

Flavoured dark matter versus SMS* portal

* Standard Model Scalar

Laura Lopez Honorez

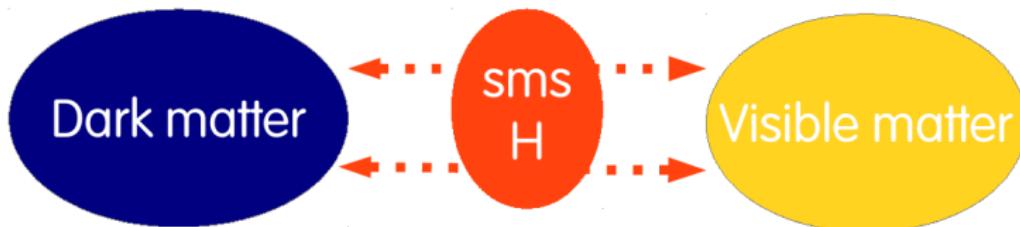
to be on ArXiv soon
in collaboration with Luca Merlo



Vrije
Universiteit
Brussel

Rencontres de Moriond-EW Session 2013

SMS portal



- $(H^\dagger H)$ - dark sector operators drive the SM-DM interactions

[Silveira & Zee'85 ; McDonald'94 ; Burgess, Pospelov& ter Veldhuis'00 ; Patt & Wilczek'06 ; Barger et al'08 ; Andreas, Hambye, Tytgat'08,...]

SMS portal



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- DM = SM singlet scalar S :
 - DM stability : Z_2 symmetry
 - sms-DM interactions : $\lambda_S S^2 (H^\dagger H)$

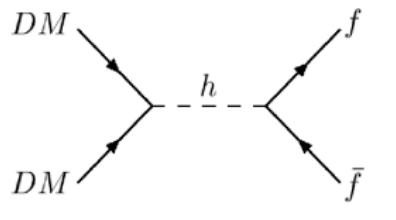
SMS portal



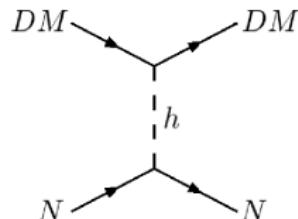
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Annihilation



Scattering

DM stability recipe within MFV context

[Batell,Pradler, Spannowsky '11]

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- Minimal Flavour Violation hypothesis

[Chivukula & Georgi'87, Hall & Randall'90, D'Ambrosio, Giudice, Isidori & Strumia'02,...]

- introduced to **protect** quark flavour mixing beyond the SM
- assume that the Flavour sym. is the one of the kinetic terms of \mathcal{L}_{SM} :
Global Flavour sym. G_f
- only broken by Yukawas promoted to be aux. fields

~~ MFV initially motivated to suppress large flavour violating processes in NP scenarios

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- Dark Matter

- charged under G_f
- representation under $G_f \rightsquigarrow$ no S decays into SM allowed

\rightsquigarrow MFV initially motivated to suppress large flavour violating processes in
 NP scenarios also provide an interesting framework for DM

Scalar flavoured DM model

- Global Flavour sym. of q sector : $G_f = SU(3)_{Q_L} \times SU(3)_{U_R} \times SU(3)_{D_R}$
- Minimal representation that guarantee stability [Batell,Pradler, Spannowsky '11] :
 $S \sim (\mathbf{1}, \mathbf{1}, \mathbf{1})|_{SM} \times (\mathbf{3}, \mathbf{1}, \mathbf{1})|_{G_f} \rightsquigarrow 3$ DM candidates

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SMS-portal :

$$\begin{aligned} V &\supset m_S^2 S_i^* \mathbf{I}_{ij} S_j + \lambda S_i^* \mathbf{I}'_{ij} S_j H^\dagger H \\ &\rightsquigarrow \mathcal{L} \supset -S_i^* [m_A^2 + m_B^2 \mathbf{y}_{u_i}^2] S_i - \frac{1}{2} \lambda_i v h S_i^* S_i \end{aligned}$$

with $\mathbf{I}_{ij} = (a \mathbf{1}_{ij} + b (Y_u Y_u^\dagger)_{ij} + \dots)$ and $m_A, m_B, \lambda_i = fn(a, a', b, b', \lambda)$

$\rightsquigarrow S_1, S_2$ quite degenerate due to $\mathbf{y}_u, \mathbf{y}_c$

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DM-q dim 6-operators :

$$\mathcal{L}_{eff} \supset \frac{c_{ijkl}}{\Lambda_{DM}^2} \mathcal{O}_{ijkl}$$

• Vector type

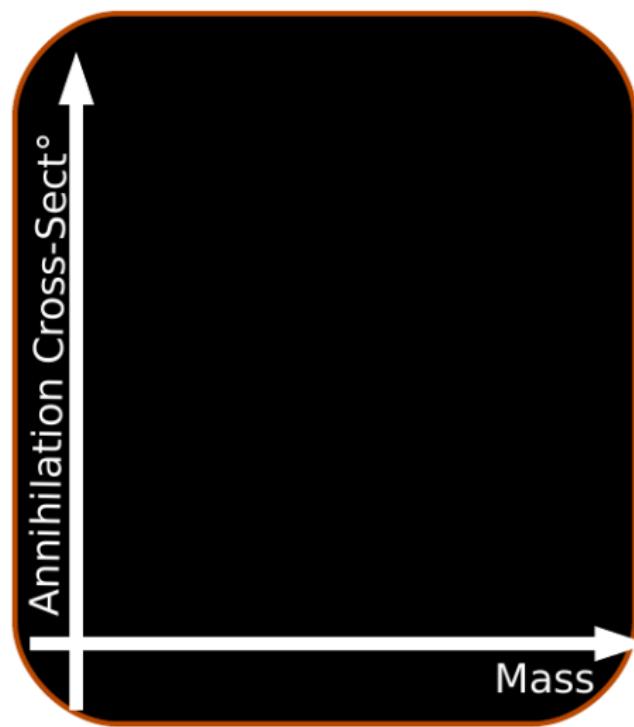
$$\mathcal{O}_{ijkl} = (\bar{Q}_{L_i} \gamma^\mu Q_{L_j})(S_k^* \overleftrightarrow{\partial}_\mu S_\ell)$$

$$\mathcal{O}_{ijkl} = (\bar{q}_{R_i} \gamma^\mu q_{R_j})(S_k^* \overleftrightarrow{\partial}_\mu S_\ell)$$

