Dark Matter & Flavor

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Based on: FB and J. Zupan. [arXiv:1408.3852] &
FB, A. Greljo, J. Kamenik, E. Stamou, and J. Zupan. [To appear]

Motivation

- ▷ There is overwhelming evidence for the existence of DM yet the SM model lacks a candidate
- ▷ The WIMP "miracle"
- ▷ There is a coincidence $\Omega_\chi/\Omega_B = 5.4$; could there be a link?
- ▷ We expect New Physics (NP) at the TeV scale (WIMP miracle, hierarchy problem)
- ▷ However, NP cannot have generic flavor structure
  - Large FCNCs if $\Lambda_{\rm NP} \sim$ TeV (NP flavor problem)
- ▷ Flavor approximately conserved in SM AND can lead to DM stability.

Outline

- The SM + NP puzzles: flavor & DM
  - Flavor breaking: MFV, maximally non-MFV.
  - Dark matter: thermal, non-thermal.
- Flavor singlet Asymmetric Dark Matter:
  - Metastability & flavor breaking.
  - ADM mass & lifetime.
  - Mediator models and experimental bounds.
- Flavored WIMP Dark Matter:
  - MFV Dark Matter.
  - Maximally non-MFV Dark Matter.

ADM, DM stability and flavor

There is a vast literature on the topic. Some examples include

- ADM

  Nussinov (1985), Hooper, March-Russell & West [hep-ph/0410114], Kaplan, Luty & Zurek [aXv:0901.4117], Feldstein & Fitzpatrick [aXv:1003.5662], Dutta & Kumar [aXv:1012.1341], Cohen, Phalen, Pierce & Zurek [aXv:1005.1655], Falkowski, Ruderman & Volansky [aXv:1101.4936]

- MFV

  Kamenik & Zupan [aXv:1107.0623], Batell, Pradler & Spannowsky [aXv:1105.1781], Batell, Lin & Wang [aXv:1309.4462], SUSY MFV: Csaki, Grossman & Heidenreich [aXv:1111.1239], Monteux & Cornell [aXv:1404.5952]

- Lepton and quark flavored DM

  Agrawal, Blanchet, Chacko & Kilic [aXv:1109.3516], Kumar & Tulin [aXv:1303.0332], Agrawal, Batell, Hooper & Lin [aXv:1404.1373]

- Beyond MFV

  Agrawal, Blanke & Gemmler [aXv:1405.6709]

Dark Matter

- Stable on cosmological time scales
  - Introduce new continuous or discrete symmetries ($U(N), Z_N$).
  - Accidental symmetries
- Observed relic density
  - Set by thermal freezeout (WIMP)
  - Non-thermal in origin (ADM)

The SM and the NP flavor problem

- Flavor is approximately conserved in the SM. In the limit $m_f \to 0$, $\mathcal{L}_{SM}$ is invariant under

$$\mathcal{G}_F = SU(3)_Q \times SU(3)_U \times SU(3)_D \times \ldots$$

where … denote the $U(1)$ factors and the flavor symmetry of the lepton sector.

- BSM models generally involve new sources of flavor breaking.

- Severely constrained by low energy flavor observables.

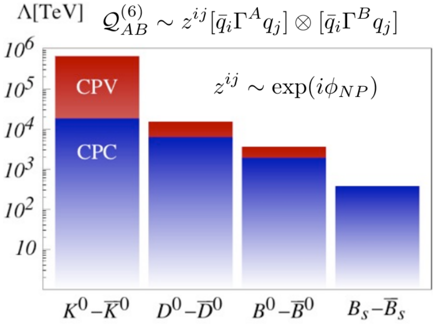


Figure credit: Jernej Kamenik

Asymmetric Dark Matter

Cosmological history of the ADM

$T \gg T_{\text{EWPT}}$	$B \longleftrightarrow \Delta\chi$	Asymmetric operators in equilibrium. Baryon asymmetry transferred to DM.
$T_f > T_{\text{EWPT}}$	$B \not\longleftrightarrow \Delta\chi$	Asymmetric operators freezeout. DM number separately conserved.
$T \lesssim m_\chi$	$\chi\bar{\chi} \longrightarrow \text{SM}, \gamma_d\gamma_d, \ldots$	Symmetric component of DM is efficiently annihilated away.

▷ N.B.: more complicated thermal histories are possible[1]

[1] See, e.g., Falkowski, Ruderman, & Volansky [arXiv:1101.4936].

