Implications of flavour constraints on dark matter

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Dark Matter at the Large Hadron Collider 2016
Amsterdam – March 31, 2016

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

➢ **New coupling to quarks:**

e. g. $\lambda^{ij}\bar{d}_{Ri}\chi_j\phi$

d_{Ri}	right-handed down quarks
χ_j	DM particle, flavoured
ϕ	new scalar, coloured

The idea is not new. . .

Flavoured DM received a lot of attention in recent years, see e. g.

- 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

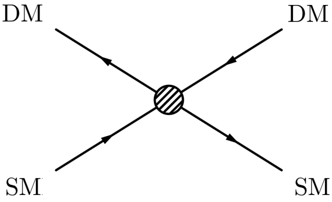
But not very exciting.

non-MFV

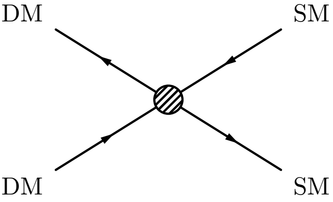
➢ DANGEROUS

But interesting if you know how to handle it!

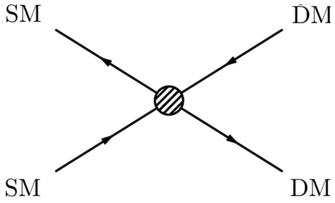
How to detect flavoured dark matter



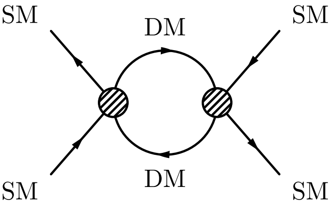
direct detection



indirect detection



collider searches



precision flavour data

A simplified model of flavoured dark matter

Flavoured Dirac-fermionic DM χ_j and couples to down quarks via a coloured scalar mediator

$$\mathcal{L}_{\rm NP} = i\bar{\chi}\not{\partial}\chi - m_\chi\bar{\chi}\chi + (D_\mu\phi)^\dagger(D^\mu\phi) - m_\phi^2\phi^\dagger\phi - \lambda^{ij}\bar{d}_{Ri}\chi_j\phi$$
$$+\lambda_{H\phi}\,\phi^\dagger\phi\,H^\dagger H + \lambda_{\phi\phi}\,\phi^\dagger\phi\,\phi^\dagger\phi$$

Assumption: Flavour symmetry

$$\underbrace{U(3)_q \times U(3)_u \times U(3)_d}_{\text{SM flavour symmetry}} \times U(3)_\chi$$

only broken by the SM Yukawa couplings and the DM-quark coupling λ

➢ "Dark Minimal Flavour Violation" (DMFV)

Consequences of DMFV

Dark matter mass

- χ_i mass splittings generated by coupling matrix λ

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

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

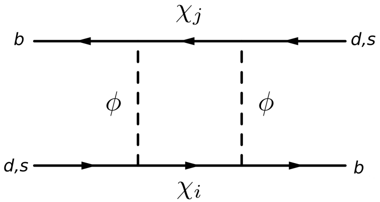
$$\lambda = U_\lambda D_\lambda$$

U_λ unitary matrix, 3 mixing angles s_{12}^λ, s_{13}^λ, s_{23}^λ and 3 phases
D_λ real diagonal matrix, e.g. $D_\lambda = \lambda_0 \cdot \mathbb{1} + \mathrm{diag}(\lambda_1, \lambda_2, -(\lambda_1 + \lambda_2))$

New contributions to meson mixing

Agrawal, MB, Gemmler (2014)

- new box diagram for $B_{d,s} - \bar{B}_{d,s}$ mixing



- dominant NP mixing amplitude for the $B_{d,s}$ meson system

$$M_{12}^{q,\text{new}} \sim (\xi_q^*)^2 F(x) \quad \text{where} \quad \xi_q = (\lambda\lambda^\dagger)_{bq} = \sum_{i=1}^{3} \lambda_{bi}\lambda_{qi}^* \quad (q = d, s)$$

