Top-Flavoured Dark Matter beyond Minimal Flavour Violation

Monika Blanke

Karlsruher Institut für Technologie

New physics at the junction of flavour and collider phenomenology
Portoroz – April 20, 2017

Flavoured dark matter?

Why should we care about dark flavours?

Flavoured dark matter?

Why should we care about dark flavours?

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. $\lambda^{ij}\bar{d}_{Ri}\chi_j\phi$ or $\lambda^{ij}\bar{u}_{Ri}\chi_j\phi$

q_{Ri} right-handed 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

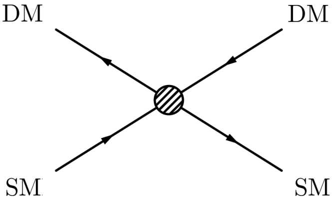
But not very exciting.

non-MFV

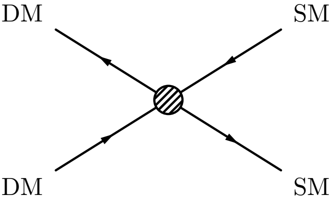
➢ DANGEROUS

But interesting if you know how to handle it!

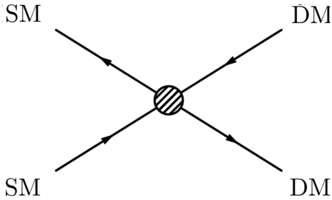
How to detect flavoured dark matter



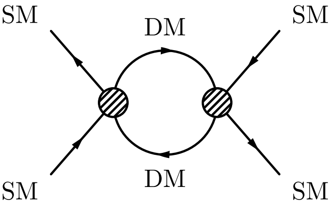
direct detection



indirect detection



collider searches



precision flavour data

Bottom-flavoured DM beyond MFV

AGRAWAL, MB, GEMMLER (2014)

Step 1: simplified model of flavoured Dirac-fermionic DM χ_j coupling to down-type quarks via a coloured scalar mediator

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

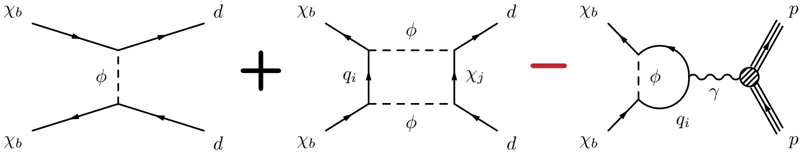
Assumptions:

- **Dark Minimal Flavour Violation (DMFV)**
  flavour symmetry $U(3)_q \times U(3)_u \times U(3)_d \times U(3)_\chi$ only broken by the SM Yukawa couplings and the DM-quark coupling λ
- DM is bottom-flavoured: $m_{\chi_b} < m_{\chi_d}, m_{\chi_s}$

➢ **rich and interesting phenomenology**

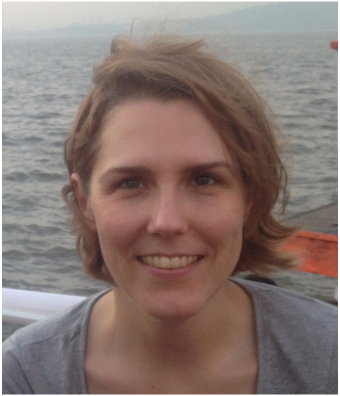
Bottom-flavoured DM pheno in a nutshell

- DMFV ansatz relates mass splitting to coupling matrix and guarantees DM stability see also BATELL, PRADLER, SPANNOWSKY (2011)
- K and $B_{d,s}$ mixing constraint imply non-generic structure for coupling matrix λ
- mediator mass constrained from LHC squark searches
- direct detection constraints require cancellation between various contributions



➢ **non-trivial interplay of constraints** AGRAWAL, MB, GEMMLER (2014)

The top-flavoured DM hunting team



MB

Simon Kast

MB, Kast, arXiv:1702.08457 – submitted to JHEP

A simplified model of top-flavoured dark matter

Flavoured Dirac-fermionic DM χ_j and couples to 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:

- DMFV: λ constitutes the *only* new source of flavour violation
- DM is top-flavoured: $m_{\chi_t} < m_{\chi_u}, m_{\chi_c}$

