Salvador Centelles Chuliá, Christian Döring, Werner Rodejohann and Ulises Saldaña-Salazar

Max-Planck Institut für Kernphysik

Natural axion model from flavour

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Motivation

- Naturalness: Dirac vs ‘t Hooft
  - Dirac: small parameters are unnatural (inspirehep id: 1227).
  - ‘t Hooft: small parameters are natural only if protected by symmetry (inspirehep id: 144074).
- SM and many of its popular extensions face naturalness issues
  - Hierarchy problem (nice intro in inspirehep id: 859892)
  - Small neutrino masses (model dependent)
  - **Fermion mass hierarchy**
  - **Strong CP problem**
  - …

Fermion mass hierarchy

- Striking pattern in the fermion masses
- Yukawas are technically natural
  - If $Y \to 0$ chiral symmetry is restored
  - Running of Y is proportional to itself
  - But such a pattern is calling for an explanation!
  - Many proposals in the literature
    - Each set of fermions may receive its mass from a different Higgs

$$m_t \sim \Lambda_{EW}$$
$$m_b, m_\tau, \mathrm{m_c} \sim 10^{-2} \Lambda_{EW}$$
$$m_s, \mathrm{m}_\mu \sim 10^{-3} \Lambda_{EW}$$
$$m_d, m_u, \mathrm{m_e} \sim 10^{-5} \Lambda_{EW}$$
$$m_\nu < 10^{-13} \Lambda_{EW}$$

Strong CP problem

- QCD allows the CP Violating term $\theta\ G_{\mu\nu}\ \tilde{G}^{\mu\nu}$
  - Neutron electric dipole moment measurements: $\theta < 10^{-10}$
  - Is this a hint of new physics?
- Popular solution: the axion
  - θ is promoted to a dynamical field, the axion
  - Can be dark matter too
  - Requires an additional global, anomalous $U(1)_{PQ}$

Inspirehep ids: 3438, 119084, 128010

The proposal

- 4HDM with sharp vev hierarchy
- Each fermion set couples to one Higgs
- Both require symmetry protection
- A flavoured $U(1)_{PQ}$ can do all!

	Fields	$SU(2)_L \times U(1)_Y$	$U(1)_{\text{PQ}}$
Leptons	L_i	$(\mathbf{2}, -1/2)$	l
	$\nu_{R,i}$	$(\mathbf{1}, 0)$	0
	e_R	$(\mathbf{1}, -1)$	$2l$
	μ_R	$(\mathbf{1}, -1)$	$2l - k$
	τ_R	$(\mathbf{1}, -1)$	$2l - 2k$
Quarks	Q_i	$(\mathbf{2}, 1/6)$	q
	u_R	$(\mathbf{1}, 2/3)$	$q - l$
	c_R	$(\mathbf{1}, 2/3)$	$q - l + 2k$
	t_R	$(\mathbf{1}, 2/3)$	$q - l + 3k$
	d_R	$(\mathbf{1}, -1/3)$	$q + l$
	s_R	$(\mathbf{1}, -1/3)$	$q + l - k$
	b_R	$(\mathbf{1}, -1/3)$	$q + l - 2k$
Scalars	ϕ_t	$(\mathbf{2}, 1/2)$	$3k - l$
	ϕ_b	$(\mathbf{2}, 1/2)$	$2k - l$
	ϕ_μ	$(\mathbf{2}, 1/2)$	$k - l$
	ϕ_d	$(\mathbf{2}, 1/2)$	$-l$
	χ	$(\mathbf{1}, 0)$	k
	A	$(\mathbf{1}, 0)$	$k/2$

Fermion masses

$$\begin{pmatrix} \overline{Q}_1 & \overline{Q}_2 & \overline{Q}_3 \end{pmatrix} \begin{pmatrix} Y_{u,1}\,\tilde{\phi}_d & Y_{c,1}\,\tilde{\phi}_b & Y_{t,1}\,\tilde{\phi}_t \\ Y_{u,2}\,\tilde{\phi}_d & Y_{c,2}\,\tilde{\phi}_b & Y_{t,2}\,\tilde{\phi}_t \\ Y_{u,3}\,\tilde{\phi}_d & Y_{c,3}\,\tilde{\phi}_b & Y_{t,3}\,\tilde{\phi}_t \end{pmatrix} \begin{pmatrix} u_R \\ c_R \\ t_R \end{pmatrix}$$