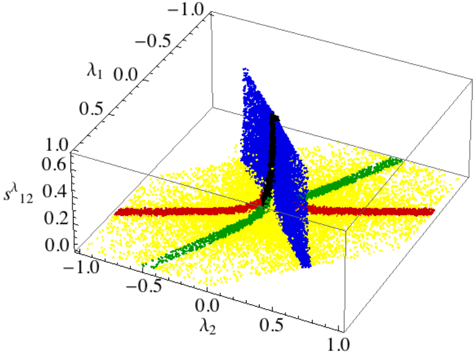
- analogous contributions to $K^0 - \bar{K}^0$ mixing

Lessons from meson mixing

Large contributions to $K^0 - \bar{K}^0$ and $B_{d,s} - \bar{B}_{d,s}$ mixing

➢ **λ has to be non-generic**

- **3-flavour universality**
  (black): $\lambda_1 = \lambda_2 = 0$
- **2-flavour universalities**
  (blue): $\lambda_1 = \lambda_2$
  (red): $\lambda_2 = -2\lambda_1$
  (green): $\lambda_2 = -1/2\lambda_1$
- **small mixing**
  (yellow): arbitrary D_λ



$$D_\lambda = \lambda_0 \cdot \mathbb{1} + \mathrm{diag}(\lambda_1, \lambda_2, -(\lambda_1 + \lambda_2))$$

fixed: $m_\phi = 850$ GeV, $m_\chi = 200$ GeV, $\lambda_0 = 1$

Agrawal, MB, Gemmler (2014)

Dark sector mass spectrum

- Meson mixing observables place strong constraints on the structure of λ but do not fix the mass spectrum in the dark matter sector!
- Mass m_ϕ of coloured scalar mediator strongly constrained by LHC
- Good reasons for b-flavoured dark matter:

  ➢ **less constrained** by direct detection experiments and LHC

  ➢ interesting ***b*-jet signatures** at colliders

  ➢ possible explanation of γ **ray signal from galactic center**

  Hooper et al. (2009)..., Agrawal et al. (2014)

For now we assume DM to be

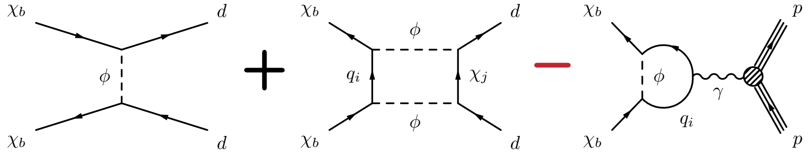
➢ b-flavoured, i. e. coupling dominantly to b quarks

➢ a thermal relic

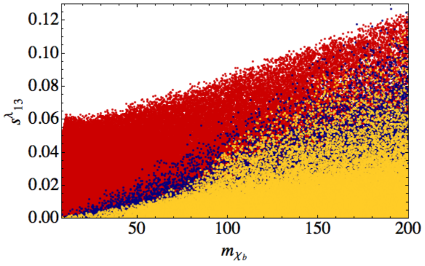
➢ significantly split from $\chi_{d,s}$

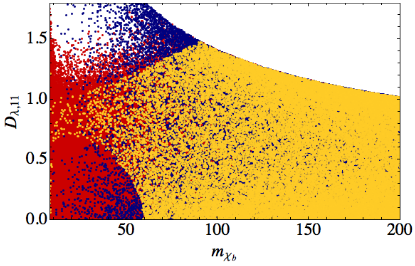
Constraints from LUX & co.

Dark matter scattering off nuclei...



...constrains the DM coupling matrix λ

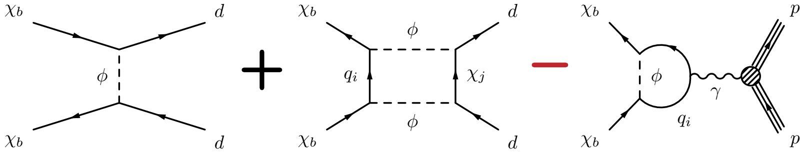




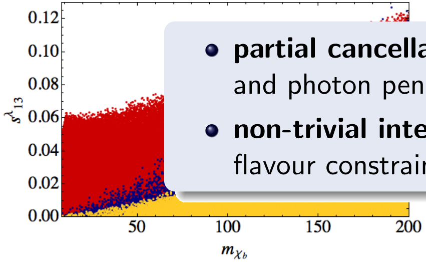
constraints imposed: LUX only, flavour only , LUX & flavour

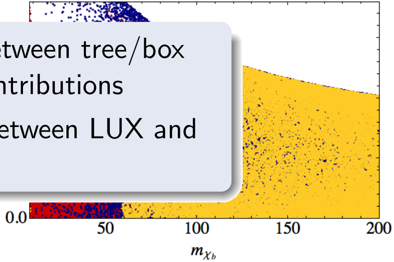
Constraints from LUX & co.

