Higgs-Flavon mixing and Dark Matter?

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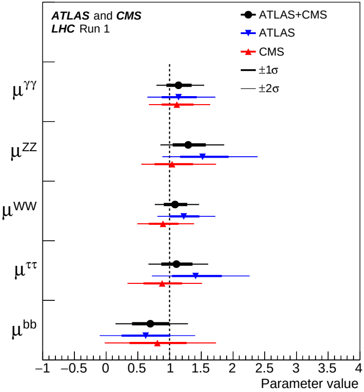
The Standard Model and its shortcomings

- A Higgs boson discovered
- No significant deviation from the SM
- No signs of new physics

But no explanation for

- Dark Matter
- Fermion mass hierarchy
- Vacuum stability
- ...



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Motivation

- Yukawa couplings in SM are free parameters with no explanation for the hierarchy among them.
- The Froggatt-Nielsen mechanism naturally generates the SM Yukawa couplings by introducing a complex scalar field (flavon) which acquires a VEV.
- The Yukawa matrix is then given in terms of the flavon VEV.

In the absence of CPV, Higgs-flavon mixing leads to:

- h and $\mathrm{Re}\phi \quad \Rightarrow \quad$ two states H_1 and H_2.
- third state $\mathrm{Im}\phi$

The Froggatt-Nielsen mechanism

with a leptophilic flavon

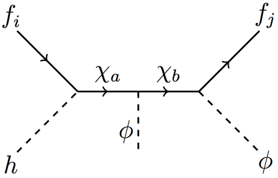
Froggatt-Nielsen mechanism

A Higgs doublet and a flavon singlet:

$$H = \begin{pmatrix} 0 \\ \frac{v_h + h}{\sqrt{2}} \end{pmatrix}, \qquad \Phi = \left(\frac{v_\phi + \phi}{\sqrt{2}} \right), \quad \text{with} \quad \phi = \mathrm{Re}\phi + i\ \mathrm{Im}\phi$$

The effective operators after integrating out the heavy fermions:

$$c_{ij} \left(\frac{\Phi}{\Lambda} \right)^{n_{ij}} \bar{f}_{L,i} f_{R,j} H$$



Each vertex is $U(1)$ symmetric:

$$c_{ij} \left(\frac{\Phi}{\Lambda}\right)^{n_{ij}} \bar{f}_{L,i} f_{R,j} H, \qquad q_{\bar{L},i} + q_{R,j} + q_h + q_\phi n_{ij} = 0$$

Particle	$f^c_{L,i}$	$f_{R,i}$	H	Φ
$U(1)$ charge	$q_{\bar{L},i}$	$q_{R,i}$	q_h	q_ϕ

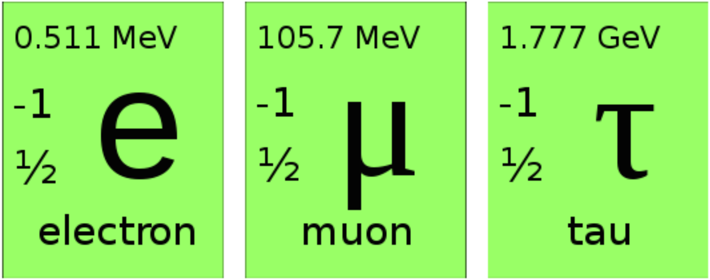
After SSB:

$$\mathcal{L}_{Yukawa} \supset c_{ij} \left(\frac{v_\phi}{\sqrt{2}\Lambda}\right)^{-\frac{1}{q_\phi}(q_{\bar{L},i}+q_{R,j}+q_h)} \bar{f}_{L,i} f_{R,j} \frac{h}{\sqrt{2}}$$

The SM Yukawa coupling ($q_\phi = -1, q_h = 0$)

$$Y_{ij} = c_{ij}\ \epsilon^{\overbrace{(q_{\bar{L},i} + q_{R,j})}^{n_{ij}}} \quad \text{with} \quad \epsilon = \frac{v_\phi}{\sqrt{2}\Lambda}$$

What ϵ to choose?



$$Y = \begin{pmatrix} \epsilon^3 & & \\ & \epsilon^2 & \\ & & \epsilon \end{pmatrix}, \qquad Y = \begin{pmatrix} \epsilon^6 & & \\ & \epsilon^4 & \\ & & \epsilon^3 \end{pmatrix}$$

$\epsilon = 0.01$ $\qquad$ $\epsilon = 0.1$

What charges to assign?

$$Y = \begin{pmatrix} \epsilon^3 & & \\ & \epsilon^2 & \\ & & \epsilon \end{pmatrix}, \qquad \epsilon = 0.01$$