The roadmap

- $\triangleright$ Flavor & SM gauge singlet DM charged under $U(1)_{(B-L)}$

  $\Rightarrow$ DM is either a Dirac fermion or a complex scalar

- $\triangleright$ Assume that $B \neq 0$ and $L = 0$ to focus the discussion

- $\triangleright$ DM is a color singlet $\Rightarrow$ carries integer Baryon number

- $\triangleright$ Will not assume any discrete symmetry to stabilize DM

Goal

A cosmologically stable DM with $\Lambda_{\mathrm{NP}} \sim \mathcal{O}(\mathrm{TeV})$

ADM mass

Assumptions

- ▷ $B - L$ is a conserved quantum number
- ▷ Symmetric component efficiently annihilated

In this case, the ADM mass (with SM field content) is given by

$$m_\chi = m_p \frac{\Omega_\chi}{\Omega_B} \left(\frac{B}{B-L} \right) \left(\frac{B-L}{\Delta\chi} \right) = (12.5 \pm 0.8\,\mathrm{GeV}) \frac{1}{(B-L)_\chi^{\mathrm{sum}}}$$

where

$$(B-L)_\chi^{\mathrm{sum}} \equiv \sum_i \hat{g}_\chi^i (B-L)_\chi^i$$

ADM mass

- E.g., for one Dirac fermion DM, $g_\chi = 2$ and

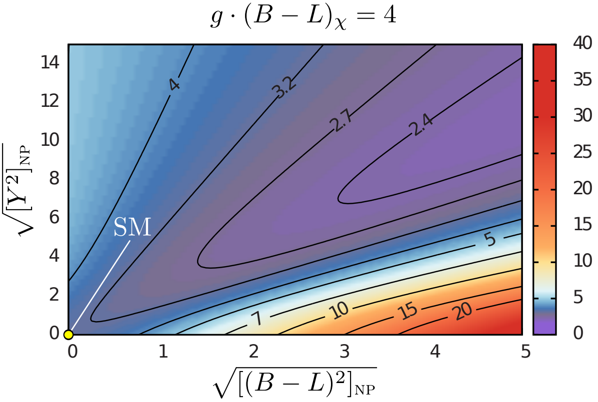
$$m_\chi = (6.2 \pm 0.4\,\text{GeV})\frac{1}{(B-L)_\chi}$$

$$m_\chi = \{6.2,\ 3.1,\ 2.1\}\,\text{GeV}, \qquad \text{for } (B-L)_\chi = \{1, 2, 3\}$$

ADM mass in the presence of New Physics (NP)

- If the visible sector contains more states beyond the SM, the DM mass will be affected.

- For a complex scalar DM with $B = 2$, the DM mass is



Asymmetric EFT operators

The lowest dimensional asymmetric operators are of the form

$$\mathcal{L} = \sum_i \frac{\mathcal{C}_i}{\Lambda^{(D_i-4)}} \chi \mathcal{O}_i^{\rm SM},$$

$$\text{with}^1\ \mathcal{O}^{\rm SM} = [u^c]^{n_u}\ [d^c]^{n_d}\ [q^*]^{n_q}\,,$$

$$\text{and}\ \begin{cases} (n_d + n_u + n_q) \mod 3 = 0 \\ n_d - 2n_u - n_q/2 = 0 \end{cases}$$

[1] The fields u^c and d^c are the $SU(2)_L$ singlet up and down type quark fields while q is the $SU(2)_L$ doublet quark field in two component spinor notation.

Freeze-out temperature of asymm. operators

- The NDA estimate for the freeze-out temperature is (FN flavor breaking)

$$T_f \sim \left(1.66 \times \sqrt{g_*}\,(16\pi^2)^3 \frac{8\pi}{C^2} \frac{\Lambda^{12}}{M_{\rm pl}}\right)^{1/11} \simeq 480\ \text{GeV} \left(\frac{\Lambda}{1.9\,\text{TeV}}\right)^{12/11}$$

- The EFT scale $\Lambda > 1.9$ TeV is bounded by indirect detection searches.
- Dominated by the $2 \to 5$ process.
- DM number is conserved below T_f.

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Metastability and flavor breaking

To calculate the DM lifetime we must

- Choose the flavor structure. We will consider two flavor breaking scenarios: Minimal Flavor Violation (MFV) and Froggatt-Nielsen (FN)

- Rotate to the mass eigenbasis. We will work in the down mass basis where

$$u^c \to u^c_{\text{MASS}}, \qquad d^c \to d^c_{\text{MASS}}, \qquad q = \begin{pmatrix} u \\ d \end{pmatrix} \to \begin{pmatrix} V_{\text{CKM}}\, u_{\text{MASS}} \\ d_{\text{MASS}} \end{pmatrix}.$$

  and the Yukawa matrices are

$$Y_D \to Y_D^{\text{diag}}, \quad Y_U \to V_{\text{CKM}}\, Y_U^{\text{diag}}$$

- Using Naive dimensional analysis (NDA), estimate DM total width

Minimal Flavor Violation[1] (MFV)

- $\mathcal{L}_{\text{SM}}$ enjoys an enhanced symmetry G_F in the limit $m_q \to 0$
- $G_F = SU(3)_Q \times SU(3)_U \times SU(3)_D$
- Symmetry is retained if Yukawa matrices are promoted to spurions that transform under G_F as

$$Y_U \sim (\mathbf{3}, \overline{\mathbf{3}}, \mathbf{1}), \qquad Y_D \sim (\mathbf{3}, \mathbf{1}, \overline{\mathbf{3}})$$

- The Yukawa interactions $u^c Y_U^\dagger q H$, $d^c Y_D^\dagger q H^c$ are then formally invariant under G_F

The SM Yukawas are the only source of flavor breaking.

