivial flavour structure
- induces LHC single-top signatures as promising future search channels
- Majorana case:
  predicts smoking gun same-sign di-top+$\not{E}_T$ signature
  & explains measured CP violation in charm