Synergy of Flavour with the Energy and Cosmic Frontier

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TRR 257 - Particle Physics Phenomenology
after the Higgs Discovery

Future flavours: Prospects for beauty, charm and tau physics
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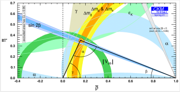
Motivation

Why study flavour beyond the Standard Model (BSM)?

- flavour and CP are not good symmetries of nature, already violated in the SM (Yukawa couplings, CKM matrix)
- concrete BSM models generally introduce new sources of flavour and CP violation
- B meson anomalies provide the most promising experimental hints for breakdown of SM at the TeV scale

Flavour vs. Rest of the World

flavour physics

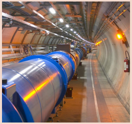


connection

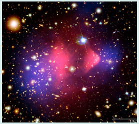
?

synergy

energy frontier



cosmic frontier



In this Talk

Two examples for flavour–collider–cosmology synergies

1. B anomalies and complementary probes at the LHC
2. flavoured Dark Matter and its LHC signatures

Part I

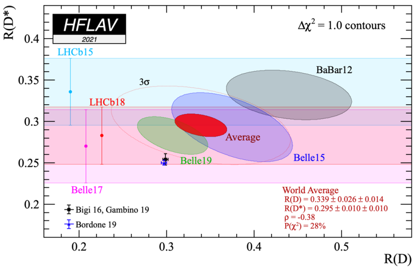
B anomalies and complementary probes at the LHC

The $\mathcal{R}(D^{(*)})$ Anomaly

Test of lepton flavour universality in semi-leptonic B decays

$$\mathcal{R}(D^{(*)}) = \frac{\text{BR}(B \to D^{(*)}\tau\nu)}{\text{BR}(B \to D^{(*)}\ell\nu)} \qquad (\ell = e, \mu)$$

➢ tension between SM prediction and data for 10 years!



- theoretically clean, as hadronic uncertainties largely cancel in ratio
- measurements by BaBar, Belle, and LHCb (so far $\mathcal{R}(D^*)$ only) in good agreement with each other
- LHCb found $\mathcal{R}(J/\psi)$ to be larger than expected in SM

➢ **3.4σ anomaly** HFLAV (2021)

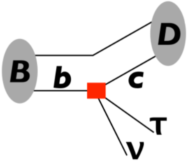
Effective Hamiltonian for $b \to c\tau\nu$

New Physics above B meson scale described model-independently[1] by

$$\mathcal{H}_{\rm eff} = 2\sqrt{2}G_F V_{cb}\Big[(1+C_V^L)O_V^L + C_S^R O_S^R + C_S^L O_S^L + C_T O_T\Big]$$

with the vector, scalar and tensor operators

$$O_V^L = (\bar{c}\gamma^\mu P_L b)\,(\bar{\tau}\gamma_\mu P_L \nu_\tau)$$
$$O_S^R = (\bar{c}P_R b)\,(\bar{\tau}P_L \nu_\tau)$$
$$O_S^L = (\bar{c}P_L b)\,(\bar{\tau}P_L \nu_\tau)$$
$$O_T = (\bar{c}\sigma^{\mu\nu} P_L b)\,(\bar{\tau}\sigma_{\mu\nu} P_L \nu_\tau)$$



Note: $(\bar{c}\gamma^\mu P_R b)\,(\bar{\tau}\gamma_\mu P_L \nu_\tau)$ not generated at dimension-six level in the $SU(2)_L \times U(1)_Y$-invariant theory

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[1] assuming heavy/no ν_R and NP only in τ channel

Possible Single-Particle Explanations

New Physics fit scenarios (tree level contributions)

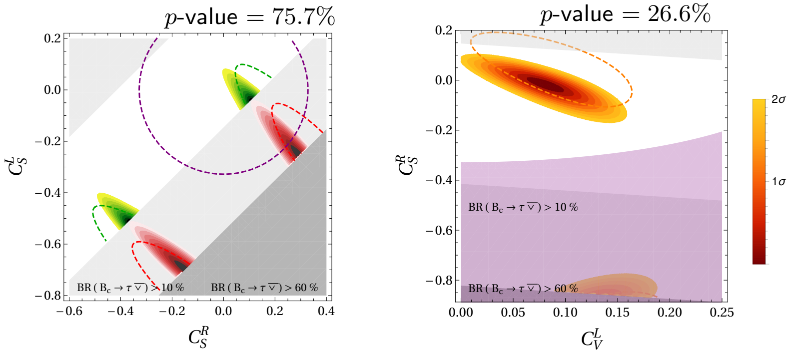
MB, Crivellin, Kitahara, Moscati, Nierste, Nišandžić (2019)