Parametrisation of DM-quark coupling: $\lambda = U_\lambda D_\lambda$

U_λ unitary matrix, 3 mixing angles θ_{12}, θ_{13}, θ_{23} and 3 phases

D_λ real diagonal matrix, e.g. $D_\lambda = \mathrm{diag}(D_{\lambda,11}, D_{\lambda,22}, D_{\lambda,33})$

LHC constraints

- most stringent constraints from mediator pair production
- signatures similar to SUSY squarks
  - ➢ $t\bar{t} + \not{E}_T$, $jj + \not{E}_T$
  - ➢ also $tj + \not{E}_T$

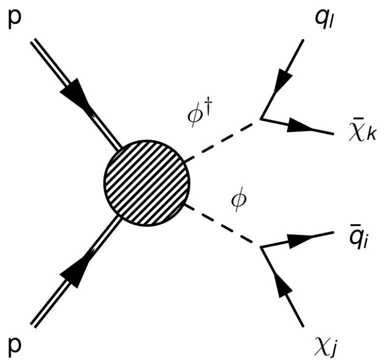
recall Flavoured Naturalness:
MB, Giudice, Paradisi, Perez, Zupan (2014)

- imposing ATLAS run 1 cross-section limits on our model, we find

$$m_\phi \gtrsim 850\,\text{GeV}$$

for DM couplings $D_{\lambda,ii} \leq 2$

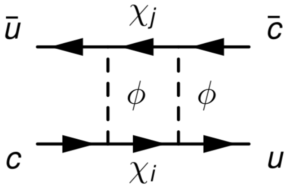
MB, Kast (2017)

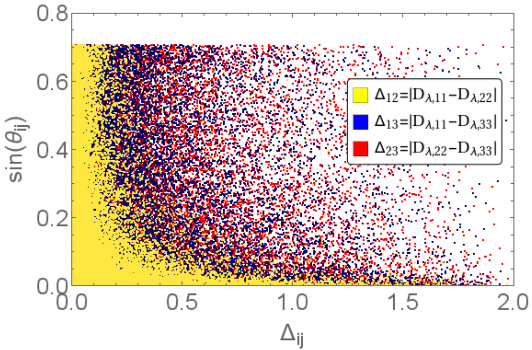


Flavour constraints

MB, Kast (2017)

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



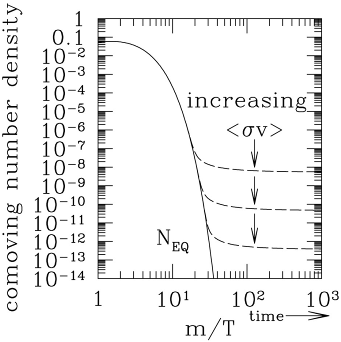


large 12-mixing only for quasi-degenerate $\chi_{u,c}$:

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

Dark matter as thermal relic

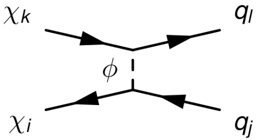
- WIMP production and annihilation in equilibrium in the early universe
- dark matter "freezes out" when annihilation rate $\langle \sigma v \rangle$ drops below Hobble expansion rate
- relic abundance determined by solving Boltzmann equation for DM number density n at late times



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

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

Flavored dark matter freeze-out



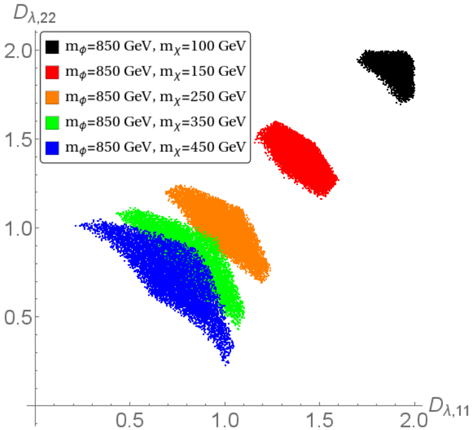
MB, Kast (2017)
following Agrawal, MB, Gemmler (2014)

- freeze-out condition depends on life time of heavier dark flavours and on DM mass
- for significant mass splitting $\gtrsim 10\%$ heavy flavours decay fast
  ➢ only χ_t contributes to relic abundance
- for small mass splittings $\lesssim 1\%$ multiple flavours $\chi_{i,k}$ present at freeze-out temperature
  ➢ sum over all DM flavours that are still present
  this talk: small mass splitting assumed
- only sum over final states $q_{j,l}$ that are kinematically accessible