• Scalar type

$$\mathcal{O}_{ijkl} = (\bar{Q}_{L_i} q_{R_j})(S_k^* S_\ell) H + \text{h.c.}$$

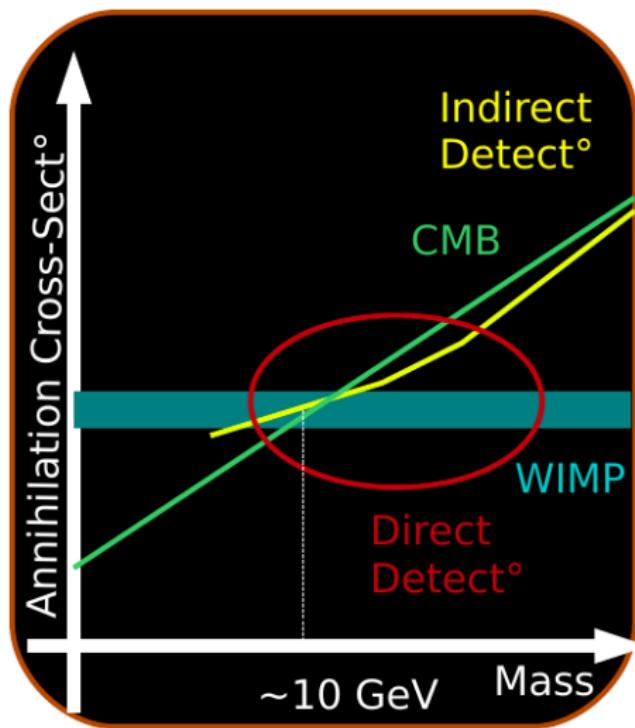
Constraints SMS Portal only



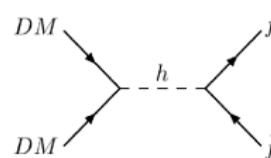
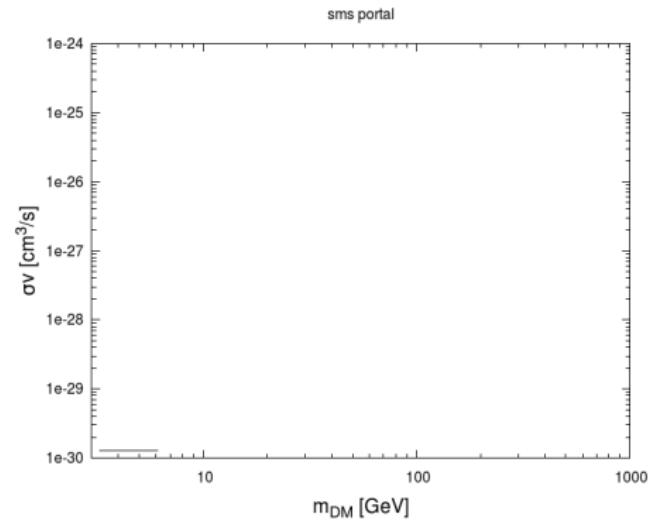
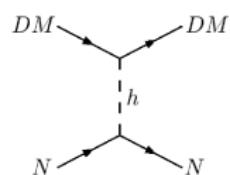
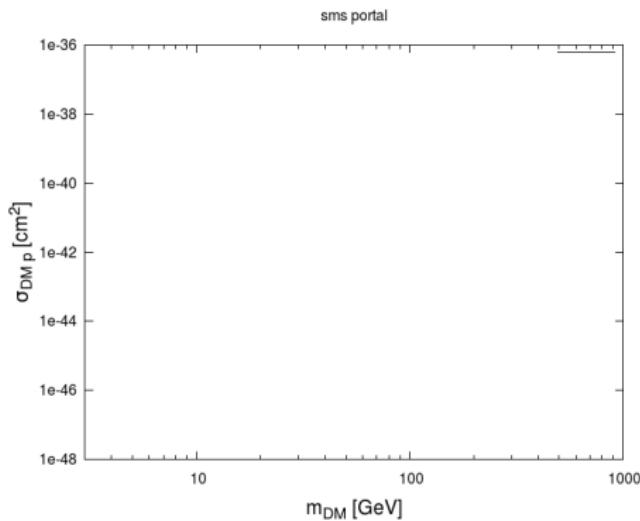
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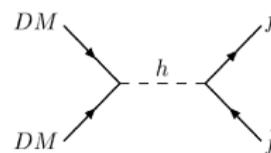
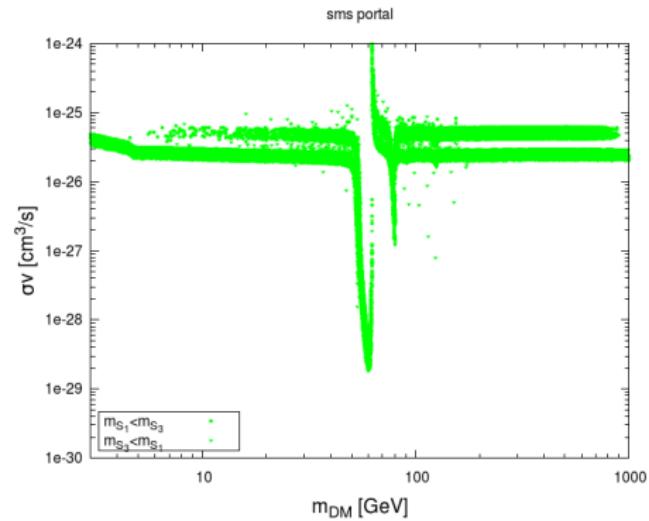
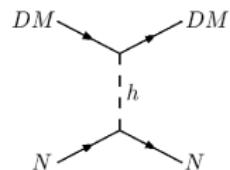
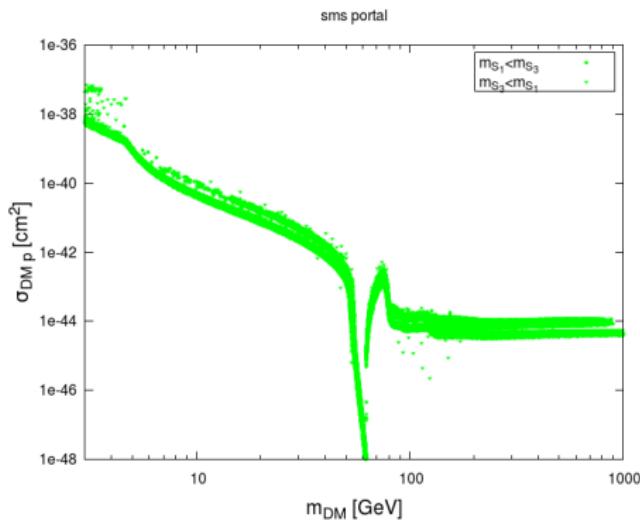
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$$\mathcal{L} \supset -\lambda_i v h S_i^* S_i$$