C_V^L	vector SU$(2)_L$-triplet W' boson – disfavoured by EW precision constraints
(C_S^R, C_S^L)	**charged Higgs boson**
(C_V^L, C_S^R)	SU$(2)_L$-singlet **vector leptoquark**
$(C_V^L, C_S^L = -4C_T)$	SU$(2)_L$-singlet scalar leptoquark
$(\mathrm{Re}[C_S^L = 4C_T],$ $\mathrm{Im}[C_S^L = 4C_T])$	scalar SU$(2)_L$-doublet leptoquark with CP-violating couplings

see also Aebischer et al (2019); Murgui et al (2019); Shi et al (2019)...

Two-Dimensional Fit Results

MB, Crivellin, Kitahara, Moscati, Nierste, Nišandžić (2019)

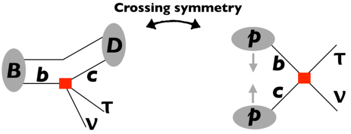


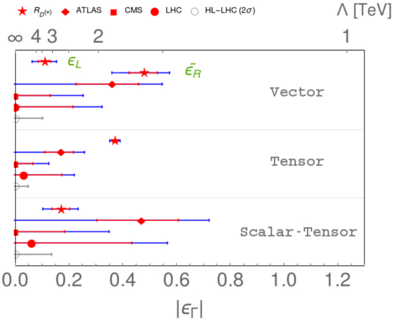
- good fit for both **charged Higgs** and **vector leptoquark** scenarios
- charged Higgs predicts large BR$(B_c \to \tau\nu)$ (not excluded!)
- in agreement with current LHC mono-τ constraints

More on LHC Mono-τ Searches

Greljo, Martin Camalich, Ruiz-Alvarez (2018)

- crossing symmetry relates $b \to c\tau\nu$ to $pp \to X\tau\nu$
- mono-$\tau + \not{E}_T$ signature probes NP models for $\mathcal{R}(D^{(*)})$ anomaly





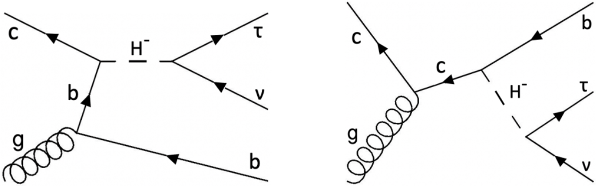
➢ **LHC has become competitive in testing the $\mathcal{R}(D^{(*)})$ anomaly**

- vector LQ not yet challenged
- charged Higgs resonantly produced
  ➢ ruled out for $m_{H^-} > 400$ GeV

Iguro, Omura, Takeuchi (2018)

What about a Light Charged Higgs?

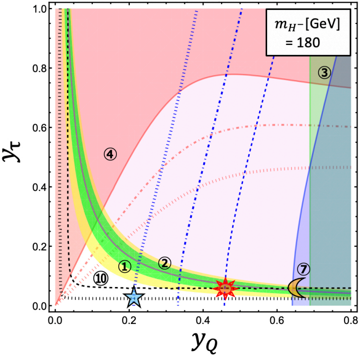
- light charged Higgs ($m_{H^-} < 400\,\mathrm{GeV}$) not excluded by mono-$\tau$ data due to huge $W \to \tau\nu$ background
- efficient background suppression by requiring additional b-tagged jet



➢ **Is this sufficient to exclude the charged Higgs solution to the $\mathcal{R}(D^{(*)})$ anomaly?**

MB, Iguro, Zhang (2022)

Reach of the $b\tau\nu$ Signature



MB, Iguro, Zhang (2022)

- H^- close to top threshold most difficult to exclude
- relevant constraints from SUSY stau and dijet searches at the LHC

Iguro (2022)