$\bar{e}_L$	e_R	$\bar{\mu}_L$	μ_R	$\bar{\tau}_L$	τ_R
2	1	1	1	0	1

$$Y = \begin{pmatrix} \epsilon^6 & & \\ & \epsilon^3 & \\ & & \epsilon^3 \end{pmatrix}, \qquad \epsilon = 0.1$$

$\bar{e}_L$	e_R	$\bar{\mu}_L$	μ_R	$\bar{\tau}_L$	τ_R
6	0	3	0	3	0

Leptonic part of the Lagrangian

$$\mathcal{L}_{eff} \supset \frac{v_h}{\sqrt{2}}\ Y_{ij}\ \left(1 + \frac{h}{v_h} + n_{ij}\frac{\phi}{v_\phi}\right)\bar{l}'_{L,i} l'_{R,j}$$

Diagonalising the Yukawa matrix

$$Y_{\rm diag} = U_L\ \ Y_{ij}\ \ U_R^\dagger$$

In the lepton mass basis

$$\mathcal{L}_{eff} \supset \bar{l}_L M_{\rm diag} l_R + \frac{h}{\sqrt{2}}\bar{l}_L Y_{\rm diag} l_R + \frac{v_h}{v_\phi}\frac{\phi}{\sqrt{2}}\bar{l}_{L,i}\kappa_{ij} l_{R,j} + h.c.$$

CLFV processes with coupling

$$\tilde{\kappa}_{ij} = \frac{v_h \kappa_{ij}}{\sqrt{2} v_\phi} = \left[y_j \sum_{k=1}^{3} q_{\bar{L},k}(U_L)_{ik}(U_L)^*_{jk} + y_i \sum_{k=1}^{3} q_{R,k}(U_R)_{ik}(U_R)^*_{jk} \right]$$

The scalar potential

$$V(H,\Phi) = -\mu_h^2(H^\dagger H)+\lambda_h(H^\dagger H)^2-\mu_\phi^2(\Phi^\dagger\Phi)+\lambda_\phi(\Phi^\dagger\Phi)^2+\lambda_{h\phi}(H^\dagger H)(\Phi^\dagger\Phi)$$

with

$$H = \left(\begin{array}{c} 0 \\ \frac{v_h+h}{\sqrt{2}} \end{array} \right), \qquad \Phi = \left(\frac{v_\phi+\phi}{\sqrt{2}}\right), \quad \text{with} \quad \phi = \mathrm{Re}\phi + i\,\mathrm{Im}\phi$$

The physical states

$$\left(\begin{array}{c} H_1 \\ H_2 \end{array} \right) \equiv \left(\begin{array}{cc} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{array} \right) \left(\begin{array}{c} h \\ \mathrm{Re}\phi \end{array} \right)$$

where

$$\tan 2\theta = \frac{\lambda_{h\phi} v_h v_\phi}{\lambda_h v_h^2 - \lambda_\phi v_\phi^2}$$

Discrete Froggatt-Nielsen symmetry

The scalar potential

$$V(H,\Phi) = -\mu_h^2(H^\dagger H) + \lambda_h (H^\dagger H)^2 - \mu_\phi^2(\Phi^\dagger\Phi) + \lambda_\phi(\Phi^\dagger\Phi)^2$$
$$+ \lambda_{h\phi}(H^\dagger H)(\Phi^\dagger\Phi) + \tilde{m}^2\Phi^2 + h.c.$$

with

$$H = \begin{pmatrix} 0 \\ \frac{v_h+h}{\sqrt{2}} \end{pmatrix}, \qquad \Phi = \left(\frac{v_\phi+\phi}{\sqrt{2}}\right), \quad \text{with} \quad \phi = \mathrm{Re}\phi + i\,\mathrm{Im}\phi$$

The physical states H_1, H_2 and $\mathrm{Im}\phi$ with masses

$$m_{H_1} = 125\text{ GeV},\ m_{H_2} \sim \text{few hundred GeV}$$
$$m_{\mathrm{Im}\phi} \sim \tilde{m}$$

The couplings to leptons

The physical states H_1, H_2 and $\mathrm{Im}\phi$ couplings to leptons

$$\tilde{\kappa}_{ij} = \frac{v_h}{\sqrt{2} v_\phi} \left[y_j \sum_{k=1}^{3} |q_{\bar{L},k}| (U_L)_{ik} (U_L)^*_{jk} + y_i \sum_{k=1}^{3} |q_{R,k}| (U_R)_{ik} (U_R)^*_{jk} \right]$$

$$\tilde{\eta}_{ij} = \frac{v_h}{\sqrt{2} v_\phi} \left[y_j \sum_{k=1}^{3} q_{\bar{L},k} (U_L)_{ik} (U_L)^*_{jk} + y_i \sum_{k=1}^{3} q_{R,k} (U_R)_{ik} (U_R)^*_{jk} \right]$$