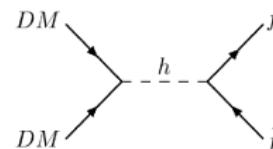
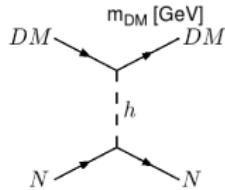
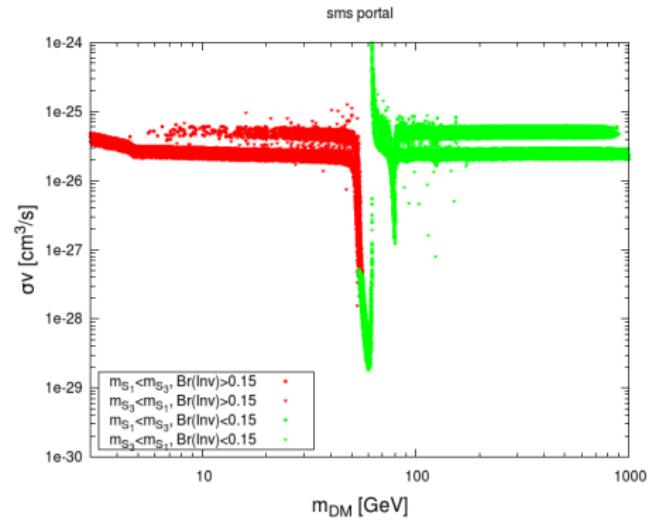
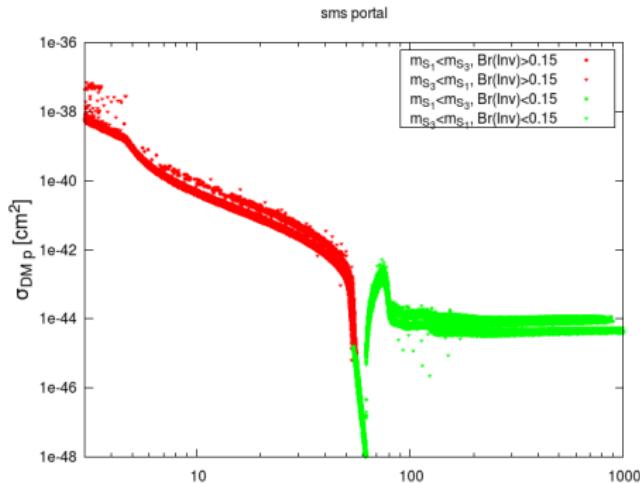


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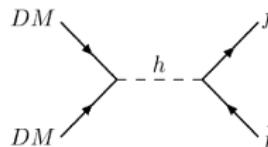
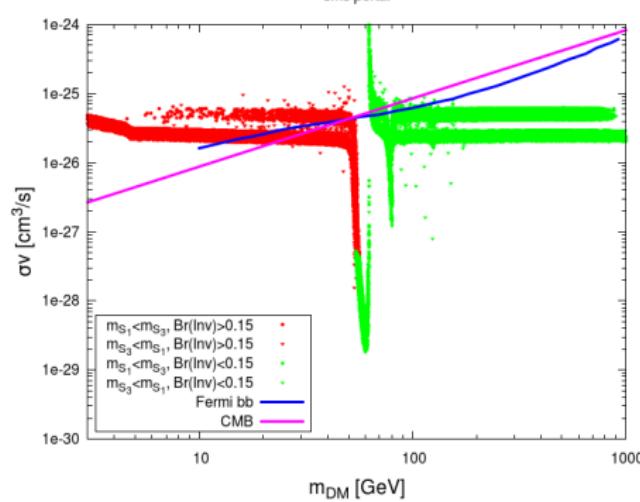
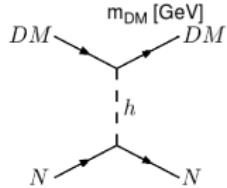
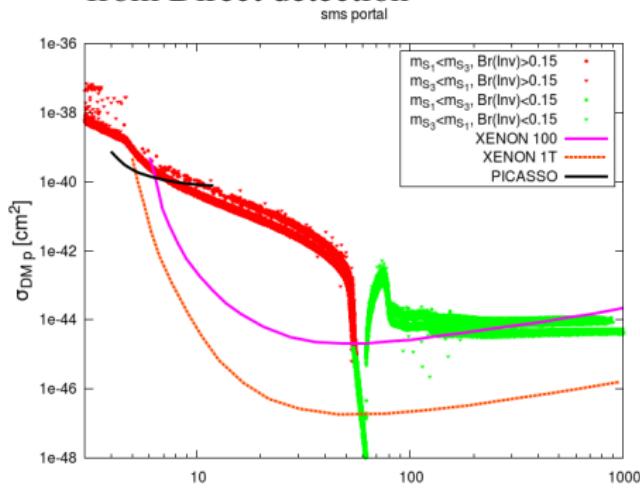
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- Constraints from Colliders : restricted $\Gamma(h \rightarrow S_i S_j^*)$ [Giardino et al. '12]



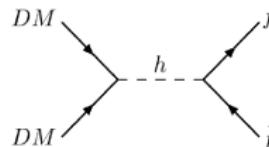
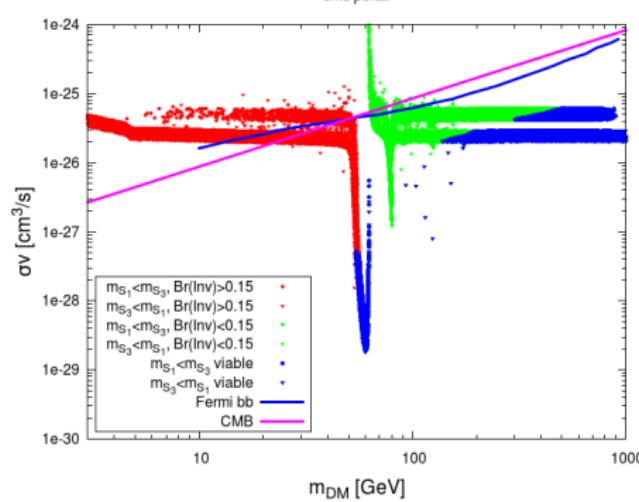
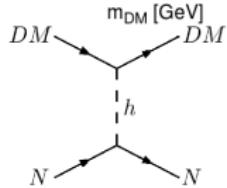
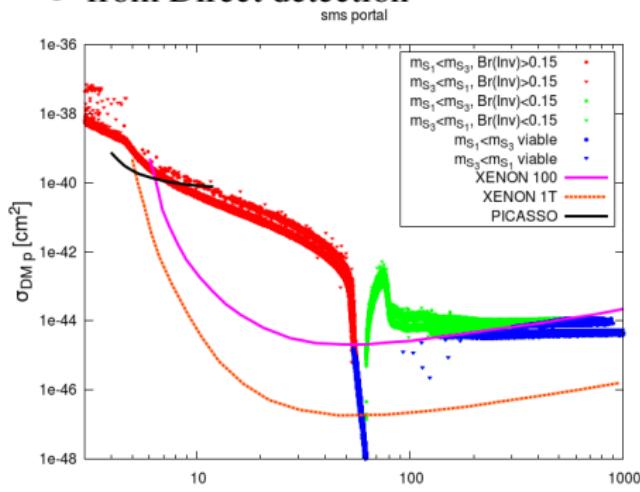
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- from Indirect detection & CMB

