LHC Signatures of Flavoured Dark Matter

Monika Blanke

Karlsruher Institut für Technologie

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Particle Physics Phenomenology after the Higgs Discovery

Roadmap of Dark Matter Models for Run 3
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What is flavoured dark matter?

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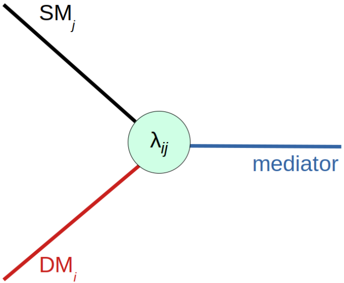
Minimal assumptions

- dark matter comes in three generations
- dark flavour triplet couples to SM flavour triplet via new mediator field ➢ t-channel DM
- new flavour-violating coupling matrix λ



The flavoured 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 flavour structure
  - Minimal Flavour Violation (MFV)
  - Dark Minimal Flavour Violation
  - ...?

In this talk

- introduction of DMFV framework
- quark-flavoured DM
  - complementary constraints
  - vanilla LHC searches
  - unexplored LHC signatures
- lepton-flavoured DM
  - complementary constraints
  - LHC current and future targets

From MFV to Dark Minimal Flavour Violation (DMFV)

Minimal flavour violation (MFV)

- SM flavour symmetry $U(3)_q \times U(3)_u \times U(3)_d \times U(3)_\ell \times U(3)_e$
- only broken by SM Yukawa couplings Y_u, Y_d

➢ all flavour-violating effects governed by the same hierarchies as in the SM

Dark Minimal Flavour Violation (DMFV)

- extended flavour symmetry $U(3)_q \times U(3)_u \times U(3)_d \times U(3)_\ell \times U(3)_e \times G(3)_\chi$
  where $G(3)_\chi = U(3)_\chi$ $(O(3)_\chi)$ for complex (real) DM field
- only broken by the SM Yukawa couplings and the DM-quark coupling λ

➢ new source of flavour violation λ implies potentially interesting non-MFV effects

➢ fewer free parameters than for generic flavour structure

Consequences of DMFV

Dark matter mass

Agrawal, MB, Gemmler (2014)

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

e. g. Dirac fermion DM: $m_{\chi_i} = m_\chi(\mathbb{1} + \eta\,\lambda^\dagger\lambda + \ldots)_{ii}$

Parametrisation of DM-quark coupling

- $G(3)_\chi$ symmetry helps to remove unphysical parameters

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

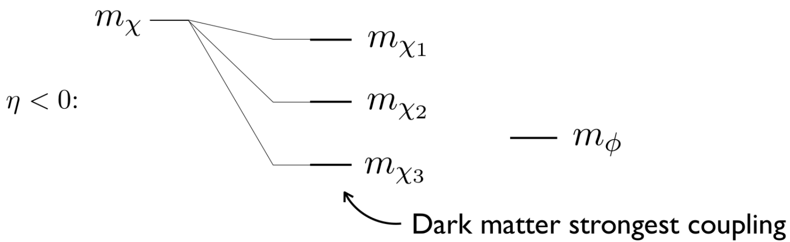
U_λ	unitary matrix, 3 mixing angles θ_{12}^λ, θ_{13}^λ, θ_{23}^λ and 3 phases
D_λ	real diagonal matrix, e.g. $D_\lambda = \mathrm{diag}(D_1, D_2, D_3)$
R_λ	additional mixing angles and phases, only for real DM

DMFV connects coupling and mass hierarchy

DMFV ansatz ties DM mass spectrum to coupling strength via spurion expansion

$$m_{\chi_i} = m_\chi (\mathbb{1} + \eta\, \lambda^\dagger \lambda + \dots)_{ii} \simeq m_\chi \left[1 + \eta\, D_i^2\right]$$

Standard hierarchy



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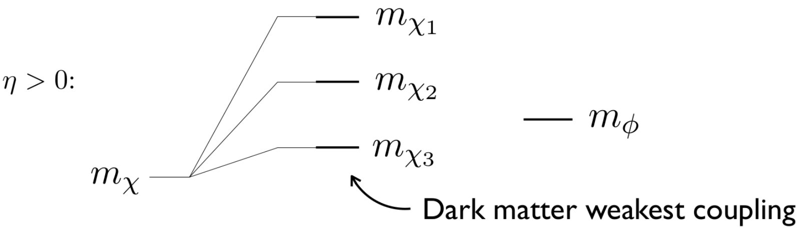
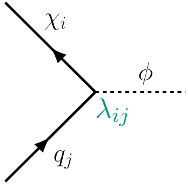
Inverse hierarchy



