Asymmetric Dark Matter Stability from Continuous Flavor Symmetries

Fady Bishara

Fermilab & University of Cincinnati

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Based on: FB and J. Zupan. arXiv:1407.XXXX

Outline

- ▷ Motivation
- ▷ ADM, DM stability, and flavor
- ▷ Asymmetric Dark Matter (ADM) mass
- ▷ ADM lifetime
- ▷ Mediator models
- ▷ Experimental constraints

Motivation

- ▷ There is overwhelming evidence for the existence of DM yet the SM model lacks a candidate
- ▷ There is a coincidence $\Omega_\chi/\Omega_B = 5.4$; could there be a link?
- ▷ We expect New Physics (NP) at the TeV scale to address the hierarchy problem
- ▷ However, NP cannot have generic flavor structure
  - Large FCNCs if $\Lambda_{\text{NP}} \sim$ TeV (NP flavor problem)
- ▷ Can flavor suppression lead to DM stability?

ADM, DM stability and flavor

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

- ADM

  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 & Gemmeler [aXv:1405.6709]

The roadmap

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

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

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

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

- Will not assume any discrete symmetry to stabilize DM

Goal

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

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ADM mass

Assumptions

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

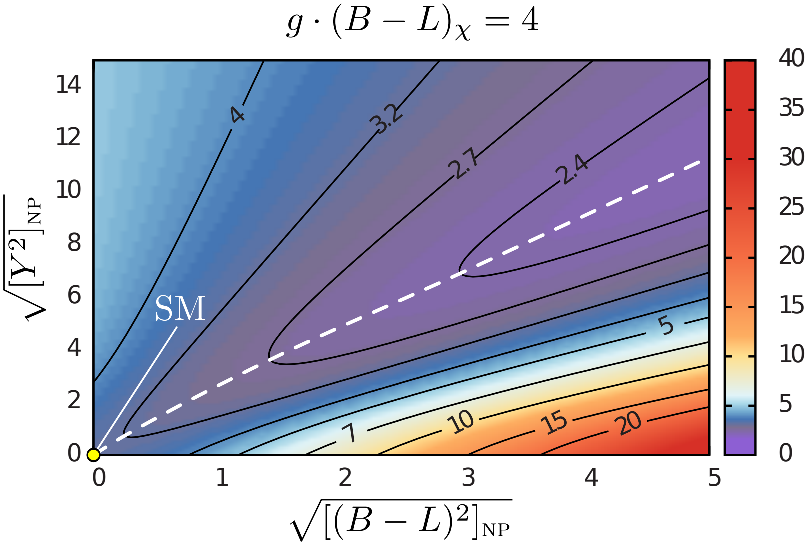
In this case, the ADM mass (with SM field content) is given by[1]

$$m_\chi = m_p \frac{\Omega_\chi}{\Omega_B} \left(\frac{B}{B-L} \right) \left(\frac{B-L}{\Delta\chi} \right) = (12.9 \pm 0.8\,\text{GeV}) \frac{1}{(B-L)_\chi^{\text{sum}}}$$

where $\Delta\chi \equiv (n_\chi - \overline{n}_\chi)/s$ and $(B-L)_\chi^{\rm sum} \equiv \sum_i \hat{g}_\chi^i (B-L)_\chi^i$.

[1] Harvey & Turner, Phys.Rev. D42 (1990) 3344-3349; Feldstein & Fitzpatrick, arXiv:1003.5662.

ADM mass in the presence of New Physics (NP)



Asymmetric EFT operators

The lowest dimensional asymmetric operators are of the form

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

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

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

[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.

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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)

- $\mathcal{L}_{\rm SM}$ 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] D'Ambrosio, Giudice, Isidori & Strumia [hep-ph/0207036]

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Example: $B = 1$ operators with MFV