where

$$\mathcal{L} \supset \left[\cos\theta \, \frac{Y^{\mathrm{diag}}_{ij}}{\sqrt{2}} + \sin\theta \, \widetilde{\kappa}_{ij} \right] \bar{l}_i P_R l_j \, H_1 + \left[-\sin\theta \, \frac{Y^{\mathrm{diag}}_{ij}}{\sqrt{2}} + \cos\theta \, \widetilde{\kappa}_{ij} \right] \bar{l}_i P_R l_j \, H_2$$
$$+ \quad i \widetilde{\eta}_{ij} \, \bar{l}_i P_R l_j \, \mathrm{Im}\phi + \mathrm{h.c.}$$

Our charge assignment

The discrete charge assignments for $\epsilon = 0.1$

Particle	e_L	e_R	μ_L	μ_R	τ_L	τ_R	H	ϕ
Charge	6	0	-3	0	-3	0	0	-1

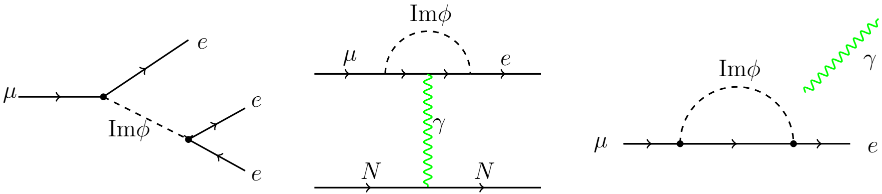
The texture leading to a long-lived DM

$$Y = \begin{pmatrix} \epsilon^6 & \epsilon^6 & \epsilon^6 \\ \epsilon^3 & \epsilon^3 & \epsilon^3 \\ \epsilon^3 & \epsilon^3 & \epsilon^3 \end{pmatrix}$$

Bounds from CLFV processes

Observable	Present limit	Experiment
$\text{BR}(\mu \to eee)$	1.0×10^{-12}	SINDRUM
$\text{BR}(\tau \to eee)$	3.0×10^{-8}	HFAG
$\text{BR}(\tau \to \mu\mu\mu)$	2.0×10^{-8}	HFAG
$\text{BR}(\mu \to e\gamma)$	5.7×10^{-13}	MEG
$\text{BR}(\tau \to \mu\gamma)$	4.4×10^{-8}	HFAG
$\text{BR}(\tau \to e\gamma)$	3.3×10^{-8}	HFAG
$\text{CR}(\mu\text{-}e, Au)$	7.0×10^{-13}	SINDRUM II

CLFV processes mediated by a light $\mathrm{Im}\phi$

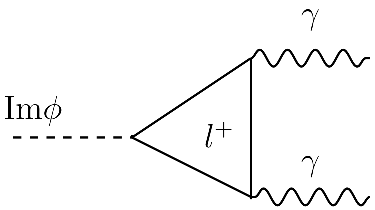


For $m_{\mathrm{Im}\phi} < 1$ MeV $\Rightarrow$ $v_\phi \gtrsim 5$ TeV

Lifetime of decaying Dark Matter

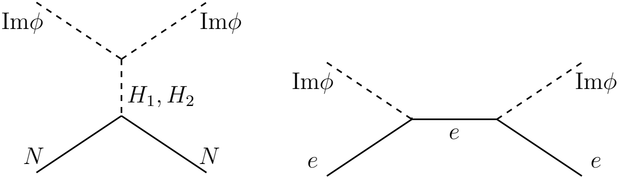
Lifetime of DM

$$\tau_{DM} = \frac{1}{\Gamma_{\mathrm{Im}\phi \to \gamma\gamma}} > 6.612 \times 10^{32} \frac{1}{ev}$$ age of the universe



- for $m_{\mathrm{Im}\phi} = 10$ KeV $\Rightarrow v_\phi \sim 10^6\, GeV$
- for $m_{\mathrm{Im}\phi} = 1$ MeV $\Rightarrow v_\phi \sim 10^{13}\, GeV$

Direct Detection of Dark Matter



Direct detection experiments are not sensitive to such low masses ($m_{DM} \sim 10$ KeV $-$ 1 MeV)