- performing dijet and **proposed $b\tau\nu$ search** with Run 2 data would *almost* exclude charged Higgs solution for $\mathcal{R}(D^{(*)})$
- final verdict from future LHC runs

Next Target: Leptoquarks

- "exotic"? – present in *any* theory unifying quarks and leptons
- favoured solution for the "B anomalies"
- most popular scenario: **$SU(2)$-singlet vector leptoquark $U_1 \equiv \Delta$**

➢ only single-particle scenario that can solve both $\mathcal{R}(D^{(*)})$ and $b \to s\mu\mu$ anomalies

➢ compatible with other flavour constraints

➢ no proton decay induced

➢ naturally contained in Pati-Salam gauge group $SU(4)_c \times SU(2)_L \times SU(2)_R$ Pati, Salam (1974)

➢ **non-trivial flavour structure required!**

Simplified Vector Leptoquark Model

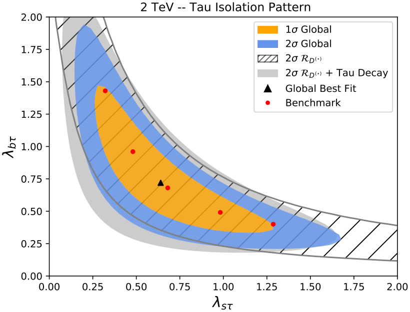
Tau isolation pattern

- minimal coupling scenario solving $\mathcal{R}(\mathcal{D}^{(*)})$

$$\lambda_{dl}^{[\tau]} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \lambda_{s\tau} \\ 0 & 0 & \lambda_{b\tau} \end{pmatrix}$$

- compatible with discrete flavour symmetry ansatz

  Bernigaud, de Medeiros, Talbert (2019)



➢ global flavour fit shows good agreement with $\mathcal{R}(D^{(*)})$ data

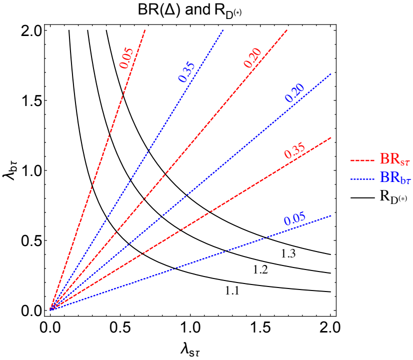
➢ benchmark points for subsequent collider analysis

Bernigaud, MB, de Medeiros, Talbert, Zurita (2021)

What Can We Learn from Direct LQ Searches?

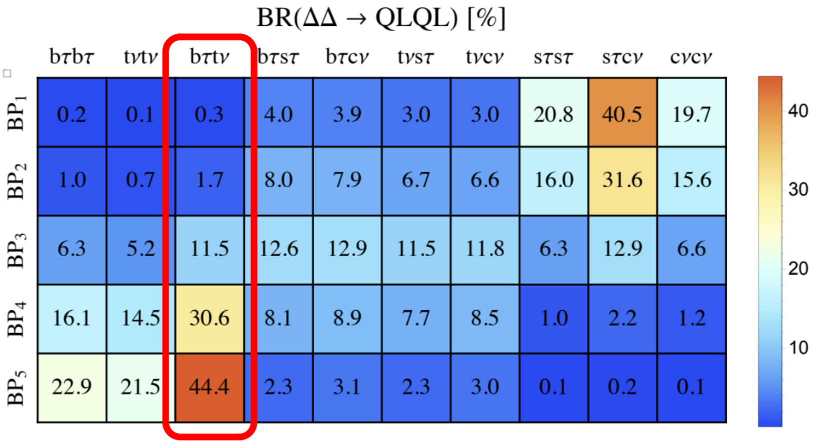
Bernigaud, MB, de Medeiros, Talbert, Zurita (2021)

- $\mathcal{R}(D^{(*)})$ constrain $\lambda_{b\tau}\lambda_{s\tau}/M^2$
- LQ mass M can be measured at LHC from pair-production cross-section and invariant mass
- branching ratios $\mathrm{BR}_{b\tau} \simeq \mathrm{BR}_{t\nu}$, $\mathrm{BR}_{s\tau} \simeq \mathrm{BR}_{c/u\nu}$ determine ratio of couplings $\lambda_{b\tau}/\lambda_{s\tau}$