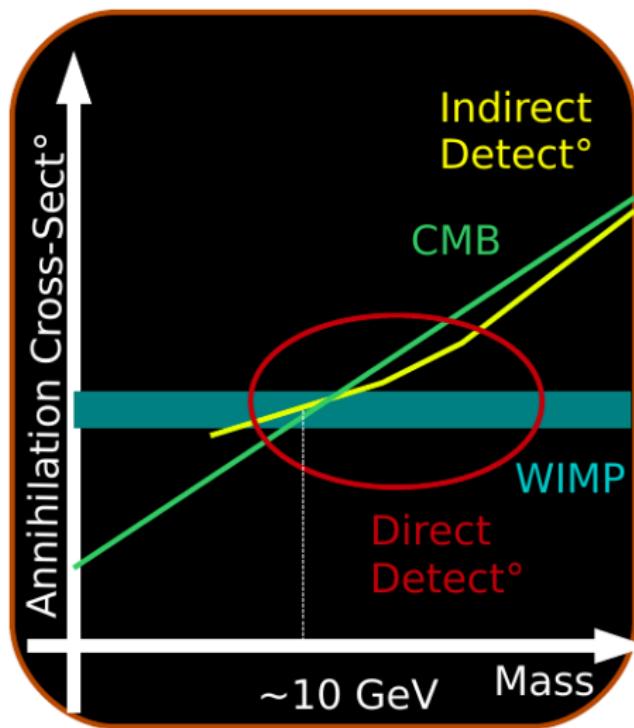


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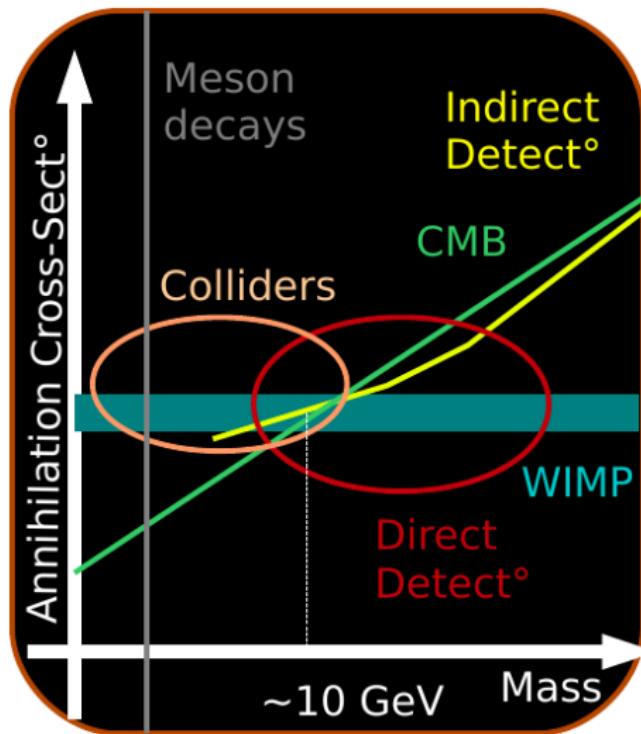
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Constraints SMS Portal + dim-6 Oper.

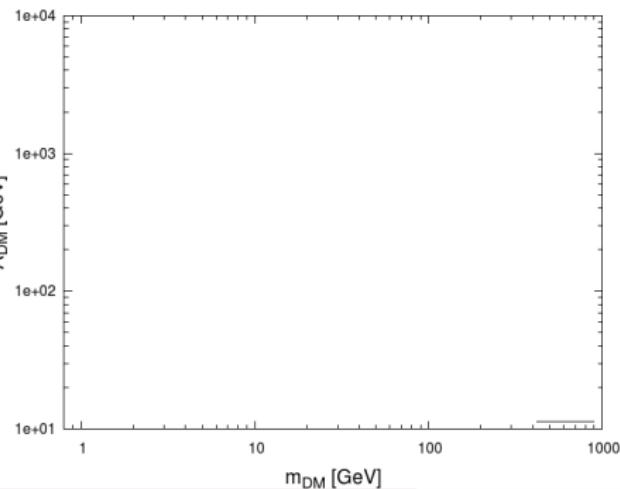


Constraints SMS Portal + dim-6 Oper.



$$\mathcal{L} \supset -\lambda_i v h S_i^* S_i + \frac{c_{ijkl}}{\Lambda_{DM}^2} \mathcal{O}_{ijkl}$$

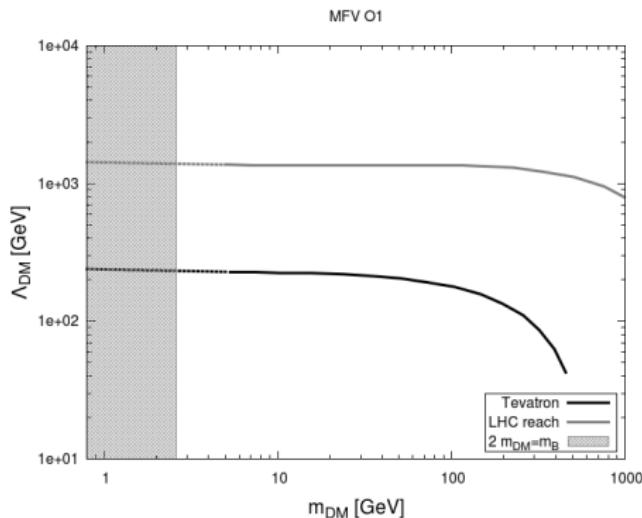
MFV O1



$$\mathcal{L} \supset -\lambda_i v h S_i^* S_i + \frac{c_{ijkl}}{\Lambda_{DM}^2} \mathcal{O}_{ijkl}$$

Extra constraints :

- from mono jets at colliders [Goodman '10]
- from flavour : meson decays constrain e.g $b \rightarrow dX$ [Kamenik '12]
 ↵ rules out $m_{DM} < m_D/2$ or $m_B/2$

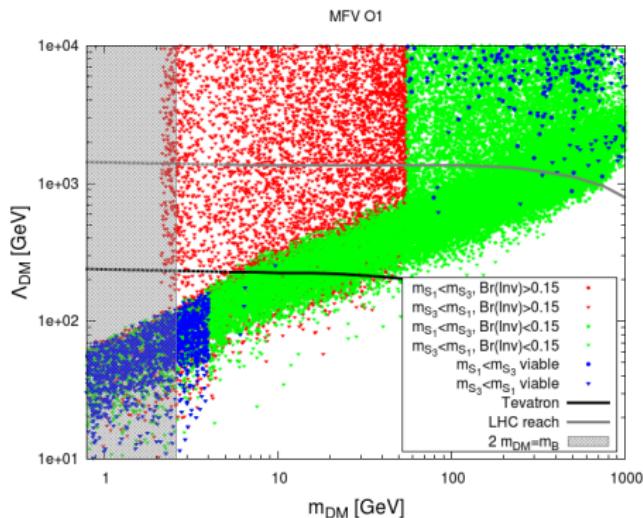


- Vector Type Interaction
 e.g. $\mathcal{O}_{ijkl} = (\bar{Q}_{Li} \gamma^\mu Q_{Lj})(S_k^* \overleftrightarrow{\partial}_\mu S_\ell)$

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Extra constraints :