Constraint from observed relic abundance

MB, Kast (2017)

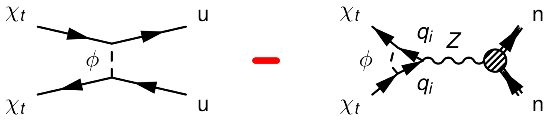
- annihilation cross-section relates mediator mass m_ϕ, DM mass m_χ, and DM couplings $D_{\lambda,ii}$
- for fixed mediator mass, smaller DM mass implies larger couplings
- $D_{\lambda,ii} > 2$ causes problems with LHC constraints



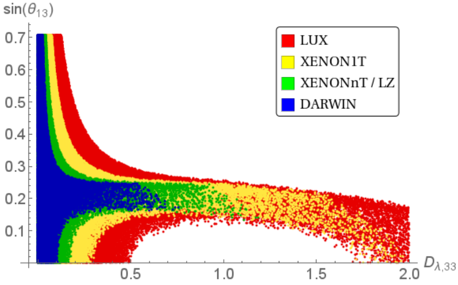
➢ **lower bound on DM mass from combination of thermal relic condition and LHC data**

Constraints from direct detection experiments

- with 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**

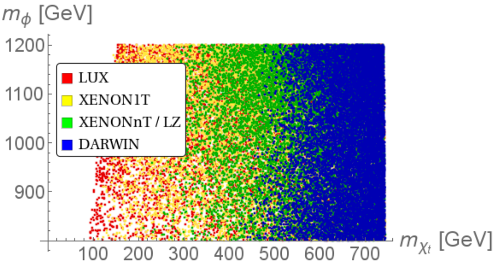
MB, Kast (2017)

Results of combined analysis

MB, Kast (2017)

Putting everything together:

- interesting interplay of different constraints
- non-trivial constraints on parameter space, i. e. masses, couplings, and mixing angles



- increasingly stringent lower bound on DM mass from future liquid xenon experiments

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

Top-flavoured DM in DMFV

- constraints from relic abundance, direct detection, LHC searches and flavour physics exhibit a non-trivial interplay
- upcoming experiments have the potential to exclude major part of parameter space **. . . or to discover our model!**

Backup slides

Dark matter stability in DMFV

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 $Y_u \ldots Y_u^\dagger \ldots Y_d \ldots Y_d^\dagger \ldots \lambda \ldots \lambda^\dagger \ldots$

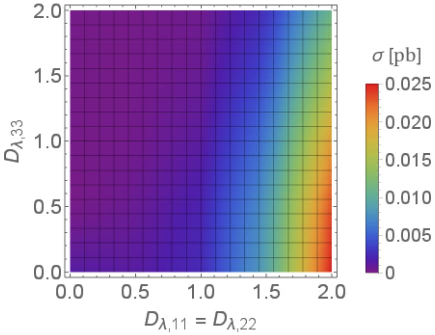
I	$SU(3)c$	$(N_\phi - N_{\phi^\dagger} + N_q + N_u + N_d - N_{\bar{q}} - N_{\bar{u}} - N_{\bar{d}}) \mod 3 = 0$
II	$U(3)_q$	$(N_q - N_{\bar{q}} + N_{Y_u} - N_{Y_u^\dagger} + N_{Y_d} - N_{Y_d^\dagger}) \mod 3 = 0$
III	$U(3)_u$	$(N_u - N_{\bar{u}} - N_{Y_u} + N_{Y_u^\dagger}) \mod 3 = 0$
IV	$U(3)_d$	$(N_d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

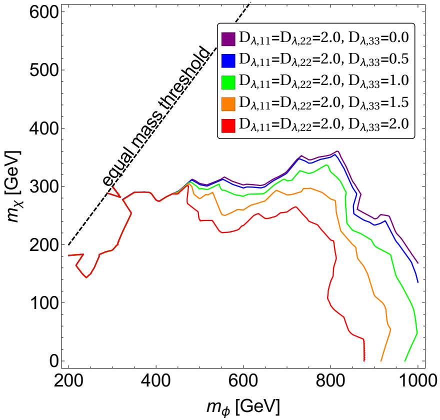
$\sum$ II+III+IV+V−I $(N_\chi - N_{\bar{\chi}} - N_\phi + N_{\phi^\dagger}) \mod 3 = 0$