Basics of quark-flavoured dark matter

- three dark generations χ_i coupled to quark flavours q_j via coloured mediator ϕ
- lightest dark flavour χ_3 stable, DM candidate
- coupling matrix λ_{ij} is a new source of flavour and CP violation



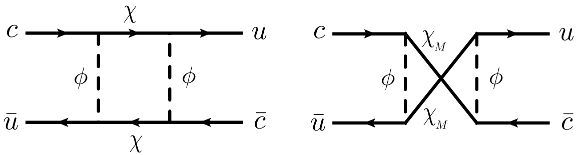
Quark-flavoured DMFV models in the literature

- flavoured Dirac DM coupled to down-type quarks — Agrawal, MB, Gemmler (2014)
- flavoured Dirac DM coupled to up-type quarks — MB, Kast (2017); Jubb, Kirk, Lenz (2017)
- flavoured Dirac DM coupled to left-handed quark doublets — MB, Das, Kast (2017)
- flavoured Majorana DM coupled to up-type quarks — Acaroğlu, MB (2021)
- . . . others not studied yet!

Flavour physics

Constraints from neutral meson mixing

- limits from $K^0 - \bar{K}^0$, $B_{d,s} - \bar{B}_{d,s}$ and/or $D^0 - \bar{D}^0$ mixing depending on quark flavours the dark sector couples to
- contributions from standard and, for Majorana DM, crossed box diagrams



➢ significant constraints on the **flavour structure** of λ, in particular for DM coupling to the down-quark sector

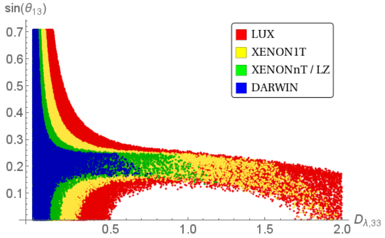
Direct and indirect detection

Direct detection

- dominant limits from liquid Xenon experiments
- constraints on DM couplings λ_{i3}

➢ flavour structure can help evade stringent bounds due to partial cancellations: "**xenophobic DM**"

Feng, Kumar, Sanford (2013)



MB, Kast (2017)

Indirect detection

- limits from antiproton flux measured by AMS-02

➢ generally not competitive with direct detection constraints

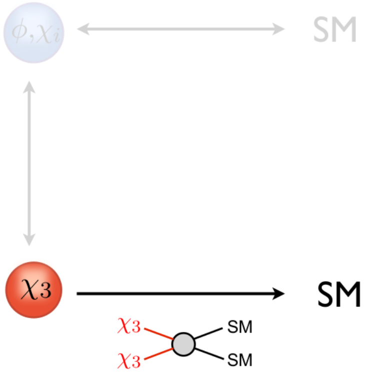
DM relic density from thermal freeze-out

Freeze-out scenarios

- standard (flavoured) WIMP freeze-out
  - single-flavour freeze-out (SFF): only χ_3 contributes
  - quasi-degenerate freeze-out (QDF): all χ_i flavours participate equally

Agrawal, MB, Gemmler (2014)

illustrations: Heisig @ MoriondEW 2024



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  Agrawal, MB, Gemmler (2014)
- including coannihilation effects

  ➢ can deplete relic abundance

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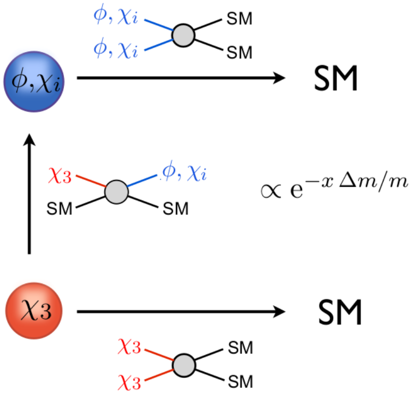

Griest, Seckel (1991)
Bell, Cai, Medina (2013)