[1] Chivukula & Georgi (1987); Hall & Randall (1990); Buras, Gambino, Gorbahn, Jager & Silvestrini (2001); D'Ambrosio, Giudice, Isidori & Strumia (2002);

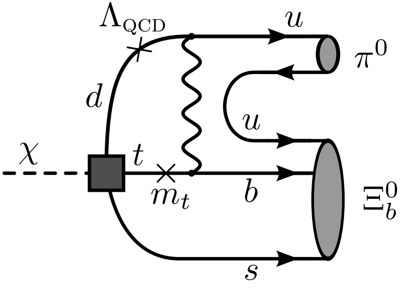
Example: $B = 1$ operators with MFV

$$\mathcal{O}_1^{(B=1)} = (\chi\, u^c)(d^c d^c), \quad \mathcal{O}_2^{(B=1)} = (\chi\, q^*_\rho)(d^c\, q^*_\sigma)\epsilon^{\rho\sigma}$$

$$\begin{aligned}\mathcal{O}_1^{(B=1)} =& \left(\chi\, u^c_\alpha Y_U^\dagger Y_D\right)_K \left(d^c_{N\beta} d^c_{M\gamma}\right)\epsilon^{KNM}\epsilon^{\alpha\beta\gamma} \\ &\to \left(\chi\, u^c_{\text{MASS}} Y_U^{\text{diag}\dagger} V^\dagger_{\text{CKM}} Y_D^{\text{diag}}\right)_{K\alpha}\left([d^c_{\text{MASS}}]_{N\beta}\,[d^c_{\text{MASS}}]_{M\gamma}\right)\epsilon^{KNM}\epsilon^{\alpha\beta\gamma}, \\ \mathcal{O}_2^{(B=1)} =& \left(\chi\, q^*_{K\alpha i}\right)\left([d^c_\beta Y_D^\dagger]_N q^*_{M\gamma j}\right)\epsilon^{ij}\epsilon^{KNM}\epsilon^{\alpha\beta\gamma} \\ &\to \left(\chi\, u^*_{\text{MASS}} V^\dagger_{\text{CKM}}\right)_{K\alpha}\left([d^c_{\text{MASS}} Y_D^{\text{diag}\dagger}]_{N\beta}[d^*_{\text{MASS}}]_{M\gamma}\right)\epsilon^{KNM}\epsilon^{\alpha\beta\gamma},\end{aligned}$$

$$\begin{aligned}\Gamma_\chi^{(1)} &\sim \frac{(y_t y_b)^2}{8\pi}\left(\frac{m_\chi}{\Lambda}\right)^4\left(\frac{1}{16\pi^2}\frac{m_t\Lambda_{\text{QCD}}}{m_W^2}\right)^2\frac{m_\chi}{16\pi^2} \\ &= 6.6\cdot 10^{-51}\text{GeV}\left(\frac{y_b}{0.024}\right)^2\left(\frac{4.0\cdot 10^6\text{TeV}}{\Lambda}\right)^4, \\ \Gamma_\chi^{(2)} &\sim \frac{|y_b V_{ub}|^2}{8\pi}\left(\frac{m_\chi}{\Lambda}\right)^4\frac{m_\chi}{16\pi^2} = 6.6\cdot 10^{-51}\text{GeV}\left(\frac{y_b}{0.024}\right)^2\left(\frac{4.3\cdot 10^7\text{TeV}}{\Lambda}\right)^4\end{aligned}$$

Example: $B = 1$ operators with MFV



$$\Gamma_\chi^{(1)} \sim \frac{(y_t y_b)^2}{8\pi}\left(\frac{m_\chi}{\Lambda}\right)^4\left(\frac{1}{16\pi^2}\frac{m_t\Lambda_{\rm QCD}}{m_W^2}\right)^2\frac{m_\chi}{16\pi^2}$$

$$= 6.6\cdot 10^{-51}\,\mathrm{GeV}\left(\frac{y_b}{0.024}\right)^2\left(\frac{4.0\cdot 10^6\,\mathrm{TeV}}{\Lambda}\right)^4,$$

$$\Gamma_\chi^{(2)} \sim \frac{|y_b V_{ub}|^2}{8\pi}\left(\frac{m_\chi}{\Lambda}\right)^4\frac{m_\chi}{16\pi^2} = 6.6\cdot 10^{-51}\,\mathrm{GeV}\left(\frac{y_b}{0.024}\right)^2\left(\frac{4.3\cdot 10^7\,\mathrm{TeV}}{\Lambda}\right)^4$$

)

DM leading decays and EFT scale

	ADM model		MFV			FN		
B	Dim.	m_χ [GeV]	decay	τ [s]	Λ [TeV]	decay	τ [s]	Λ [TeV]
1	6	6.2	$\chi \to bus$	10^{26}	4.0×10^6	$\chi \to bus$	10^{26}	8.1×10^8
2	10	3.1	$\chi \to udsuds$	10^{26}	0.63	$\chi \to udsuds$	10^{26}	2.5
3	15	2.1	forbidden	∞	–	forbidden	∞	–

Table: Leading decay modes for the $B = \{1, 2, 3\}$ operators with MFV and FN flavor breaking. The scale Λ_* is calculated such that the lifetime of the DM $\tau \sim 10^{26}$ [s]. The decay of ADM with $B = 3$ is kinematically forbidden.