Dark matter scattering off nuclei. . .



. . . constrains the DM coupling matrix λ





- **partial cancellation** between tree/box and photon penguin contributions
- **non-trivial interplay** between LUX and flavour constraints

constraints imposed: LUX only, flavour only , LUX & flavour

What about rare B and K decays?

$b \to s\gamma$ transition described by

$$\mathcal{H}_{\text{eff}} \sim (C_7 Q_7 + C_7' Q_7' + \cdots)$$

$$Q_7 \sim \bar{s}_L \sigma^{\mu\nu} b_R F_{\mu\nu}$$

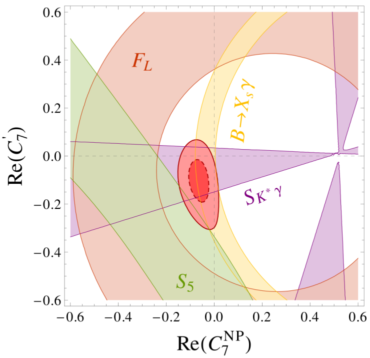
$$Q_7' \sim \bar{s}_R \sigma^{\mu\nu} b_L F_{\mu\nu}$$

➢ new contribution

$$\delta C_7' \sim 0.04 \left[\frac{500\,\text{GeV}}{m_\phi}\right]^2 \sum_{i=1}^{3} \lambda_{si}\lambda_{bi}^*$$

➢ **negligible effects in $b \to s\gamma$**

Figure from Altmannshofer, Straub (2013)



No new one-loop contribution to Z penguin and boxes:

➢ negligible effects also in $B_{s,d} \to \mu^+\mu^-$, $B \to K^{(*)}\mu^+\mu^-$, $K \to \pi\nu\bar{\nu}\ldots$

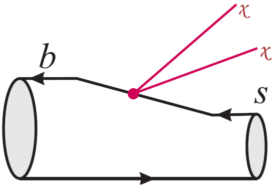
Agrawal, MB, Gemmler (2014)

Light flavoured DM in $P \to P' + \not{E}_T$ decays

BIRD ET AL. (2004), KAMENIK, SMITH (2011)

Light flavoured DM can be constrained/discovered in decays like $B \to K^{(*)}\nu\bar{\nu}, K \to \pi\nu\bar{\nu}$ if

- final state kinematically accessible $(m_\chi \lesssim m_P/2)$
- χ long-lived to escape detection



- ➢ already present data give **interesting constraints**
- ➢ **complementary** to $\Delta F = 2$ constraints
- ➢ careful study of **differential distributions** needed

Coupling DM to the up-sector

MB, Kast (in preparation)

What if we couple the dark matter χ_i to the up quark sector instead?

➢ $$\lambda^{ij}\bar{u}_{Ri}\chi_j\phi$$

Many consequences of DMFV carry over

- dark matter stability
- structure and parametrization of coupling matrix λ
- correlation between mass splittings and coupling matrix

+ phenomenologically appealing option of top-flavoured DM

see e. g. Kumar, Tulin (2013); Kilic, Klimek, Yu (2015)

Flavour constraints

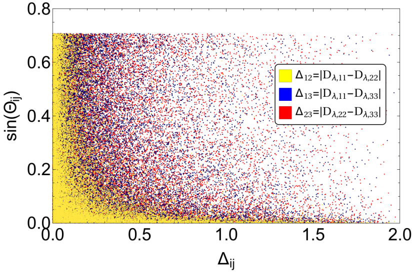
MB, Kast (in preparation)

DMFV with coupling to right-handed up-sector

- no impact on K and B meson decays
- potential effect in D meson physics

➢ relevant constraint from $D^0 - \bar{D}^0$ mixing

➢ much less constrained than down-sector case

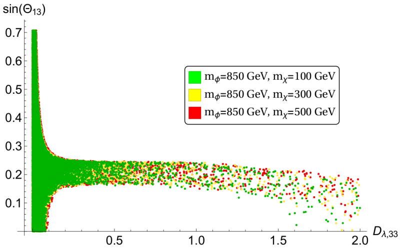


➢ large 12-mixing only for quasi-degenerate 1st and 2nd DM generation

Constraints from direct detection

MB, Kast (in preparation)