DM relic density from thermal freeze-out

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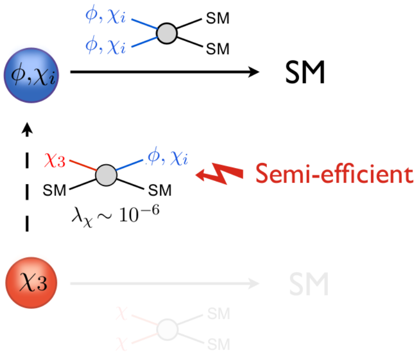
  Agrawal, MB, Gemmler (2014)
- including coannihilation effects
  ➢ can deplete relic abundance
- conversion-driven freeze-out
  for very small DM couplings (inverse hierarchy)
  co-scattering becomes semi-efficient
  ➢ can restore correct relic abundance

  Acaroğlu, MB, Heisig, Krämer, Rathmann (2023)

illustrations: Heisig @ MoriondEW 2024



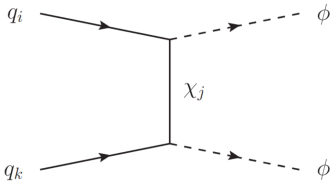
Garny, Heisig, Lülf, Vogl (2017)
D'Agnolo, Pappadopulo, Ruderman (2017)

Relevant LHC processes

Mediator pair-production

- QCD interactions (c.f. SUSY squarks)
- t-channel exchange of χ
- same-sign production if χ is Majorana
  - ➢ **enhanced** for $uu(dd) \to \phi\phi$

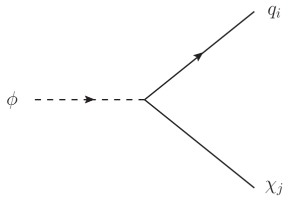
see also Garny, Ibarra, Pato, Vogl (2013)



Acaroğlu, MB (2021)
Acaroğlu, MB, Heisig, Krämer, Rathmann (2023)

Mediator decay

- determined by flavour structure of λ



- final states involving quarks and $\not{E}_T$
- chain decays via intermediate $\chi_{1,2}$ states
- soft and long-lived signatures for quasi-degenerate spectrum and/or small couplings

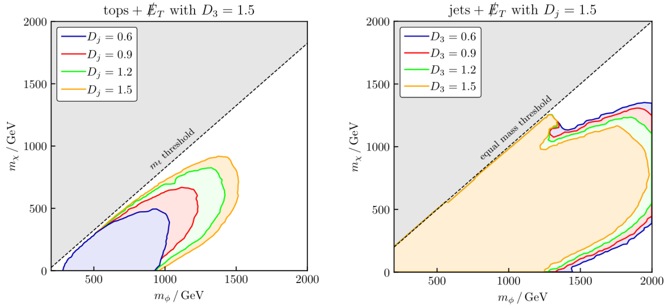
Vanilla LHC searches

Mediator pair-production

- applicable constraints from SUSY squark searches
- relevant final states $jj, cc, bb, tt + \not{E}_T$
- cross-section affected by t-channel contribution
- branching ratios determined by flavour structure of λ

Monojet

- competitive mainly in compressed region



Ex.: Limits on up-flavoured Majorana DM

- sensitivity depends on coupling pattern
- strongest bound for $m_\chi \neq 0$ due to same-sign production

Acaroğlu, MB (2021)

Unexplored signature I: same-sign tops from Majorana DM

Same-sign top signature

Acaroğlu, MB (2021)

$$pp \to \phi\phi \to tt + \not{E}_T$$

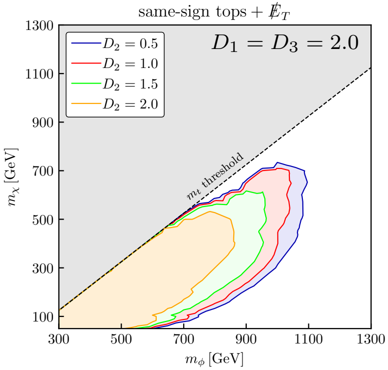
- top charge accessible in semileptonic final states
- cross-section in the fb regime