DM leading decays and EFT scale

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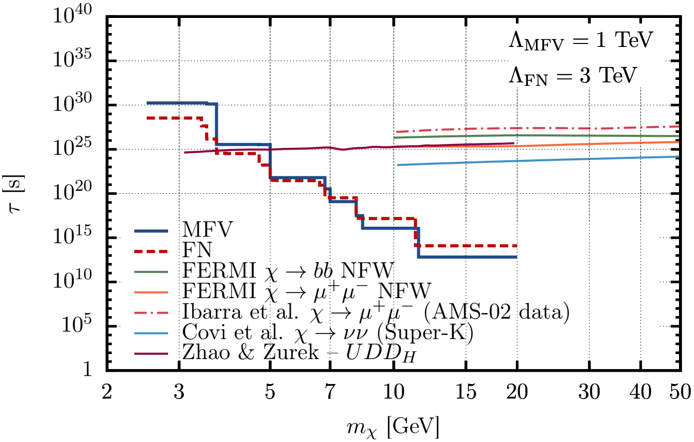
ADM model			MFV		Anarchic	
B	Dim.	m_χ [GeV]	decay	Λ_* [TeV]	decay	Λ_* [TeV]
0	4	(2)	$\chi \to \pi^0 \pi^0$	$(\tau \sim 10^{-23}$ [s])		
1	6	6.7	$\chi \to \Xi_b^0 \pi^0$	5.3×10^6		
2	10	3.3	$\chi \to \Lambda^0 \Xi^0$	0.68	$\chi \to n\, n$	7.8
3	15	2.2	forbidden	$(\tau \sim \infty)$		

Table: Leading decay modes for the $B = \{1, 2, 3\}$ operators with MFV and FN flavor breaking. The scale Λ_* is calculated such that the lifetime of the DM $\tau \sim 10^{26}$ [s]. The decay of ADM with $B = 3$ is kinematically forbidden.

ADM lifetime



Ackermann et al. [aXv:1205.6474]; Ibarra, Lamperstorfer, & Silk [aXv:1309.2570]; Aguilar et al. [Phys.Rev.Lett. 110, 141102 (2013)]; Covi, Grefe, Ibarra, & Tran [aXv:0912.3521]; Desai et al. [aXv:hep-ex/0404025]; Zhao & Zurek [aXv:1401.7664]

MFV model with scalar mediators

$$\mathcal{L}_{\rm INT} \supset \kappa_1 [\phi_L]^{AB}_{\gamma} \left(q^*_{A,\alpha i} q^*_{B,\beta j}\right) \epsilon^{ij}\epsilon^{\alpha\beta\gamma} + \kappa_2 [\varphi_L]^{\alpha\beta}_{A} \left(q^*_{B,\alpha i} q^*_{C,\beta j}\right) \epsilon^{ij}\epsilon^{ABC}$$
$$+ \kappa_3 [Y_D]^A_X [\phi_R]_{A,\alpha} \left(d^c_{Y,\beta}\, d^c_{Z,\gamma}\right) \epsilon^{\alpha\beta\gamma}\epsilon^{XYZ} + \kappa_4 \chi^\dagger [\phi_L]^{AB}_{\alpha} [\varphi_L]^{\alpha\beta}_{A} [\phi_R]_{B,\beta}$$
$$+ h.c.$$

The gauge and global charge assignment for the three scalar mediators, ϕ_L, φ_L and ϕ_R, in the first UV completion toy model for which we also assume the MFV flavor breaking pattern

Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	G_F	$U(1)_{B-L}$
ϕ_L	$\bar{\mathbf{3}}$	$\mathbf{1}$	$1/3$	$(\mathbf{6},\mathbf{1},\mathbf{1})$	$2/3$
φ_L	$\mathbf{6}$	$\mathbf{1}$	$1/3$	$(\bar{\mathbf{3}},\mathbf{1},\mathbf{1})$	$2/3$
ϕ_R	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-2/3$	$(\bar{\mathbf{3}},\mathbf{1},\mathbf{1})$	$2/3$

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$$+ \kappa_3 [Y_D]^A_X [\phi_R]_{A,\alpha} \left(d^c_{Y,\beta}\, d^c_{Z,\gamma} \right) \epsilon^{\alpha\beta\gamma} \epsilon^{XYZ} + \kappa_4 \chi^\dagger [\phi_L]^{AB}_{\alpha} [\varphi_L]^{\alpha\beta}_{A} [\phi_R]_{B,\beta}$$
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φ_L	$\mathbf{6}$	$\mathbf{1}$	$1/3$	$(\bar{\mathbf{3}}, \mathbf{1}, \mathbf{1})$	$2/3$
ϕ_R	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-2/3$	$(\bar{\mathbf{3}}, \mathbf{1}, \mathbf{1})$	$2/3$