CMB constraints on decaying DM

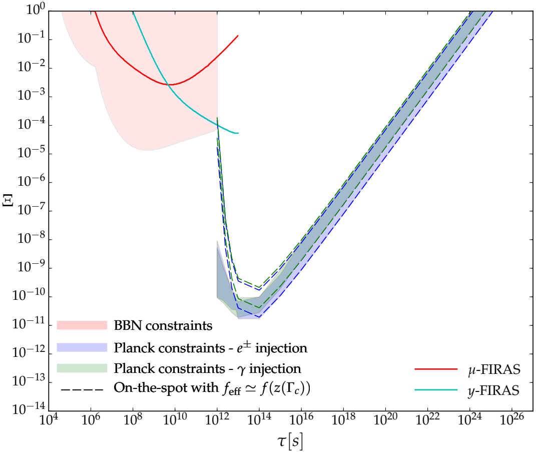
Assuming $\tau_{DM} \gtrsim 10^{17}$ s (age of the universe)

$$\Longrightarrow$$

DM will only contribute to 10^{-8} of observed relic density

If $m_{\mathrm{Im}\phi}$ is 100% of DM:

- $m_{\mathrm{Im}\phi} = 10$ KeV
  $v_\phi \sim 10^{10}\,GeV$
- for $m_{\mathrm{Im}\phi} = 1$ MeV
  $v_\phi \sim 10^{17}\,GeV$



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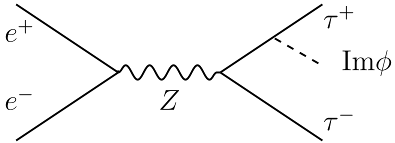
Summary

- Froggatt-Nielsen mechanism predicts a complex flavon responsible for producing the SM fermion Yukawa couplings.
- In the case of a lepto-philic FN mechanism, the imaginary part of the flavon could be very long-lived $\sim$ the age of the universe.
- It will only contribute negligibly to the observed Dark Matter relic density due to constraints from CMB anisotropy.
- Requiring this particle to account for 100% of the observed DM density, derives the model into "un-observable" realms.

BACKUP SLIDES

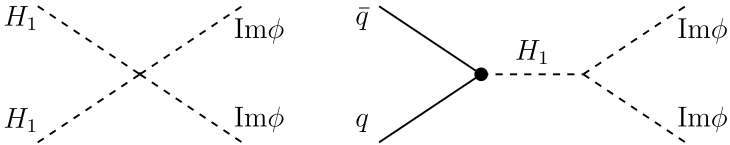
How to observe this?

At an e^+e^- collider

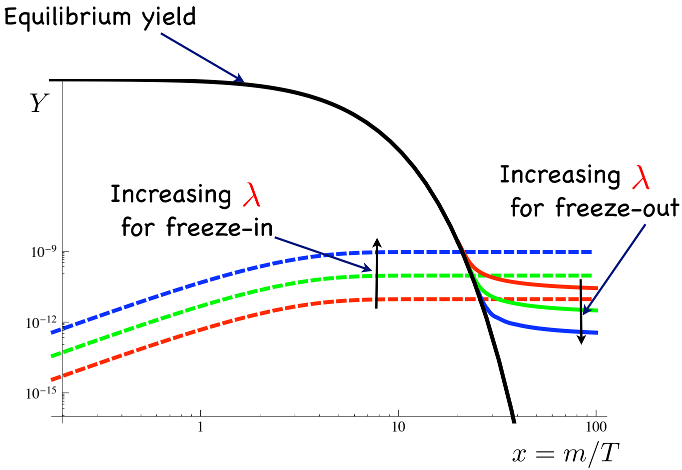


Relic density of Dark Matter

Main production channels of DM in early universe

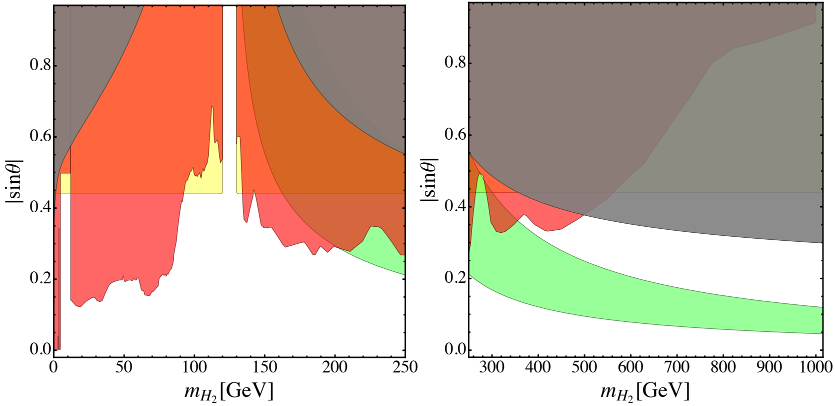


Freeze-in vs. Freeze-out



(borrowed from S. West's talk in ULB in 2010)

How much Higgs-flavon mixing is allowed?



Excluded at 95 % CL by direct searches (red), precision tests (gray), and H_1 couplings measurements (yellow). [Falkowski *et al* (2015)]