- with top-flavoured DM, Z-penguin contribution becomes relevant
- dominant contributions:



➢ cancellation between tree-level and Z-penguin contribution requires non-zero mixing angle θ_{13}

Conclusions

- mechanism generating the flavour structure of the SM is unknown, assuming a similar mechanism in the dark sector suggests

> **"Dark Minimal Flavour Violation"**
> additional $U(3)_\chi$ flavour symmetry
> only broken by the new coupling matrix λ

- DMFV (if exact) ensures stability of lightest dark flavour

- various simplified models possible, depending on coupling to SM quarks

- constraints from relic abundance, direct detection, LHC searches and flavour physics exhibit a non-trivial interplay

Backup slides

Dark matter stability

Similar proof in MFV: Batell, Pradler, Spannowsky (2011)

Consider $\mathcal{O} \sim \chi \ldots \bar{\chi} \ldots \phi \ldots \phi^\dagger \ldots q_L \ldots \bar{q}_L \ldots u_R \ldots \bar{u}_R \ldots d_R \ldots \bar{d}_R \ldots$

invariant under ...

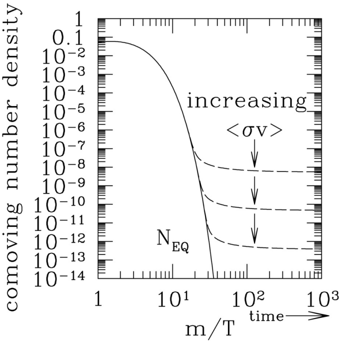
- QCD if the number of $SU(3)_c$ triplet minus the number of $SU(3)_c$ antitriplets is a multiple of three
- flavour symmetry: include $Y_u \ldots Y_u^\dagger \ldots Y_d \ldots Y_d^\dagger \ldots \lambda \ldots \lambda^\dagger \ldots$

I	$SU(3)c$	$(N_\phi - N_{\phi^\dagger} + N_q + N_u + N_d - N_{\bar{q}} - N_{\bar{u}} - N_{\bar{d}}) \mod 3 = 0$
II	$U(3)_q$	$(N_q - N_{\bar{q}} + N_{Y_u} - N_{Y_u^\dagger} + N_{Y_d} - N_{Y_d^\dagger}) \mod 3 = 0$
III	$U(3)_u$	$(N_u - N_{\bar{u}} - N_{Y_u} + N_{Y_u^\dagger}) \mod 3 = 0$
IV	$U(3)_d$	$(N_d - N_{\bar{d}} - N_{Y_d} + N_{Y_d^\dagger} + N_\lambda - N_{\lambda^\dagger}) \mod 3 = 0$
V	$U(3)_\chi$	$(N_\chi - N_{\bar{\chi}} - N_\lambda + N_{\lambda^\dagger}) \mod 3 = 0$
$\sum$ II+III+IV+V−I		$(N_\chi - N_{\bar{\chi}} - N_\phi + N_{\phi^\dagger}) \mod 3 = 0$

➢ **$\mathbb{Z}_3$ symmetry forbids χ and ϕ decays into SM fields**

Dark matter as thermal relic

- WIMP production and annihilation in equilibrium in the early universe
- dark matter "freezes out" when annihilation rate $\langle \sigma v \rangle$ drops below Hobble expansion rate
- relic abundance determined by solving Boltzmann equation for DM number density n at late times



$$\frac{dn}{dt} + 3Hn = - \underbrace{\langle \sigma v \rangle_{eff}}_{2.2\times 10^{-26}\mathrm{cm}^3/\mathrm{s}} (n^2 - n_{eq}^2)$$

n	dark matter number density
H	Hubble constant
n_{eq}	equilibrium number density of χ

✓ relic density

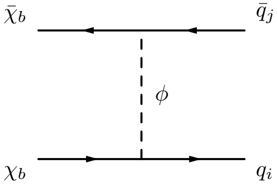
Flavored dark matter freeze-out

Agrawal, MB, Gemmler (2014)