MFV model with scalar mediators

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$$+ \kappa_3[Y_D]^{A}_{X}[\phi_R]_{A,\alpha}\left(d^c_{Y,\beta}\,d^c_{Z,\gamma}\right)\epsilon^{\alpha\beta\gamma}\epsilon^{XYZ} + \kappa_4\chi^\dagger[\phi_L]^{AB}_{\alpha}[\varphi_L]^{\alpha\beta}_{A}[\phi_R]_{B,\beta}$$
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ϕ_L	$\bar{\mathbf{3}}$	$\mathbf{1}$	$1/3$	$(\mathbf{6},\mathbf{1},\mathbf{1})$	$2/3$
φ_L	$\mathbf{6}$	$\mathbf{1}$	$1/3$	$(\bar{\mathbf{3}},\mathbf{1},\mathbf{1})$	$2/3$
ϕ_R	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-2/3$	$(\bar{\mathbf{3}},\mathbf{1},\mathbf{1})$	$2/3$

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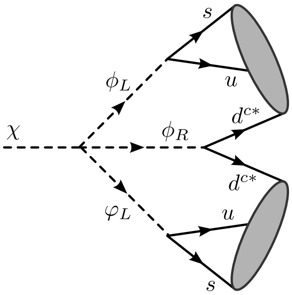
$$+ \kappa_3[Y_D]^{A}_{X}[\phi_R]_{A,\alpha}\left(d^c_{Y,\beta}\, d^c_{Z,\gamma}\right)\epsilon^{\alpha\beta\gamma}\epsilon^{XYZ} + \kappa_4\chi^\dagger[\phi_L]^{AB}_{\alpha}[\varphi_L]^{\alpha\beta}_{A}[\phi_R]_{B,\beta}$$
$$+ h.c.$$



FN model with scalar and fermionic mediators

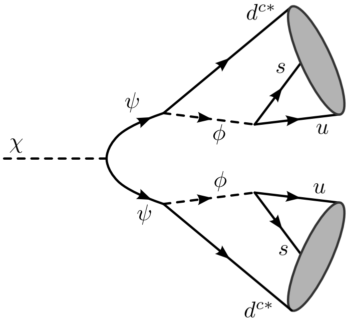
$$\mathcal{L}_{\mathrm{INT}} \supset g_{q,AB}\phi_\gamma \left(q^{*j}_{A,\alpha i} q^{*k}_{B,\beta j}\right) \epsilon^{ij}\epsilon^{\alpha\beta\gamma} + g_{d,A}\phi^{*\alpha}\left(d^c_{A,\alpha}\,\psi\right) + g_\chi\,\chi(\psi^c\,\psi^c) + h.c.$$

Gauge and $B-L$ charges of the mediators ϕ and ψ in the second UV model. We also assume FN flavor breaking pattern

Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{B-L}$
ϕ	$\bar{\mathbf{3}}$	$\mathbf{1}$	$1/3$	$2/3$
ψ	$\mathbf{1}$	$\mathbf{1}$	0	1

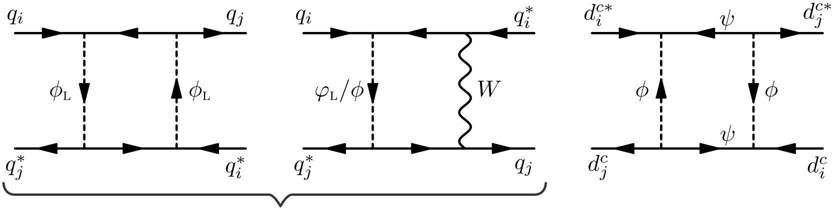
FN model with scalar and fermionic mediators

$$\mathcal{L}_{\rm INT} \supset g_{q,AB}\phi_\gamma \left(q^{*j}_{A,\alpha i} q^{*k}_{B,\beta j}\right) \epsilon^{ij}\epsilon^{\alpha\beta\gamma} + g_{d,A}\phi^{*\alpha}\left(d^c_{A,\alpha}\,\psi\right) + g_\chi\,\chi(\psi^c\,\psi^c) + h.c.$$



Flavor constraints

Mediators contribute to $\Delta_F = 2$ processes at the one loop level via



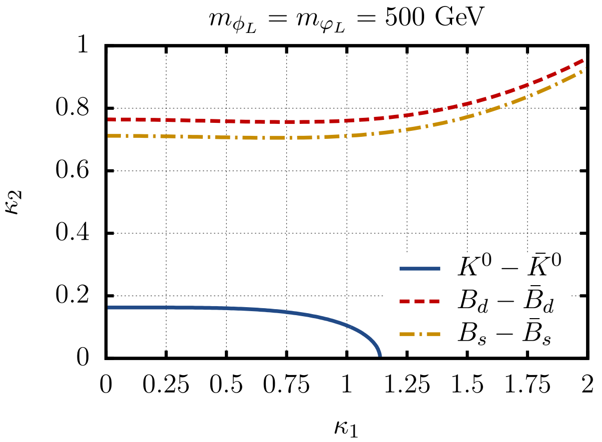
As in the SM, there is a GIM cancellation in these diagrams and the contribution is additionally suppressed by the internal quark Yukawa.