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 - ~~ rules out low $m_{DM} \sim \text{GeV}$ for vector type interactions
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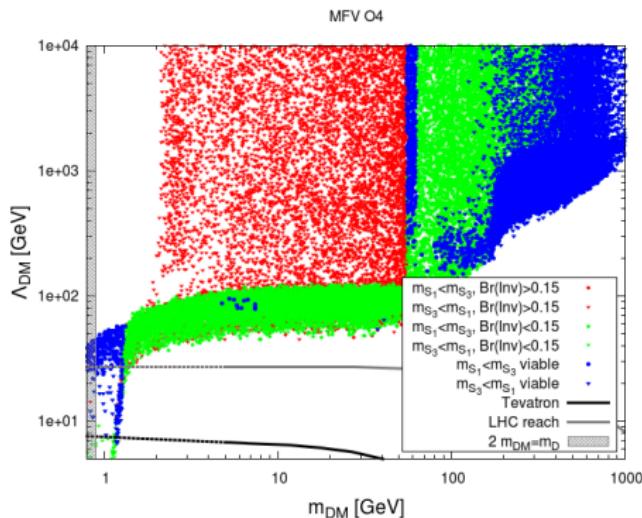


- Vector Type Interaction
 - e.g. $\mathcal{O}_{ijkl} = (\bar{Q}_{L_i} \gamma^\mu Q_{L_j})(S_k^* \overleftrightarrow{\partial}_\mu S_\ell)$
 - ~~ monojets rules out small m_{DM}

$$\mathcal{L} \supset -\lambda_i v h S_i^* S_i + \frac{c_{ijkl}}{\Lambda_{DM}^2} \mathcal{O}_{ijkl}$$

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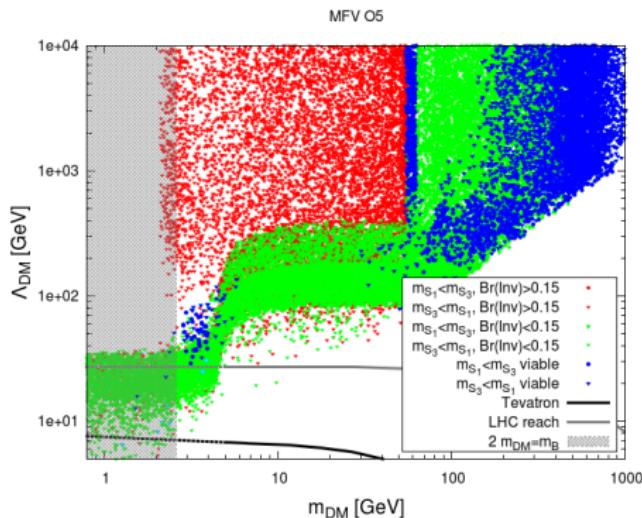


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 e.g. $\mathcal{O}_{ijkl} = (\bar{Q}_{L_i} \gamma^\mu Q_{L_j})(S_k^* \overleftrightarrow{\partial}_\mu S_\ell)$
 ↵ monojets rules out small m_{DM}
- Scalar Type Interaction
 e.g. $\mathcal{O}_{ijkl} = (\bar{Q}_{L_i} q_{R_j})(S_k^* S_\ell) \tilde{H} + \text{h.c.}$
 ↵ $m_q \bar{u}_i u_j S_k^* S_\ell$
 ↵ less constrained

$$\mathcal{L} \supset -\lambda_i v h S_i^* S_i + \frac{c_{ijkl}}{\Lambda_{DM}^2} \mathcal{O}_{ijkl}$$

Extra constraints :

- from monojets at colliders [Goodman '10]
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- from flavour : meson decays constrain e.g $b \rightarrow dX$ [Kamenik '12]
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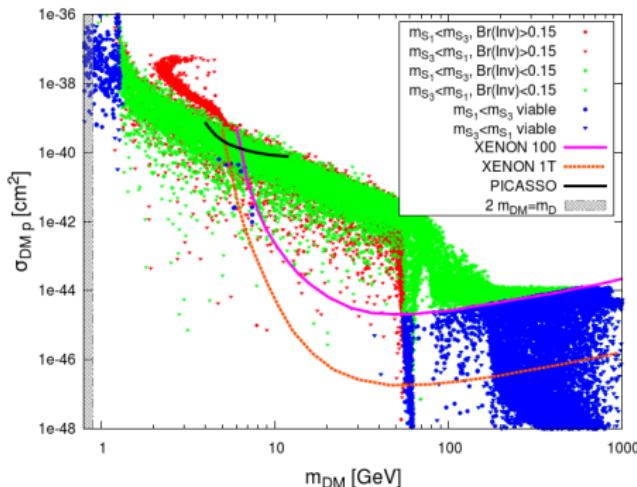
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 e.g. $\mathcal{O}_{ijkl} = (\bar{Q}_{L_i} q_{R_j})(S_k^* S_\ell) \tilde{H} + \text{h.c.}$
 ↵ $m_q \bar{u}_i u_j S_k^* S_\ell$ or $m_q \bar{d}_i d_j S_k^* S_\ell$
 ↵ less constrained

$\mathcal{L} \supset -\lambda_i v h S_i^* S_i + \frac{c_{ijkl}}{\Lambda_{DM}^2} \mathcal{O}_{ijkl}$ with scalar type interaction

- $\mathcal{O}_{ijkl} = (\bar{Q}_{L_i} u_{R_j})(S_k^* S_\ell) \tilde{H} + \text{h.c.}$

$$\rightsquigarrow m_{u_\alpha} \bar{u}_i u_j S_k^* S_\ell$$

MFV O4



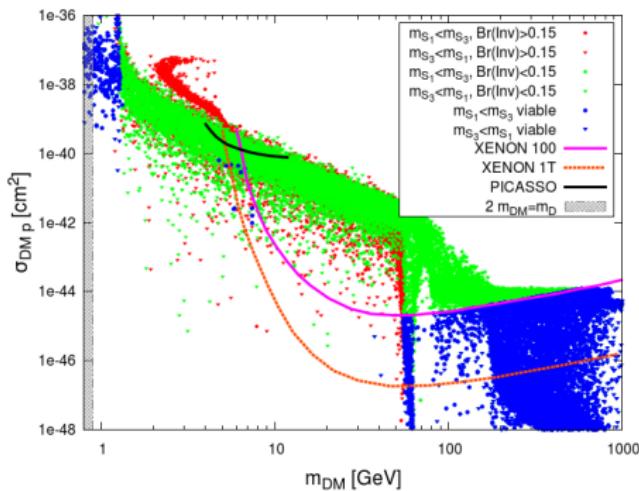
Allow for $m_{DM} < 10$ GeV and $m_{DM} > m_h/2$ in particular :

- for $m_{DM} < 10$ GeV : coannihilations $S_1 S_2^* \xrightarrow{\Lambda_{DM}} \bar{c} u$
- for $m_{DM} > m_t$: annihilations $S_i S_i^* \xrightarrow{\Lambda_{DM}} \bar{t} t$

$\mathcal{L} \supset -\lambda_i v h S_i^* S_i + \frac{c_{ijkl}}{\Lambda_{DM}^2} \mathcal{O}_{ijkl}$ with scalar type interaction