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

$$\mathcal{O}_1^{(B=1)} = \left(\chi\, u^c_\alpha Y_U^\dagger Y_D\right)_K \left(d^c_{N\beta} d^c_{M\gamma}\right)\epsilon^{KNM}\epsilon^{\alpha\beta\gamma}$$
$$\to \left(\chi\, u^c_{\rm MASS} Y_U^{\rm diag\dagger} V^\dagger_{\rm CKM} Y_D^{\rm diag}\right)_{K\alpha}\left([d^c_{\rm MASS}]_{N\beta}\,[d^c_{\rm MASS}]_{M\gamma}\right)\epsilon^{KNM}\epsilon^{\alpha\beta\gamma},$$
$$\mathcal{O}_2^{(B=1)} = (\chi\, q^*_{K\alpha i})([d^c_\beta Y_D^\dagger]_N q^*_{M\gamma j})\epsilon^{ij}\epsilon^{KNM}\epsilon^{\alpha\beta\gamma}$$
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$$\Gamma_\chi^{(1)} \sim \frac{(y_t y_b)^2}{8\pi}\left(\frac{m_\chi}{\Lambda}\right)^4\left(\frac{1}{16\pi^2}\frac{m_t\Lambda_{\rm QCD}}{m_W^2}\right)^2\frac{m_\chi}{16\pi^2}$$
$$= 6.6\cdot 10^{-51}{\rm GeV}\left(\frac{y_b}{0.024}\right)^2\left(\frac{5.3\cdot 10^6{\rm TeV}}{\Lambda}\right)^4,$$

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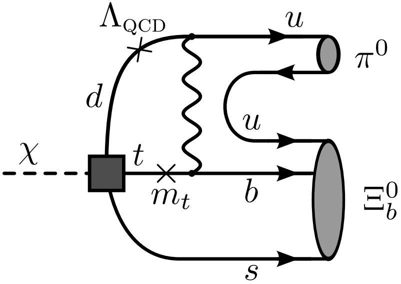

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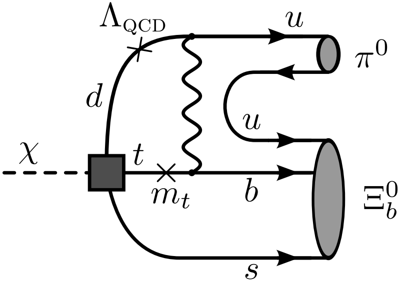

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DM leading decays and EFT scale

ADM model			MFV		FN	
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])	$\chi \to \pi^0\,\pi^0$	$(\tau \sim 10^{-23}$ [s])
1	6	6.7	$\chi \to \Xi_b^0\,\pi^0$	5.3×10^6	$\chi \to \Xi_b^0\,\pi^0$	2.1×10^9
2	10	3.3	$\chi \to \Lambda^0\Xi^0$	0.68	$\chi \to \Lambda^0\Lambda^0$	1.8
3	15	2.2	forbidden	$(\tau \sim \infty)$	forbidden	$(\tau \sim \infty)$

Table: Leading decay modes for the $B = \{0, 1, 2, 3\}$ operators with MFV and FN flavor breaking. The scale Λ_* is calculated such that the lifetime of the DM $\tau \sim 10^{26}$ [s]. For $B = 0$, standard equilibrium thermodynamics gives $m_\chi = 0$ since $[X]^{\text{sum}}_{B-L} = 0$. In this case, $m_\chi = 2$ was chosen to calculate the lifetime. The decay of ADM with $B = 3$ is kinematically forbidden.

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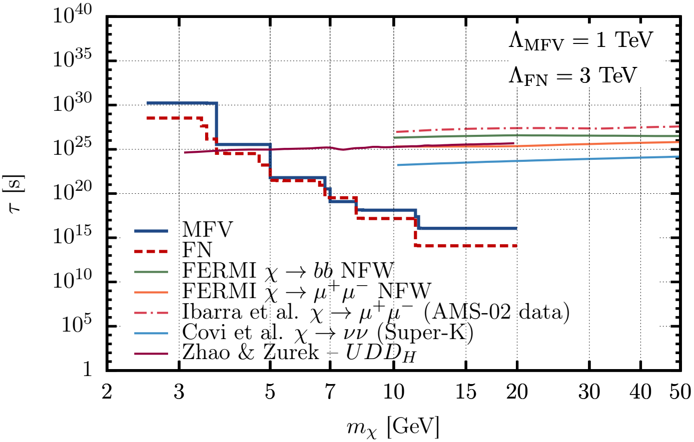
ADM lifetime



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]

Mediator models

MFV model with scalar mediators

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

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	$\mathbf{6}$	$\mathbf{1}$	$1/3$	$(\bar{\mathbf{3}}, \mathbf{1}, \mathbf{1})$	$2/3$
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MFV model with scalar mediators

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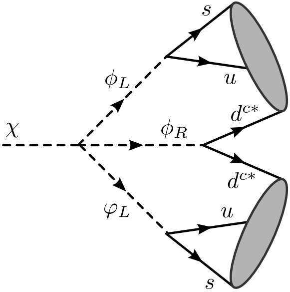