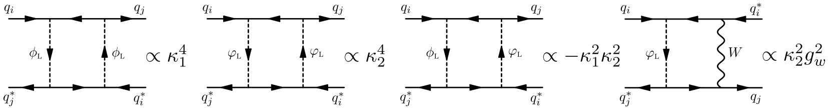
Flavor constraints

	MFV		FN	
	$\kappa_{1,2} <$	$m_{\phi_L,\varphi_L} >$	$g_{q,d} <$	$m_\phi >$
$K^0 - \bar{K}^0$	0.33	2.9 TeV	0.63	570 GeV
$B_d - \bar{B}_d$	1.3	710 GeV	0.54	1 TeV
$B_s - \bar{B}_s$	1.3	780 GeV	0.59	840 GeV
$D^0 - \bar{D}^0$	30	34 GeV	4.3	56 GeV

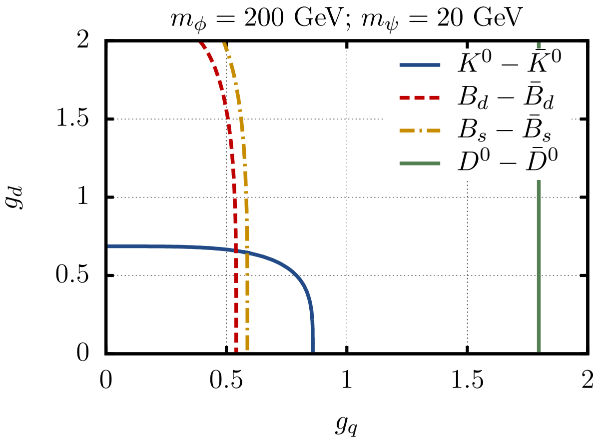
Table: The 95 % C.L. bounds on the MFV and FN mediator models from meson mixing. Taking $m_{\phi_L} = m_{\varphi_L} = m_\phi = 1$TeV and $\kappa_1 = \kappa_2$ gives the upper bounds on the couplings in the 2nd column and 4th column for $g_q = g_d$. Taking $\kappa_{1,2} = g_{q,d} = 1$ gives lower bounds on the mediator masses in the 3rd and 5th columns. The mass of the fermion in the FN model is fixed to $m_\psi = 20$ GeV.

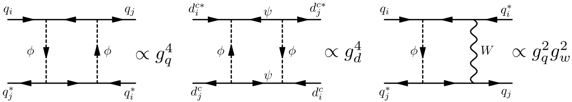
Flavor constraints – MFV mediator model



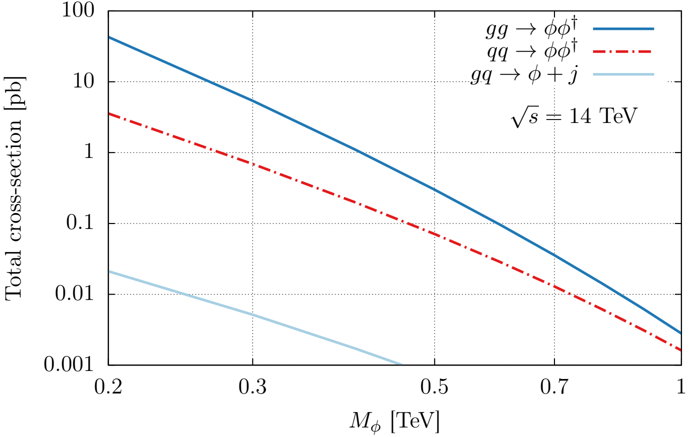


Flavor constraints – FN mediator model

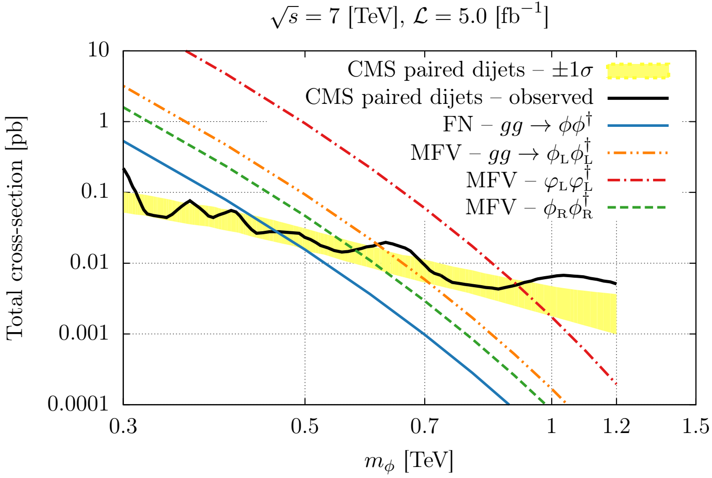




Collider signatures: single and pair production

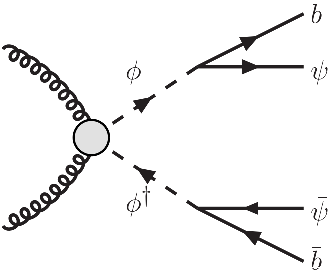


Collider signatures: paired dijets constraints



Search for New Physics in the Paired Dijet Mass Spectrum – CMS. [arXiv:1302.0531]