Naive reach estimate using CMS $ttjj + \not{E}_T$ search

CMS-SUS-19-008

- different kinematics ➢ not fully applicable
- highest reach for non-zero DM mass
- rate suppressed by $\mathrm{BR}(t \to b\ell\nu)^2 \sim 0.05$ and requirement of extra jets

➢ **not competitive** (?) **with jets+$\not{E}_T$**

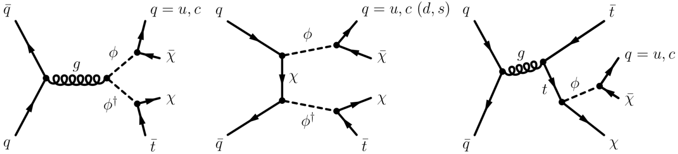


Acaroğlu, MB, Heisig, Krämer, Rathmann (2023)

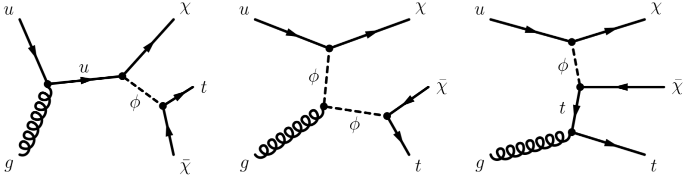
Unexplored signature II: single-top final states

Flavoured DM also induces **flavour-violating final states** – accessible with single-top

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



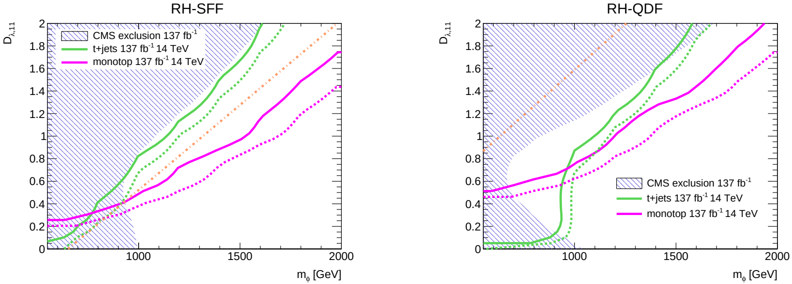
- "monotop" $t + \not{E}_T$



MB, Pani, Polesello, Rovedi (2020)

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

MB, Pani, Polesello, Rovedi (2020)

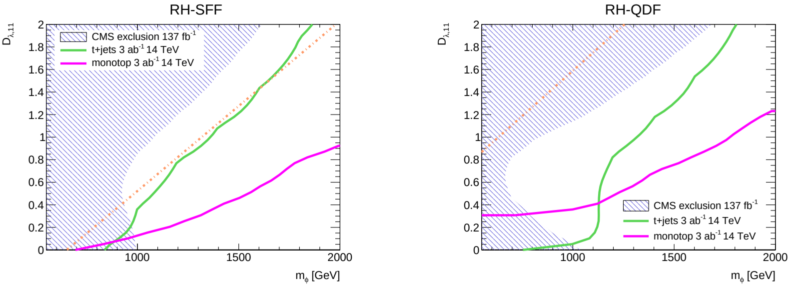


Dedicated single-top searches (shown: up-flavoured Dirac DM)

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

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

MB, Pani, Polesello, Rovedi (2020)



Dedicated single-top searches (shown: up-flavoured Dirac DM)

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

Unexplored signature III: single-top charge asymmetry

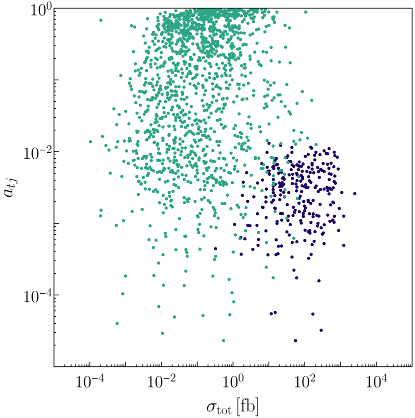
Single-top charge asymmetry for Majorana DM

- combine previous insights on same-sign production and flavour-violating final states
- consider single-top charge asymmetry

$$a_{tj} = \frac{\sigma(tj + \not{E}_T) - \sigma(\bar{t}j + \not{E}_T)}{\sigma(tj + \not{E}_T) + \sigma(\bar{t}j + \not{E}_T)}$$