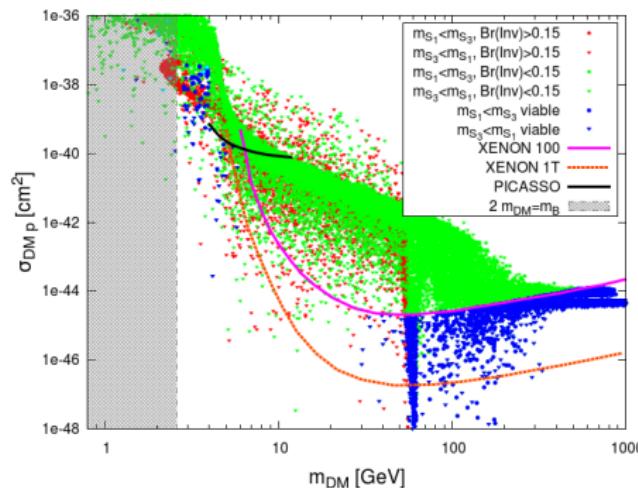
- $\mathcal{O}_{ijkl} = (\bar{Q}_{L_i} u_{R_j})(S_k^* S_\ell) \tilde{H} + \text{h.c.}$
- $\rightsquigarrow m_{u_\alpha} \bar{u}_i u_j S_k^* S_\ell$

MFV O4



- $\mathcal{O}_{ijkl} = (\bar{Q}_{L_i} d_{R_j})(S_k^* S_\ell) \tilde{H} + \text{h.c.}$
- $\rightsquigarrow m_{d_\alpha} \bar{d}_i d_j S_k^* S_\ell$

MFV O5



Allow for $m_{DM} < 10$ GeV and $m_{DM} > m_h/2$ in particular :

- for $m_{DM} < 10$ GeV : coannihilations $S_1 S_2^* \xrightarrow{\Lambda_{DM}} \bar{c}u, S_1 S_3^* \xrightarrow{\Lambda_{DM}} \bar{b}d, S_2 S_3^* \xrightarrow{\Lambda_{DM}} \bar{b}s$
- for $m_{DM} > m_t$: annihilations $S_i S_i^* \xrightarrow{\Lambda_{DM}} \bar{t}t$

Conclusion

Embedding DM within DM scenario in the MFV framework can be interesting as **DM stability is granted** for certain representations under the flavour group.

We analyzed the parameter space in agreement with $\Omega_{DM} h^2$ and studied

- the constraints by **DM direct and indirect searches**
- the constraints by **CMB, colliders and SMS searches**
- the constraints by **flavour observables** such as Meson decays

The flavour structure allows for extra DM-f interactions that give rise to a new parameter space that could evade future searches such as Xenon 1T

- for $m_{DM} < 10 \text{ GeV}$ thanks to coannihilations into two flavours of quarks
- for $m_{DM} > m_t$ thanks to annihilation into $t\bar{t}$ through Λ_{DM} interactions

Thank you for your attention !!!

Backup

Representations under Gf

Focusing on the quark sector only, the latter presents a global flavour symmetry whose non-Abelian part is given by

$$G_f = SU(3)_{Q_L} \times SU(3)_{U_R} \times SU(3)_{D_R}. \quad (1)$$

The $SU(2)_L$ doublet Q_L and singlets u_R and d_R transform according to

$$Q_L \sim (\mathbf{3}, \mathbf{1}, \mathbf{1}), \quad u_R \sim (\mathbf{1}, \mathbf{3}, \mathbf{1}), \quad d_R \sim (\mathbf{1}, \mathbf{1}, \mathbf{3}), \quad (2)$$

while the Yukawa spurions transform as

$$Y_u \sim (\mathbf{3}, \bar{\mathbf{3}}, \mathbf{1}), \quad Y_d \sim (\mathbf{3}, \mathbf{1}, \bar{\mathbf{3}}), \quad (3)$$

ensuring the invariance under G_f of the Yukawa Lagrangian,

$$\mathcal{L}_Y = -\bar{Q}_L \tilde{H} Y_u u_R - \bar{Q}_L H Y_d d_R + \text{h.c.}.$$

$$\mathcal{L} \supset \frac{c_{ijkl}}{\Lambda_{DM}^2} \mathcal{O}_{ijkl}$$

$$\begin{aligned}
(\mathcal{O}_1)_{ijkl} &= (\bar{Q}_{L_i} \gamma^\mu Q_{L_j})(S_k^* \overleftrightarrow{\partial_\mu} S_\ell), \\
(\mathcal{O}_2)_{ijkl} &= (\bar{u}_{R_i} \gamma^\mu u_{R_j})(S_k^* \overleftrightarrow{\partial_\mu} S_\ell), \\
(\mathcal{O}_3)_{ijkl} &= (\bar{d}_{R_i} \gamma^\mu d_{R_j})(S_k^* \overleftrightarrow{\partial_\mu} S_\ell), \\
(\mathcal{O}_4)_{ijkl} &= (\bar{Q}_{L_i} u_{R_j})(S_k^* S_\ell) \tilde{H} + \text{h.c.}, \\
(\mathcal{O}_5)_{ijkl} &= (\bar{Q}_{L_i} d_{R_j})(S_k^* S_\ell) H + \text{h.c.},
\end{aligned}$$

$$\begin{aligned}
c_{ijkl}^1 &= c_1^1 \mathbf{1}_{ij} \mathbf{1}_{kl} + c_2^1 \mathbf{1}_{il} \mathbf{1}_{kj} + c_3^1 (Y_u Y_u^\dagger)_{ij} \mathbf{1}_{kl} + \\
&\quad + c_4^1 \mathbf{1}_{ij} (Y_u Y_u^\dagger)_{kl} + c_5^1 (Y_u Y_u^\dagger)_{i\ell} \mathbf{1}_{kj} + \dots \\
c_{ijkl}^2 &= c_1^2 \mathbf{1}_{ij} \mathbf{1}_{kl} + c_2^2 (Y_u^\dagger Y_u)_{ij} \mathbf{1}_{kl} + \\
&\quad + c_3^2 \mathbf{1}_{ij} (Y_u Y_u^\dagger)_{kl} + c_4^2 (Y_u^\dagger)_{i\ell} (Y_u)_{kj} + \dots \\
c_{ijkl}^3 &= c_1^3 \mathbf{1}_{ij} \mathbf{1}_{kl} + c_2^3 (Y_d^\dagger Y_d)_{ij} \mathbf{1}_{kl} + \\
&\quad + c_3^3 \mathbf{1}_{ij} (Y_u Y_u^\dagger)_{kl} + c_4^3 (Y_d^\dagger)_{i\ell} (Y_d)_{kj} + \dots \\
c_{ijkl}^4 &= c_1^4 (Y_u)_{ij} \mathbf{1}_{kl} + c_2^4 \mathbf{1}_{i\ell} (Y_u)_{kj} + \\
&\quad + c_3^4 (Y_u)_{ij} (Y_u Y_u^\dagger)_{kl} + c_4^4 (Y_u Y_u^\dagger)_{i\ell} (Y_u)_{kj} + \dots \\
c_{ijkl}^5 &= c_1^5 (Y_d)_{ij} \mathbf{1}_{kl} + c_2^5 \mathbf{1}_{i\ell} (Y_d)_{kj} + \\
&\quad + c_3^5 (Y_d)_{ij} (Y_u Y_u^\dagger)_{kl} + c_4^5 (Y_u Y_u^\dagger)_{i\ell} (Y_d)_{kj} + \dots
\end{aligned}$$