- Up type quarks receive mass from ϕ_d, ϕ_b, ϕ_t
- Down type quarks and charged leptons receive mass from $\phi_d, \phi_\mu\ \phi_b$

$$\begin{pmatrix} \overline{Q}_1 & \overline{Q}_2 & \overline{Q}_3 \end{pmatrix} \begin{pmatrix} Y_{d,1}\,\phi_d & Y_{s,1}\,\phi_\mu & Y_{b,1}\,\phi_b \\ Y_{d,2}\,\phi_d & Y_{s,2}\,\phi_\mu & Y_{b,2}\,\phi_b \\ Y_{d,3}\,\phi_d & Y_{s,3}\,\phi_\mu & Y_{b,3}\,\phi_b \end{pmatrix} \begin{pmatrix} d_R \\ s_R \\ b_R \end{pmatrix} \qquad \begin{pmatrix} \overline{L}_1 & \overline{L}_2 & \overline{L}_3 \end{pmatrix} \begin{pmatrix} Y_{e,1}\,\phi_d & Y_{\mu,1}\,\phi_\mu & Y_{\tau,1}\,\phi_b \\ Y_{e,2}\,\phi_d & Y_{\mu,2}\,\phi_\mu & Y_{\tau,2}\,\phi_b \\ Y_{e,3}\,\phi_d & Y_{\mu,3}\,\phi_\mu & Y_{\tau,3}\,\phi_b \end{pmatrix} \begin{pmatrix} e_R \\ \mu_R \\ \tau_R \end{pmatrix}$$

- Neutrino masses come from a type-I seesaw $Y_{\nu,ij}\,\overline{L}_i\,\tilde{\phi}_d\,\nu_{R,j} + \frac{M_{ij}}{2}\overline{\nu}^c_{R,i}\,\nu_{R,j}$
- No prediction for mixing (we just fit).

FCNC

- Singular/flavour alignment Ansatz (see inspirehep ids: 1628834, 1723269)
- Columns of each mass matrix are assumed to be orthogonal to each other
- Under this Ansatz the tree-level FCNC are 0
- Loop corrections are small enough to escape constraints

Vev cascade

- The PQ symmetry is broken at a high scale f_a
- f_a induces a small vev for χ $\quad v_\chi \simeq \frac{\kappa_{AA\chi} v_A^2}{\mu_\chi^2 + \lambda_{\chi A} v_A^2}$
- ϕ_t is a SM-like Higgs. $\mu_t^2 < 0$ leads to a standard EWSB
- $\mu_b^2, \mu_\mu^2, \mu_d^2 > 0$. No mexican hat potential!