- freeze-out condition depends on life time of heavier dark flavours

- for significant mass splitting $\gtrsim 10\%$ heavy flavours decay fast
  - ➢ only χ_b contributes to relic abundance

$$\langle \sigma v \rangle_{bb} = \frac{D^4_{\lambda,33} m^2_{\chi_b}}{32\pi (m^2_{\chi_b} + m^2_\phi)^2}$$



- for small mass splittings $\lesssim 1\%$ multiple flavours present at freeze-out temperature
  - ➢ sum over all flavours i, j present at freeze-out

$$\langle \sigma v \rangle = \sum_{i,j} \langle \sigma v \rangle_{ij}$$

Flavoured dark matter at the LHC

Agrawal, MB, Gemmler (2014)

DMFV ➢ unbroken $\mathbb{Z}_3$ ➢ new particles have to be pair-produced

dark matter fermion χ_b and the heavier flavours $\chi_{d,s}$

- nearly degenerate due to DMFV
- $\chi_{d,s}$ decay to χ_b produces soft particles (jets, photons) + missing E_T
  ➢ LHC monojet+$\not{E}_T$ searches sensitive to χ pair production

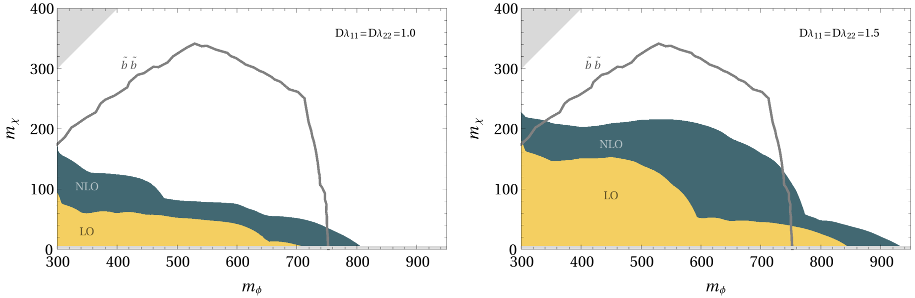
coloured scalar mediator ϕ

- pair-produced through QCD and through t-channel χ_d exchange
- decay $\phi \to q_i \chi_i$ with branching ratios given by $D^2_{\lambda,ii}$
  ➢ $bb + \not{E}_T$, $bj + \not{E}_T$, $jj + \not{E}_T$ signatures

Constraints from $bb + \not{E}_T$

AGRAWAL, MB, GEMMLER (2014)

- CMS (& ATLAS) put strong bounds on bottom squark pair-production from $bb + \not{E}_T$ CMS-PAS-SUS-13-018
- bound on cross-section can be applied to DMFV
  - production cross section enhanced by t-channel χ_d exchange
  - $bb + \not{E}_T$ signal suppressed by $\phi \to b\chi_b$ branching ratio



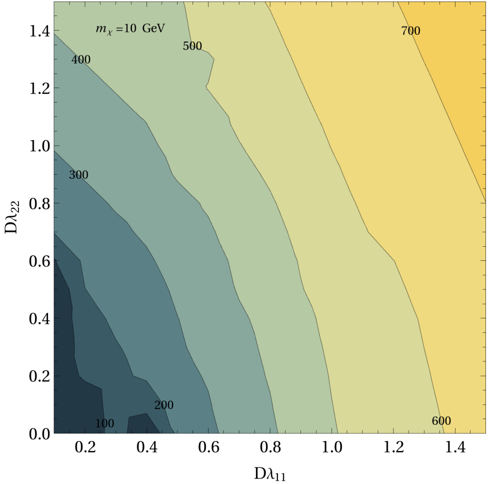
Constraints from monojet searches I

- monojet searches sensitive to χ pair-production with ISR hard jet
- recansting exp. bounds

  ATLAS-CONF-2012-147
  CMS-PAS-EXO-12-048

  ➢ limit on m_ϕ depending on couplings $D_{\lambda,ii}$
- rather independent of m_χ

Agrawal, MB, Gemmler (2014)



Constraints from monojet searches II

Agrawal, MB, Gemmler (2014)

- monojet searches also sensitive to ϕ pair-production if decay products are soft
- constraint on the compressed region $m_\chi \lesssim m_\phi$