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

t-DMFV and $jj + \not{E}_T$ at LHC8

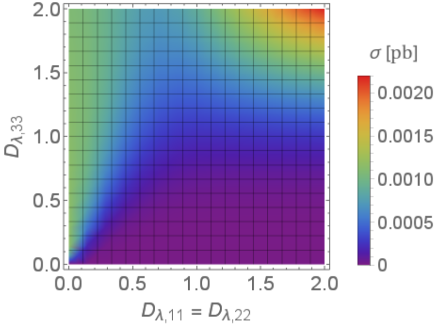
MB, Kast (2017)

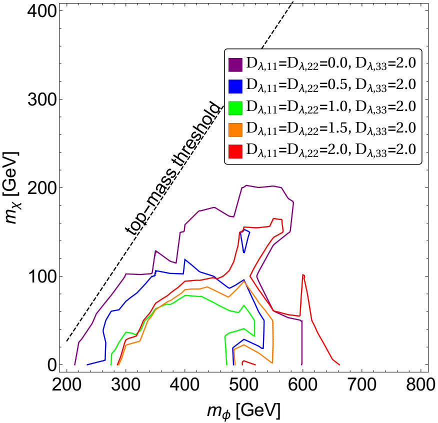




t-DMFV and $t\bar{t} + \not{E}_T$ at LHC8

MB, Kast (2017)

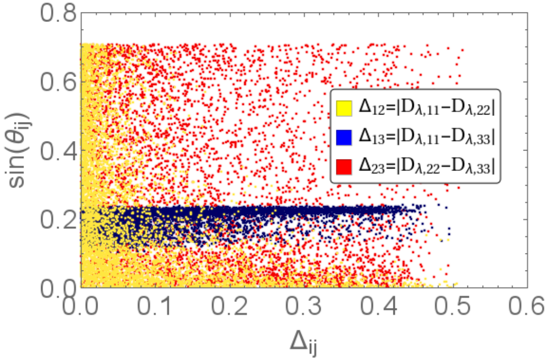




t-DMFV: Constraints on mixing angles

MB, Kast (2017)

combination of constraints implies non-trivial structure of coupling matrix



θ_{ij}: flavour mixing angles

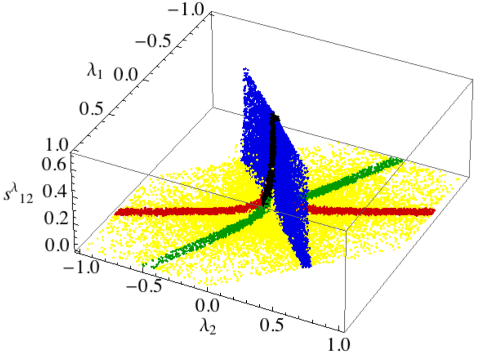
Δ_{ij}: splitting in coupling strength

b-DMFV: 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: $m_\phi = 850\,\mathrm{GeV}, m_\chi = 200\,\mathrm{GeV}, \lambda_0 = 1$

Agrawal, MB, Gemmler (2014)

b-DMFV: What about rare B and K decays?

$b \to s\gamma$ transition described by

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

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

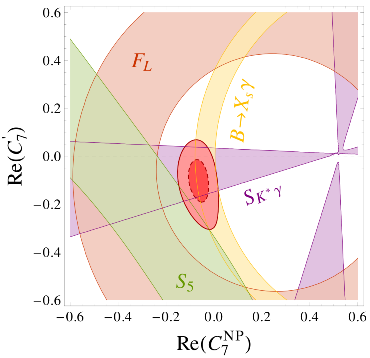
$$Q_7' \sim \bar{s}_R \sigma^{\mu\nu} b_L F_{\mu\nu}$$

➢ 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)



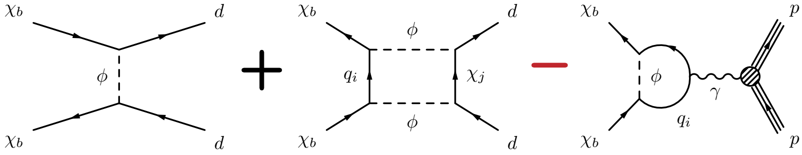
No new one-loop contribution to Z penguin and boxes:

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

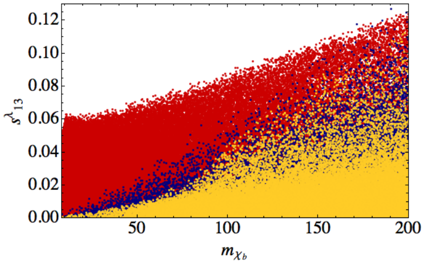
Agrawal, MB, Gemmler (2014)

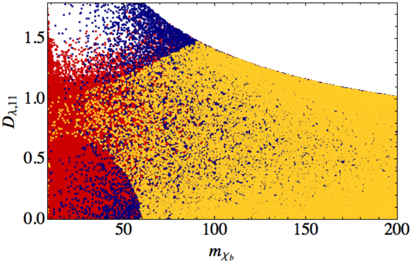
b-DMFV: Constraints from LUX & co.

Dark matter scattering off nuclei...



...constrains the DM coupling matrix λ

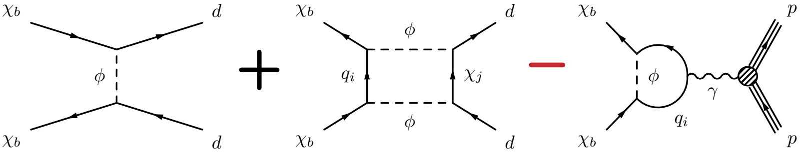




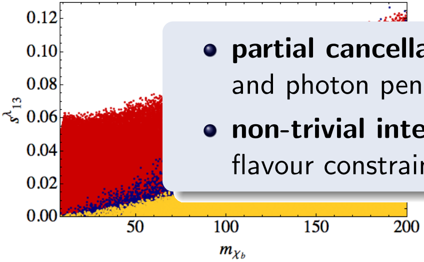
constraints imposed: LUX only, flavour only , LUX & flavour

b-DMFV: Constraints from LUX & co.

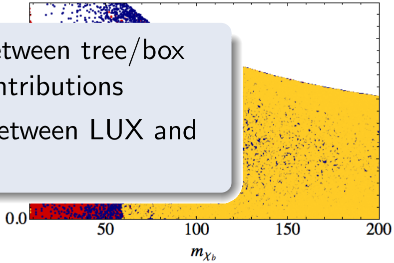
Dark matter scattering off nuclei...



...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

b-DMFV 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

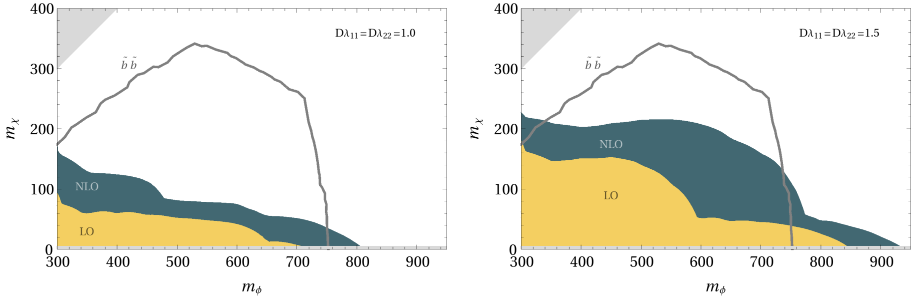
coloured scalar mediator ϕ

- 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

b-DMFV: 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



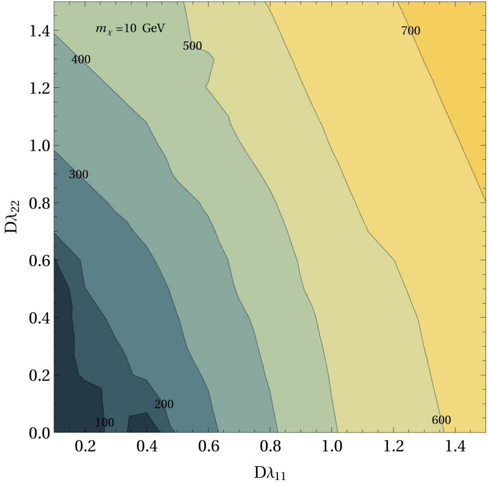
b-DMFV: Constraints from monojet searches I

- monojet searches sensitive to χ pair-production with ISR hard jet
- recasting 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)



b-DMFV: 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 $m_\chi \lesssim m_\phi$