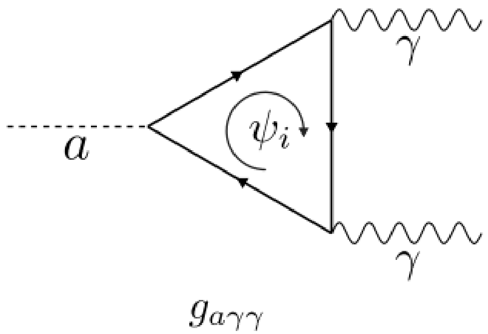
Vev cascade

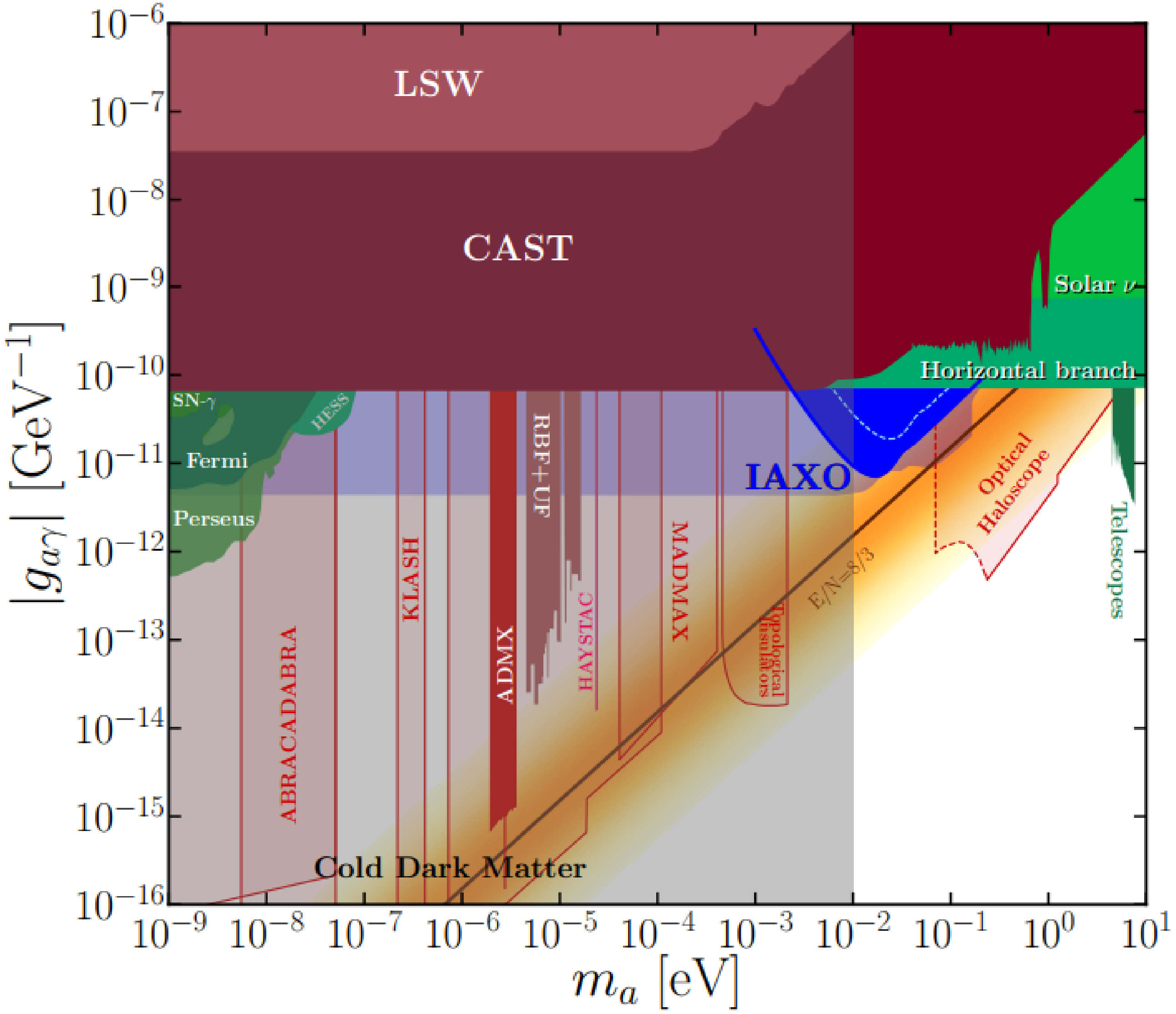
- However, the interaction between ϕ_t, ϕ_b and χ induces a suppressed vev for ϕ_b $v_b \simeq \frac{\kappa_{tb\chi} v_\chi v_t}{\mu_b^2 + (\lambda_{tb1} + \lambda_{tb2}) v_t^2 + \lambda_{b\chi} v_\chi^2}$;
- Sequentially, ϕ_b induces a vev to ϕ_μ $v_\mu \simeq \frac{\kappa_{b\mu\chi} v_\chi v_b}{\mu_\mu^2 + (\lambda_{t\mu1} + \lambda_{t\mu2}) v_t^2 + \lambda_{\mu\chi} v_\chi^2}$,
- And ϕ_μ to ϕ_d $v_d \simeq \frac{\kappa_{\mu d\chi} v_\chi v_\mu}{\mu_d^2 + (\lambda_{td1} + \lambda_{td2}) v_t^2 + \lambda_{d\chi} v_\chi^2}$
- The vev hierarchy implies a fermión mass hierarchy with

order 1 Yukawas!

The axion

- DFSZ type axion
- $\frac{E}{N} = \frac{8}{3}$
- m_a and $g_{a\gamma\gamma}$ related through f_a





Axion-fermion couplings

- There is a diagonal coupling between the axion and the fermions (suppressed by f_a)
- It is a *flavoured* axion, but non-diagonal interactions can be rotated away
  - Left handed charges are generation-independent
  - Right-handed mixing is unphysical unless a new gauge interaction is added

$$\mathcal{L}_{a\psi} = \frac{\partial_\mu a}{2 f_a} \left[\bar{\psi}_i \gamma^\mu \left(C^V_{\psi ij} - C^A_{\psi ij} \gamma_5 \right) \psi_j \right], \quad C^{V,A}_{\psi ij} = \frac{1}{2N} \left(\mathbf{U}^{\psi\dagger}_L \mathbf{X}_{\psi L} \mathbf{U}^{\psi}_L \pm \mathbf{U}^{\psi\dagger}_R \mathbf{X}_{\psi R} \mathbf{U}^{\psi}_R \right)_{ij}$$

Summary and conclusions

- 4HDM framework
- $U(1)_{PQ}$ has a double role: solves the Strong CP problem and generates the vev hierarchy which in turn explains the fermion mass hierarchy with order one Yukawas
- Singular alignment prevens unwanted FCNC