Collider signatures: 2*b* jets + MET

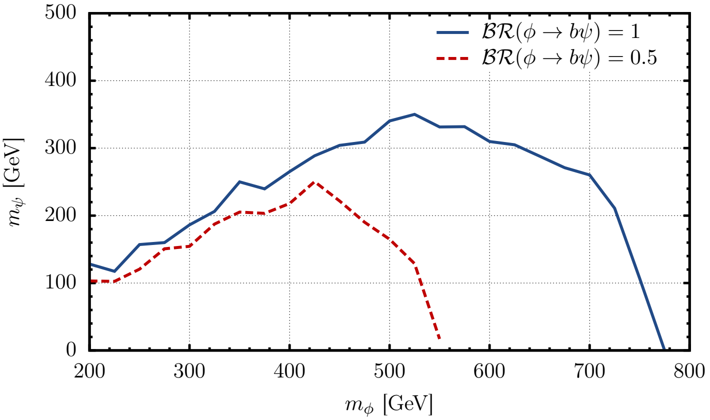


▷ The NDA decay length of ψ is given by

$$c\tau(\psi \to bbc) \sim \left(g_q^2 g_d^2 \lambda^8 \frac{1}{8\pi} \frac{1}{16\pi^2} \frac{m_\psi^5}{m_\phi^4}\right)^{-1}$$

$$\sim 30\text{m} \left(\frac{20\,\text{GeV}}{m_\psi}\right)^5 \left(\frac{m_\phi}{750\,\text{GeV}}\right)^4 \left(\frac{0.03}{g_q g_d}\right)^2$$

Constraints from sbottom pair production



Search for direct production of a pair of bottom squarks – CMS. [PAS-SUS-13-018]

Flavored DM

A closer look at MFV[1]

- ▷ In MFV, G_F is not completely broken. The spurions $Y_{u,d}$ leave the center group product $\mathcal{Z}_3^{QUD} \subset U(1)_B$ exactly preserved.

- ▷ Under this subgroup the quark fields transform, e.g.

$$\{Q, U, D\} \xrightarrow{\mathcal{Z}_3^{QUD}} e^{2\pi i/3}\{Q, U, D\}$$

- ▷ Combining this discrete symmetry with the center product of $SU(3)_C$ such that

$$\{Q, U, D\} \xrightarrow{\mathcal{Z}_3^{C}} e^{-2\pi i/3}\{Q, U, D\},$$

we see that all SM fields are singlets under $\mathcal{Z}_3^{\chi} \subset \mathcal{Z}_3^{QUD} \times \mathcal{Z}_3^{C}$.

- ▷ Matter charged under $\mathcal{Z}_3^{\chi}$ is automatically stable.

[1]Batell, Pradler & Spannowsky (2011); Batell, Lin & Wang (2013);

A closer look at MFV[1]

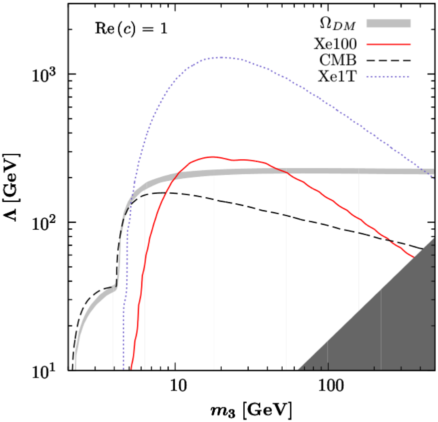
- For example, consider $S \sim (\mathbf{1},\mathbf{1},0)_{\text{SM}} \times (\mathbf{3},\mathbf{1},\mathbf{1})_{G_F}$

$$\Delta\mathcal{L}_{\text{eff}} = \frac{c}{\Lambda^2}[\bar{Q}_i S_i][S_j^*(Y_d)_{jk} D_{Rk}]H + h.c.$$

- For inverted spectrum, $m_3 < m_1 \simeq m_2$, S_3 is stable.

$$\langle \sigma v \rangle_{33\to d_i d_j} \propto |V_{ti}|^2 |V_{tj}|^2 \frac{m_i m_j}{\Lambda^4}$$

- Dominant decays to $b\bar{b}$, $b\bar{s}$, …



Batell, Pradler & Spannowsky (2011)

[1] Batell, Pradler & Spannowsky (2011); Batell, Lin & Wang (2013);

Maximally Gauged Flavor

- Based on fully gauged $SU(3)^3$ flavor model[1].
- Spontaneously broken by scalar flavons

$$\Phi_u \sim (\bar{\mathbf{3}}, \mathbf{3}, \mathbf{1}), \qquad \Phi_d \sim (\bar{\mathbf{3}}, \mathbf{1}, \mathbf{3})$$

- Anomaly cancellation requires four quark partners[2]

	Q_L	U_R	D_R	H	Ψ_{u_R}	Ψ_{d_R}	Ψ_{u_L}	Ψ_{d_L}	Y_u	Y_d
$SU(3)_c$	**3**	**3**	**3**	**1**	**3**	**3**	**3**	**3**	**1**	**1**
$SU(2)_L$	**2**	**1**	**1**	**2**	**1**	**1**	**1**	**1**	**1**	**1**
$U(1)_Y$	$+^1/_6$	$+^2/_3$	$-^1/_3$	$+^1/_2$	$+^2/_3$	$-^1/_3$	$+^2/_3$	$-^1/_3$	0	0
$SU(3)_{Q_L}$	**3**	**1**	**1**	**1**	**3**	**3**	**1**	**1**	$\bar{\mathbf{3}}$	$\bar{\mathbf{3}}$
$SU(3)_{U_R}$	**1**	**3**	**1**	**1**	**1**	**1**	**3**	**1**	**3**	**1**
$SU(3)_{D_R}$	**1**	**1**	**3**	**1**	**1**	**1**	**1**	**3**	**1**	**3**