➢ **synergy between flavour and collider data fully determines leptoquark parameters**

Leptoquark Branching Ratios: Pair Production



BR($\Delta\Delta \to QLQL$) [%]

	$b\tau b\tau$	$t\nu t\nu$	$b\tau t\nu$	$b\tau s\tau$	$b\tau c\nu$	$t\nu s\tau$	$t\nu c\nu$	$s\tau s\tau$	$s\tau c\nu$	$c\nu c\nu$
BP_1	0.2	0.1	0.3	4.0	3.9	3.0	3.0	20.8	40.5	19.7
BP_2	1.0	0.7	1.7	8.0	7.9	6.7	6.6	16.0	31.6	15.6
BP_3	6.3	5.2	11.5	12.6	12.9	11.5	11.8	6.3	12.9	6.6
BP_4	16.1	14.5	30.6	8.1	8.9	7.7	8.5	1.0	2.2	1.2
BP_5	22.9	21.5	44.4	2.3	3.1	2.3	3.0	0.1	0.2	0.1

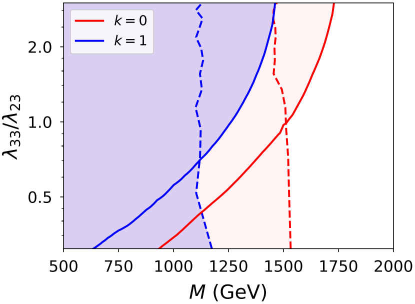
Bernigaud, MB, de Medeiros, Talbert, Zurita (2021)

Constraints from $b\tau\, t\nu$ – and jets+$\not\!\!E_T$

Bernigaud, MB, de Medeiros, Talbert, Zurita (2021)

Mixed channel $\Delta\Delta \to b\tau\, t\nu$

- reinterpretation of existing experimental analysis ATLAS (2021)
- strong sensitivity to coupling ratio $\lambda_{b\tau}/\lambda_{s\tau}$



jets+$\not\!\!E_T$ from final-state neutrinos

- identified in CheckMATE analysis
- less sensitive to LQ couplings
- complementary to $b\tau\, t\nu$

Part I Summary

- B **anomalies** among strongest hints for BSM physics
- dedicated LHC searches yield complementary information on underlying new particles and their coupling structure

NP scenarios for $\mathcal{R}(D^{(*)})$ anomaly

- charged Higgs explanation on the verge of being excluded by LHC $b\tau\nu$ data
- leptoquark pair-production with different final states can shed light on coupling structure

Part II

Flavoured Dark Matter and its LHC signatures

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?*

Kile, Soni (2011); Batell et al. (2011)
Kamenik, Zupan (2011)
Agrawal et al (2011)...

➢ **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

A Simplified Model of Top-Flavoured Dark Matter

Flavoured Dirac-fermionic DM[2] 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:[3] $m_{\chi_t} < m_{\chi_u}, m_{\chi_c}$

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[2] for flavoured Majorana DM see Acaroglu, MB (2021)

[3] 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)