[Batell,Pradler, Spannowsky '11]

(n, m)	$SU(3)_Q \times SU(3)_{u_R} \times SU(3)_{d_R}$	Stable?
$(0, 0)$	$(\mathbf{1}, \mathbf{1}, \mathbf{1})$	
$(1, 0)$	$(\mathbf{3}, \mathbf{1}, \mathbf{1}), (\mathbf{1}, \mathbf{3}, \mathbf{1}), (\mathbf{1}, \mathbf{1}, \mathbf{3})$	Yes
$(0, 1)$	$(\bar{\mathbf{3}}, \mathbf{1}, \mathbf{1}), (\mathbf{1}, \bar{\mathbf{3}}, \mathbf{1}), (\mathbf{1}, \mathbf{1}, \bar{\mathbf{3}})$	Yes
$(2, 0)$	$(\mathbf{6}, \mathbf{1}, \mathbf{1}), (\mathbf{1}, \mathbf{6}, \mathbf{1}), (\mathbf{1}, \mathbf{1}, \mathbf{6})$ $(\mathbf{3}, \mathbf{3}, \mathbf{1}), (\mathbf{3}, \mathbf{1}, \mathbf{3}), (\mathbf{1}, \mathbf{3}, \mathbf{3})$	Yes
$(0, 2)$	$(\bar{\mathbf{6}}, \mathbf{1}, \mathbf{1}), (\mathbf{1}, \bar{\mathbf{6}}, \mathbf{1}), (\mathbf{1}, \mathbf{1}, \bar{\mathbf{6}})$ $(\bar{\mathbf{3}}, \bar{\mathbf{3}}, \mathbf{1}), (\bar{\mathbf{3}}, \mathbf{1}, \bar{\mathbf{3}}), (\mathbf{1}, \bar{\mathbf{3}}, \bar{\mathbf{3}})$	Yes
$(1, 1)$	$(\mathbf{8}, \mathbf{1}, \mathbf{1}), (\mathbf{1}, \mathbf{8}, \mathbf{1}), (\mathbf{1}, \mathbf{1}, \mathbf{8})$ $(\mathbf{3}, \bar{\mathbf{3}}, \mathbf{1}), (\mathbf{3}, \mathbf{1}, \bar{\mathbf{3}}), (\mathbf{1}, \mathbf{3}, \bar{\mathbf{3}})$ $(\bar{\mathbf{3}}, \mathbf{3}, \mathbf{1}), (\bar{\mathbf{3}}, \mathbf{1}, \mathbf{3}), (\mathbf{1}, \bar{\mathbf{3}}, \mathbf{3})$	

TABLE I. Flavored DM candidates. Listed are the lowest-dimensional representations of G_q , organized according (n, m) where $n \equiv n_Q + n_u + n_d$, $m \equiv m_Q + m_u + m_d$. We have also indicated the representations that are stable once MFV is imposed. Depending on their electroweak quantum numbers, these multiplets may contain viable DM candidates.

parameter ranges for the scans

$$0.3 < |a, a', b, b', c_a^\alpha| < 1.3$$

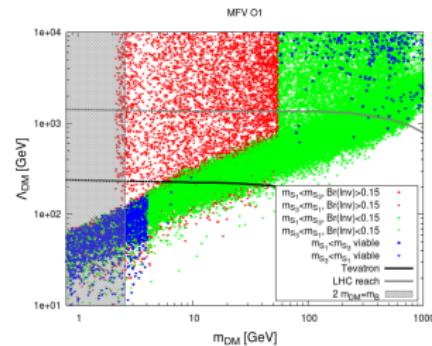
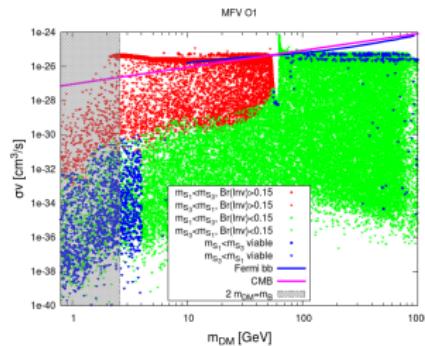
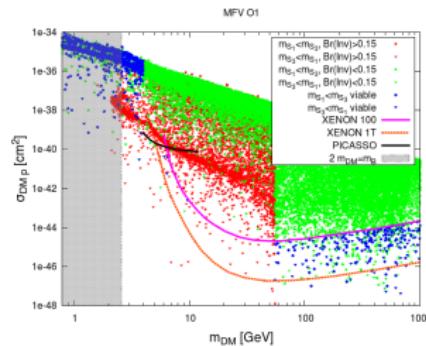
$$0.1 \text{ GeV} < m_{S_3} < 1 \text{ TeV}$$

$$m_{DM} < \Lambda_{DM} < 10 \text{ TeV}$$

$$10^{-5} < |\lambda| < \pi$$

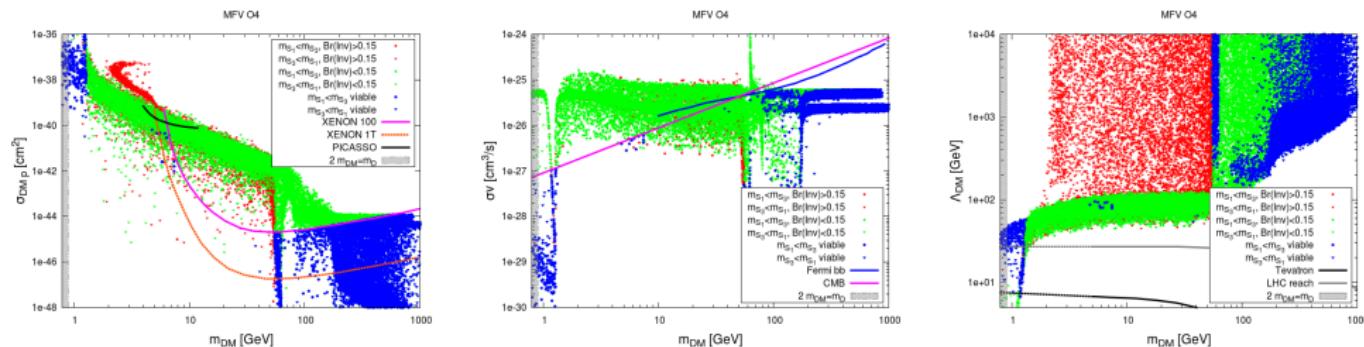
$$\mathcal{L} \supset \frac{c_{ijkl}}{\Lambda_{DM}^2} \mathcal{O}_{ijkl}$$

$$\mathcal{O}_{ijkl} = (\bar{Q}_{L_i} \gamma^\mu Q_{L_j})(S_k^* \overleftrightarrow{\partial}_\mu S_\ell)$$