FN model with scalar and fermionic mediators

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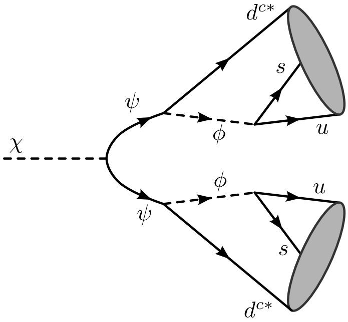
Gauge and $B - L$ charges of the mediators ϕ and ψ in the second UV model. We also assume FN flavor breaking pattern

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

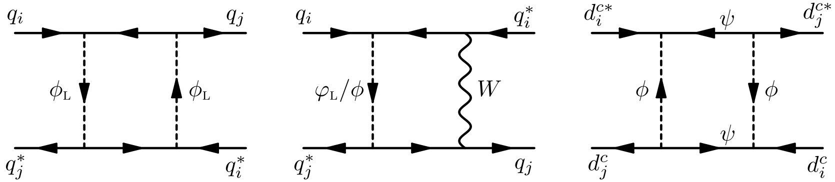
FN model with scalar and fermionic mediators

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



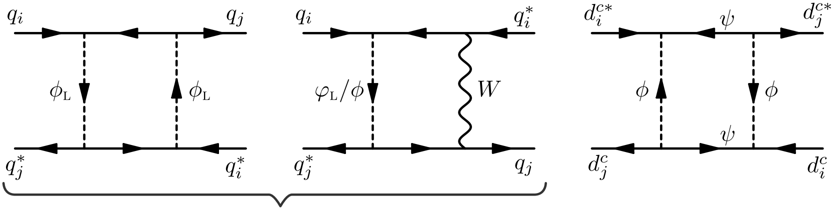
Flavor constraints

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



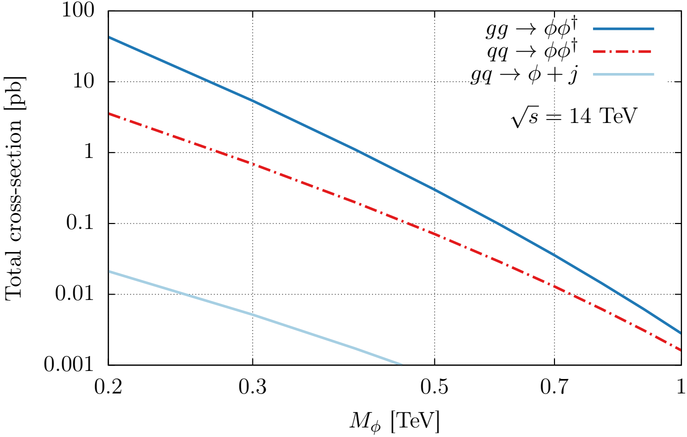
Flavor constraints

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

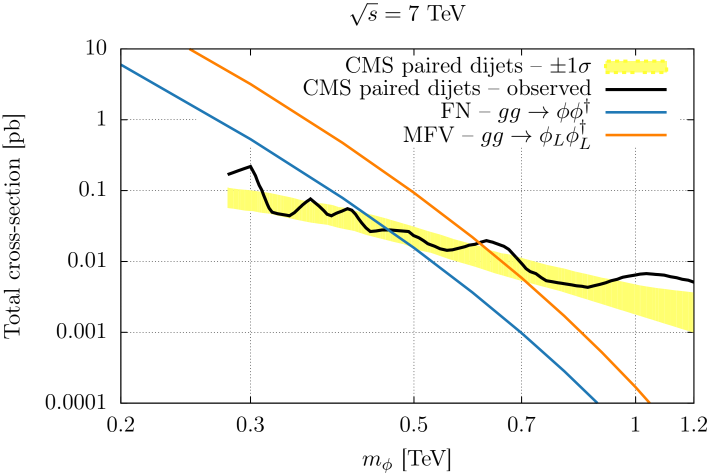


As in the SM, there is a GIM cancellation in these diagrams and the contribution is additionally suppressed by the internal quark Yukawa.

Collider signatures: single and pair production



Collider signatures: paired dijets constraints



Summary & conclusions

- ▷ Showed that flavor symmetries can allow us to have a cosmologically stable ADM even if the DM is not 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 mediator models can have interesting signatures at the LHC

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]

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

- 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]