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

Dark matter stability

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

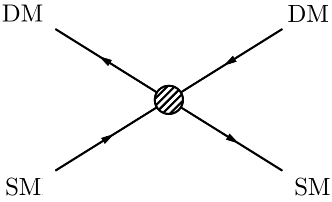
Parametrisation of DM-quark coupling

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

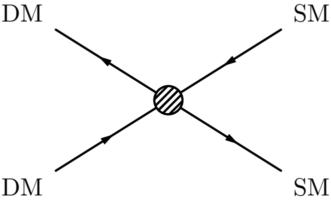
$$\lambda = U_\lambda D_\lambda$$

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

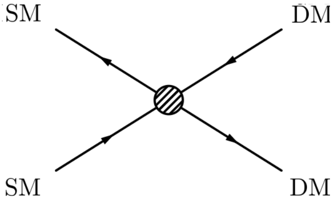
Constraints on Flavoured Dark Matter



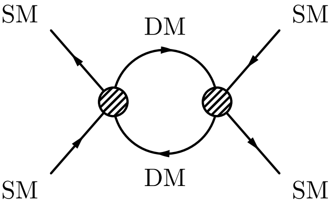
direct DM detection



DM relic abundance



LHC searches

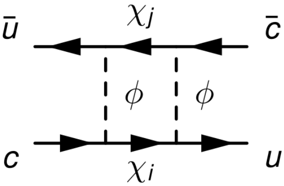


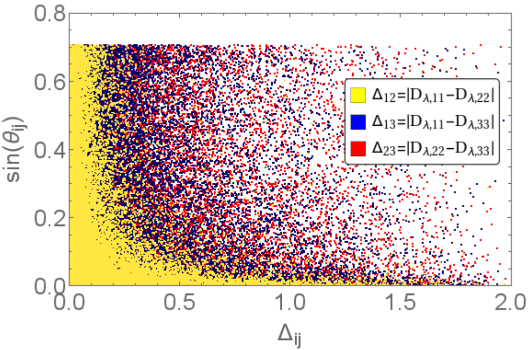
precision flavour data

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 $\chi_{u,c}$:

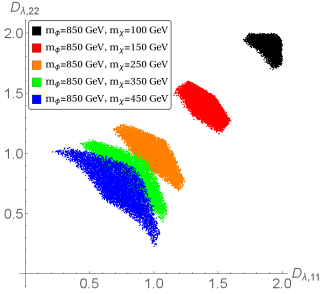
$$\boxed{\Delta_{12} \ll 1 \quad \text{or} \quad \theta_{12} \sim 0}$$

Constraint from Observed Relic Abundance

- 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**

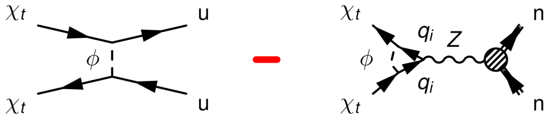
MB, Kast (2017)



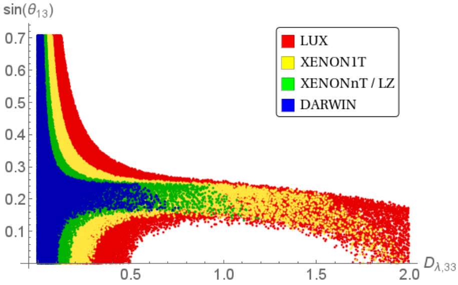
QDF scenario

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)

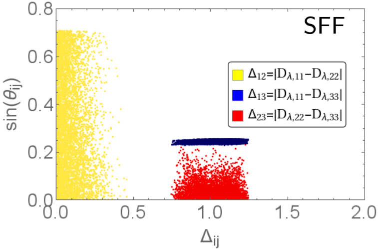
Phenomenological Sweet-Spots

Experimental constraints from

- flavour physics
- DM relic abundance
- DM direct detection

place **stringent limits** on the model

MB, Kast (2017)



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

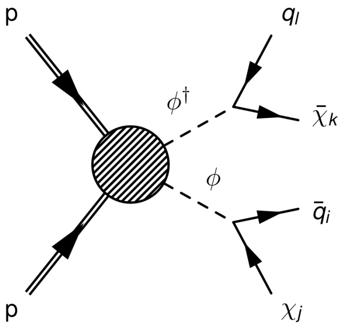
Benchmark Scenarios for LHC Studies

	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 ($\propto D^2_{\lambda,11}$)
  ➢ most stringent constraints
- signatures similar to SUSY squarks

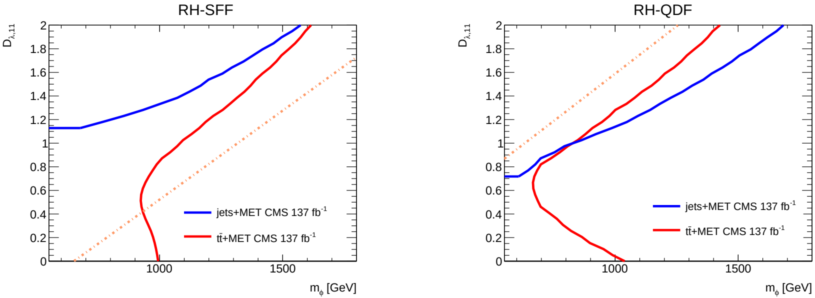
$$t\bar{t} + \not{E}_T \qquad jj + \not{E}_T$$