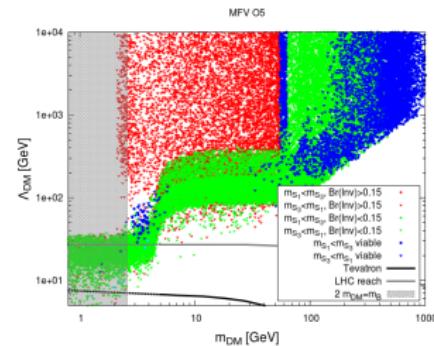
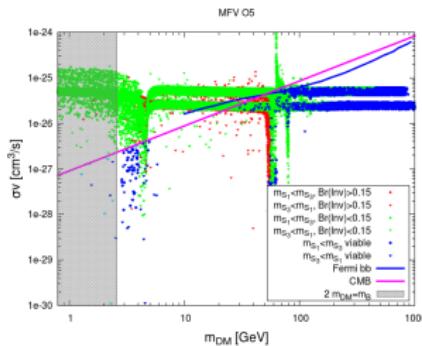
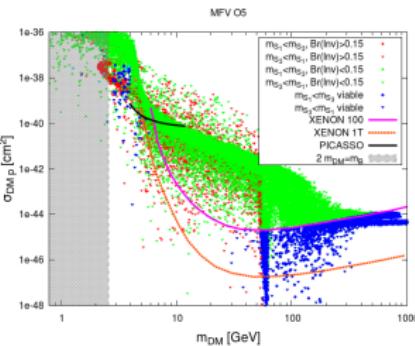
$$\mathcal{L} \supset \frac{c_{ijkl}}{\Lambda_{DM}^2} \mathcal{O}_{ijkl}$$

$$\mathcal{O}_{ijkl} = (\bar{Q}_{L_i} u_{R_j})(S_k^* S_\ell) H + \text{h.c.}$$



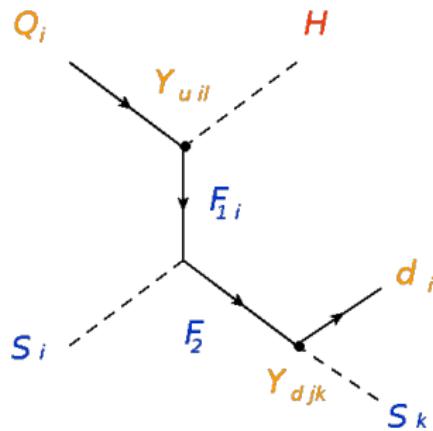
$$\mathcal{L} \supset \frac{c_{ijkl}}{\Lambda_{DM}^2} \mathcal{O}_{ijkl}$$

$$\mathcal{O}_{ijkl} = (\bar{Q}_{L_i} d_{R_j})(S_k^* S_\ell) H + \text{h.c.}$$



Possible UV completion

$$\begin{aligned}\mathcal{O}_{ijkl} &= (\bar{Q}_{L_i} d_{R_j})(S_k^* S_\ell) H + \text{h.c.} \rightsquigarrow \frac{c}{\Lambda_{DM}^2} (\bar{Q}_{L_i} S_i)(S_k^* Y_{d\,kj} d_{R_j}) H \\ &\rightsquigarrow \text{coannihilations } S_1 S_3^* \xrightarrow{\Lambda_{DM}} \bar{b} d, S_2 S_3^* \xrightarrow{\Lambda_{DM}} \bar{b} s\end{aligned}$$



A possibility :

$$\begin{aligned}\mathcal{L} \supset & \alpha \bar{Q}_i Y_{u\,i\ell} F_{1\,\ell} + \beta \bar{F}_2 S_j^* Y_{d\,kj} d_k \\ & + \gamma S_i \bar{F}_1 F_2 + h.c\end{aligned}$$

$$F_1 \sim (\mathbf{1}, \mathbf{3}, \mathbf{1}), \quad F_2 \sim (\mathbf{1}, \mathbf{1}, \mathbf{1}).$$

[D'Ambrosio, Giudice, Isidori & Strumia'02]

Minimally flavour violating dimension six operator	main observables	Λ [TeV]
		− +
$\mathcal{O}_0 = \frac{1}{2}(\bar{Q}_L \lambda_{\text{FC}} \gamma_\mu Q_L)^2$	$\epsilon_K, \Delta m_{B_d}$	6.4 5.0
$\mathcal{O}_{F1} = H^\dagger (\bar{D}_R \lambda_d \lambda_{\text{FC}} \sigma_{\mu\nu} Q_L) F_{\mu\nu}$	$B \rightarrow X_s \gamma$	9.3 12.4
$\mathcal{O}_{G1} = H^\dagger (\bar{D}_R \lambda_d \lambda_{\text{FC}} \sigma_{\mu\nu} T^a Q_L) G_{\mu\nu}^a$	$B \rightarrow X_s \gamma$	2.6 3.5
$\mathcal{O}_{\ell 1} = (\bar{Q}_L \lambda_{\text{FC}} \gamma_\mu Q_L)(\bar{L}_L \gamma_\mu L_L)$	$B \rightarrow (X) \ell \bar{\ell}, K \rightarrow \pi \nu \bar{\nu}, (\pi) \ell \bar{\ell}$	3.1 2.7 *
$\mathcal{O}_{\ell 2} = (\bar{Q}_L \lambda_{\text{FC}} \gamma_\mu \tau^a Q_L)(\bar{L}_L \gamma_\mu \tau^a L_L)$	$B \rightarrow (X) \ell \bar{\ell}, K \rightarrow \pi \nu \bar{\nu}, (\pi) \ell \bar{\ell}$	3.4 3.0 *
$\mathcal{O}_{H1} = (\bar{Q}_L \lambda_{\text{FC}} \gamma_\mu Q_L)(H^\dagger i D_\mu H)$	$B \rightarrow (X) \ell \bar{\ell}, K \rightarrow \pi \nu \bar{\nu}, (\pi) \ell \bar{\ell}$	1.6 1.6 *
$\mathcal{O}_{q5} = (\bar{Q}_L \lambda_{\text{FC}} \gamma_\mu Q_L)(\bar{D}_R \gamma_\mu D_R)$	$B \rightarrow K \pi, \epsilon'/\epsilon, \dots$	~ 1

Table 1: **Bounds on MFV operators.** The SM is extended by adding minimally flavour-violating dimension-six operators with coefficient $\pm 1/\Lambda^2$ (+ or − denote their constructive or destructive interference with the SM amplitude). Here we report the bounds at 99% CL on Λ , in TeV, for the single operator (in the most representative cases). Fine-tuned scenarios with small Λ , such that new physics flips the sign of the SM amplitude are not reported (see text). The * signals the cases where a significant increase in sensitivity is expected in the near future.

This is really the end