[1] Grinstein, Redi & Villadoro (2010)
[2] Buras, Carlucci, Merlo & Stamou (2012)

Maximally Gauged Flavor

- The mass terms are

$$\mathcal{L}_{\text{mass}} \supset \lambda_u \bar{Q}_L \tilde{H} \Psi_{uR} + \lambda'_u \bar{\Psi}_{uL} Y_u \Psi_{uR} + M_u \bar{\Psi}_{uL} U_R$$
$$+ \lambda_d \bar{Q}_L H \Psi_{dR} + \lambda'_d \bar{\Psi}_{dL} Y_d \Psi_{dR} + M_d \bar{\Psi}_{dL} D_R + \text{h.c.},$$

- The SM Yukawas are generated after flavor and electroweak symmetry breaking

$$y_u = \frac{\lambda_u M_u}{\lambda'_u \langle Y_u \rangle}, \qquad y_d = \frac{\lambda_d M_d}{\lambda'_d \langle Y_d \rangle}.$$

- The SM Yukawas are not analytic in spurions $\langle Y_{u,d} \rangle$.
  $y_{u,d} \sim \langle Y_{u,d} \rangle^{-1} \Rightarrow$ not of MFV type!

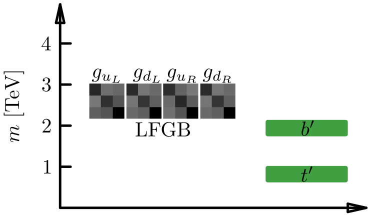
Flavor gauge boson & quark partner mass spectrum

- For the benchmark model

$$M_u = 600 \text{ [GeV]},\ \lambda_u = 1,\ \lambda'_u = 1$$
$$M_d = 100 \text{ [GeV]}\ \lambda_d = 0.25,\ \lambda'_d = 0.3$$
$$g_Q = 0.4,\ g_U = 0.3,\ g_D = 0.5$$

- Quark partners have inverted hierarchy (lightest states t', b').

- The spectrum of the lightest states is

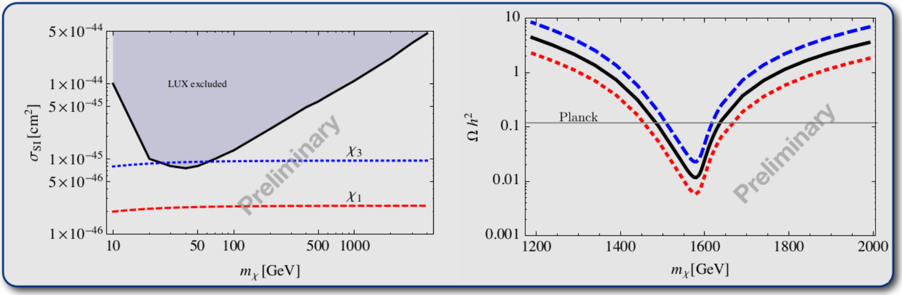


Maximally non-MFV DM

- DM is a SM gauge singlet dirac fermion with flavor quantum numbers

$$\chi_L \sim (\mathbf{1}, \mathbf{3}, \mathbf{1}), \qquad \chi_R^c \sim (\mathbf{1}, \bar{\mathbf{3}}, \mathbf{1})$$

- Multiplet is split by radiative corrections due to flavor gauge bosons.



Figures by Jernej Kamenik

Summary & conclusions

- Flavor symmetries can allow us to have a cosmologically stable ADM even if the DM is not charged under the flavor group.

- Alternatively, stability is ensured if the DM is charged under the flavor group.

- The mediators between the visible and dark sectors can be at the TeV scale without giving rise to dangerous FCNCs.

- The mediators can have interesting signatures at the LHC.
  - E.g. $\phi^\dagger\phi \to t\,\bar{t}\,b\,\bar{b}$

Backup

$U(1)$ Froggatt-Nielsen[1] (FN) model

- Spontaneously broken horizontal $U(1)$ symmetry
- Quarks carry horizontal charges under this $U(1)$
- E.g., horizontal charge assignment that gives phenomenologically satisfactory quark masses and CKM matrix elements[2]

$$H(q, d^c, u^c) \Rightarrow \begin{matrix} & 1 & 2 & 3 \\ q & 3 & 2 & 0 \\ d^c & 3 & 2 & 2 \\ u^c & 3 & 1 & 0 \end{matrix}$$

- Wilson coefficients $\mathcal{C} = \lambda^{|\sum_i H_i|}$, where $\lambda = 0.2$

[1] Froggatt & Nielsen [Nucl.Phys. B147 (1979) 277]

[2] Leurer, Nir & Seiberg [hep-ph/9310320], [hep-ph/9212278]