  ➢ 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 fb^{-1} Search for Multijet+$\not{E}_T$

MB, Pani, Polesello, Rovedi (2020)

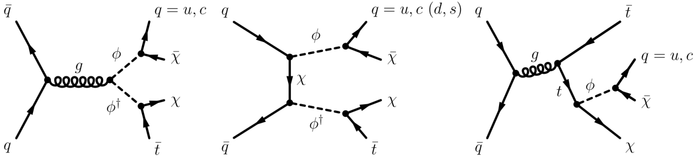


- sensitivity depends on overall coupling strength
- weaker limits in QDF scenario (approx. equal couplings)
- thermal relic scenario still viable in SFF scenario

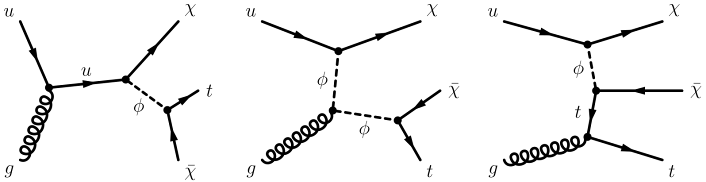
Single-Top Signatures of Top-Flavoured Dark Matter

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

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

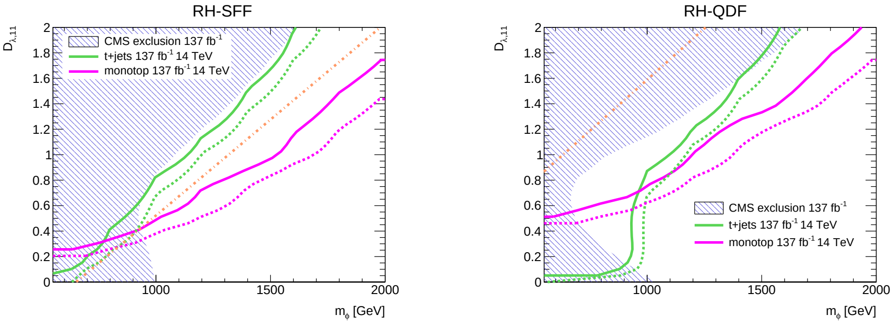


- “monotop” $t + \not{E}_T$



MB, Pani, Polesello, Rovedi (2020)

(HL-)LHC Reach for Single-Top Final States

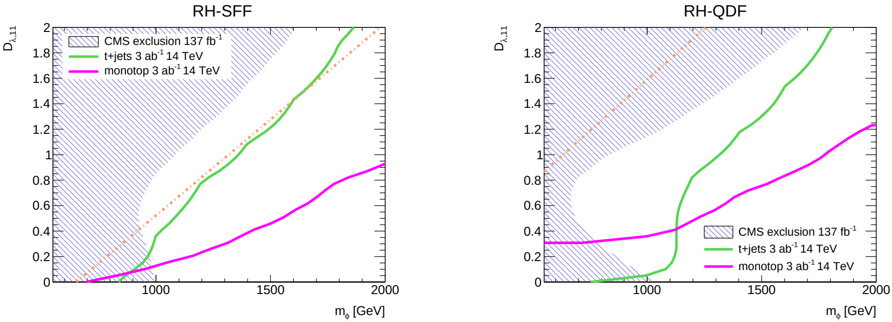


Dedicated single-top searches

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

Part II Summary

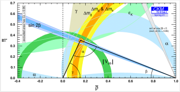
- **flavoured Dark Matter** can reconcile WIMP hypothesis
- interplay of phenomenological constraints from flavour physics, direct DM detection, DM relic abundance and collider data

Top-flavoured Dark Matter

- viable WIMP model despite stringent constraints
- induces LHC single-top signatures as promising future search channels

Flavour vs. Rest of the World?

flavour physics



connection

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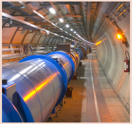
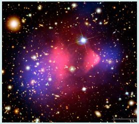
synergy

energy frontier

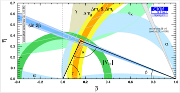


cosmic frontier



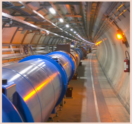
Flavour is Part of the World!

flavour physics



connection
interplay
synergy

energy frontier



cosmic frontier