- $a_{tj} > 0$ only for Majorana flavoured DM
  $a_{tj} \sim 0$ for Dirac flavoured DM

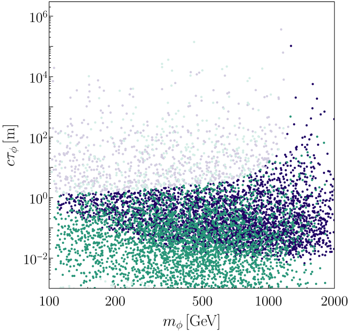
➢ **highly promising smoking gun signature!**



Acaroğlu, MB, Heisig, Krämer, Rathmann (2023)

Unexplored signatures IV: LLPs with intermediate lifetimes

Conversion-driven freeze-out



- relevant limit: stable R-hadrons (using SModelS reinterpretation tool)
- intermediate lifetimes not constrained

Opportunities for future LLP searches

➢ LLPs with intermediate decay lengths and soft decay products

Covering entire lifetime range

- searches for heavy stable charged particles
- searches for diasppearing tracks
- searches for displaced jets
- $\not{E}_T$ searches

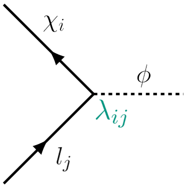
Heisig, Lessa, Ramos (2024)

see talks by A.Lessa, J.Heisig

Acaroğlu, MB, Heisig, Krämer, Rathmann (2023)

Lepton-flavoured DM in a nutshell

- three dark generations χ_i coupled to lepton flavours l_j via charged mediator ϕ
- lightest dark flavour χ_3 assumed stable, DM candidate
- coupling matrix λ_{ij} is a new source of flavour and CP violation in the lepton sector



Lepton-flavoured DMFV models in the literature

- flavoured Dirac DM coupled to right-handed leptons — Chen, Huang, Takhistov (2015)
- flavoured complex scalar DM coupled to right-handed leptons — Acaroğlu, Agrawal, MB (2022); Acaroğlu, MB, Tabet (2023)
- . . . others not studied yet!

Constraints and opportunities

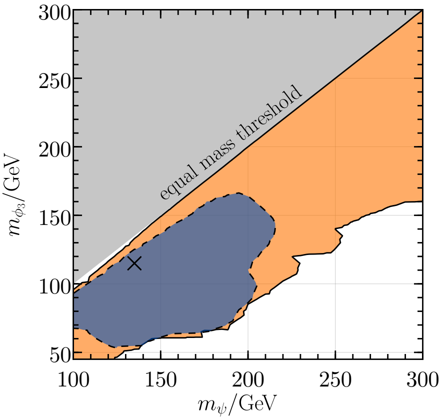
Relevant constraints

- charged lepton flavour violation
- lepton magnetic dipole moments
- direct and indirect DM detection

➢ **significantly lighter masses possible with inverse DM hierarchy** $(\eta > 0)$

Opportunities

- scalar lepton-flavoured DM allows for NP resolution of $(g-2)_\mu$ anomaly
- possible connection to neutrino mass generation? (c.f. scotogenic model)



Acaroğlu, Agrawal, MB (2022)
Acaroğlu, MB, Tabet (2023)

Lepton-flavoured DM at the LHC

Available constraints

- EW scale DM and mediator accessible to LHC searches
- mediator pair-production via Drell-Yan
- subsequent decay into $l_i + \not{E}_T$, lepton flavour depends on coupling structure
- limits from $l^+l^- + \not{E}_T$ searches, including soft lepton final states

  note: rate not lepton-flavour universal

Acaroğlu, MB, Tabet (2023)

Ideas for future targets

- lepton-flavour violating final states

  $$l_i^+ l_j^- + \not{E}_T$$

  caveat: present in SM due to neutrino flavour, often used as control region
- more complicated topologies with multi-lepton final states
- LLP signatures: displaced vertices, compressed spectra from conversion-driven freeze-out

Conclusions

Flavoured dark matter

- extension of t-channel framework with dark sector flavour structure
- many different models possible, both in the quark and lepton sectors
- rich phenomenology with complementary constraints from flavour physicss, precision tests, relic abundance, DM (in)direct detection, and LHC searches
- various novel LHC signatures to be explored