AXION MODELS WITH FLAVOR-DEPENDENT COUPLINGS

based on

- Quentin Bonnefoy, E.D and Stefan Pokorski JHEP01 (2020), 191 [arXiv:1909.05336 [hep-ph]]
- Quentin Bonnefoy, Peter Cox, E.D., Tony Gherghetta and Minh Nguyen, [arXiv:2012.09728 [hep-ph]], JHEP, to appear.

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Outline

1) Flavorful axions : phenomenology

2) Flavorful axion : models

- Froggatt-Nielsen models
- Holographic axion
- Conclusions

Even if a total derivative, the famous CP-violating QCD term

$$\frac{\theta_{QCD}}{32\pi^2} tr(G_{\mu\nu}\tilde{G}^{\mu\nu})$$

has physical effects and breaks CP in strong interactions

→ The strong CP problem

Best solution: axion a, a pseudo-goldstone boson of a global Peccei-Quinn symmetry, which couples to gluons via anomalies

$$\frac{a}{f_a} tr(G_{\mu\nu}\tilde{G}^{\mu\nu})$$

such that

$$\theta_{QCD} \to \theta_{eff} = \theta_{QCD} + \frac{32\pi^2 \langle a \rangle}{f_a} = 0$$

Good Dark Matter candidate (talk M. Hertzberg)

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1) Flavorful axions: phenomenology

The axion couples to fermions via derivative couplings

$$\mathcal{L}_{aff} = \frac{\partial_\mu a}{2 f_a} \overline{f}_i \gamma^\mu \left(c^V_{f_i f_j} + c^A_{f_i f_j} \gamma_5 \right) f_j$$

The vector and axial couplings can be non-diagonal in the quarks/leptons flavors. Define

$$F^{V,A}_{f_i f_j} \equiv \frac{2 f_a}{c^{V,A}_{f_i f_j}}$$

There are experimental constraints from flavor changing processes

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Flavors	Process	F^V_{ij} [GeV]	F^A_{ij} [GeV]	Ref.
	$K^+ \to \pi^+ a$	$\mathbf{6.8 \times 10^{11}}$	–	[85]
		$\mathbf{(2 \times 10^{12})}$	–	
	$K^+ \to \pi^+ \pi^0 a$	–	1.7×10^7	[104]
			$\mathbf{(7 \times 10^8)}$	
	$\Lambda \to n\ a$ (decay)	6.9×10^6	5.0×10^6	[10]
		(1×10^9)	$\mathbf{(8 \times 10^8)}$	
	$\Lambda \to n\ a$ (SN)	7.4×10^9 †	$\mathbf{5.4 \times 10^9}$ †	
$s \to d$	$\Sigma^+ \to p a$	6.7×10^6	2.3×10^6	[10]
		(7×10^8)	(3×10^8)	
	$\Xi^- \to \Sigma^- a$	1.0×10^7	1.3×10^7	[10]
	$\Xi^0 \to \Sigma^0 a$	1.6×10^7	$\mathbf{2.0 \times 10^7}$	[10]
		(2×10^8)	(3×10^8)	
	$\Xi^0 \to \Lambda a$	5.4×10^7	1.0×10^7	[10]
		(9×10^8)	(2×10^8)	
	$K - \overline{K}$ (Δm_K)	5.1×10^5 †	2.0×10^6	[10]
	(ϵ_K)	0.9×10^6 †	$\mathbf{4.4 \times 10^7}$	[133]

Taken from Camalich et al, hep-ph/2002.04623

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2) Flavorful axions: models

- Froggatt-Nielsen models

- Standard Model gives no hint on the hierarchies of fermion masses and mixings (talks J. Ellis,S.King).

An old profilic idea (Froggatt-Nielsen, 79) :
flavor U(1), spontaneously broken family symmetry.

Fermions of different generations have different charges

Fields: $Q_i \ , \ U_i^c \ , \ D_i^c$
Charges $q_i \ , \ u_i^c \ , \ d_i^c$ →

One needs charged « flavons » Φ breaking the symmetry.

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Yukawas (except top/bottom masses) are generated via non-renormalizable operators

$$\mathcal{L}_{Yuk} = y^u_{ij} (\frac{\Phi}{M})^{-\frac{q_i+u_j+h_2}{X_\Phi}} Q_i U^c_i h_2 + y^d_{ij} (\frac{\Phi}{M})^{-\frac{q_i+d_j+h_1}{X_\Phi}} Q_i D^c_i h_1 + \cdots$$

after symmetry breaking

$$m^u_{ij} = y^u_{ij} \ \epsilon^{-\frac{q_i+u_j+h_2}{X_\Phi}} v_2 \ , \ m^d_{ij} = y^d_{ij} \ \epsilon^{-\frac{q_i+d_j+h_1}{X_\Phi}} v_1$$

where $\epsilon = \frac{\langle \Phi \rangle}{M} \sim \lambda = 0.22$

- Origin of non-renormalizable operators ?

- String theory/supergravity

In this case $M = M_P$

- Mixing of light fermions with heavy fermions of mass $M \sim \langle \Phi_2 \rangle$

Global versus gauge symmetry :

Often FN models imply $U(1)_X \times G^2_{SM}$ mixed anomalies.

OK if $U(1)_X$ is global. In this case, the model has an axion with flavor-dependent couplings to fermions : flavorful axion (Wilczek;Calibbi,Goertz,Redigolo,Ziegler,Zupan; Ema, Hamaguchi,Moroi,Nakayama)

Stronger couplings to light quarks: $\frac{q_i}{V} \ \partial_m a \ \bar{q}_i \gamma^m \ q_i$

Couplings to gauge fields similar to DFSZ models $\frac{E}{N} = \frac{A_1+A_2}{A_3} \sim \frac{8}{3}$

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Quantum Gravity does not like global symmetries: typically broken by gravity and nonperturbative effects.

If $U(1)_X$ is gauged, models with one spurion and heavy vector-like fermions generally incompatible with anomaly cancelation →

- Stringy origin, Green-Schwarz mechanism
- Field theory, but heavy chiral fermions

Model with chiral heavy fermions

$$-\mathcal{L}_{\text{mass}} = y_i \Phi_2 \Psi_i \Psi_i^c$$

$X_2 \neq 0$ → Heavy fermions vector-like wrt SM gauge group, but chiral wrt $U(1)_X$

Anomaly cancels between heavy and light fermions

$$A_a^{SM} + A_a^{\text{heavy}} = 0$$

(see also talk S. King)

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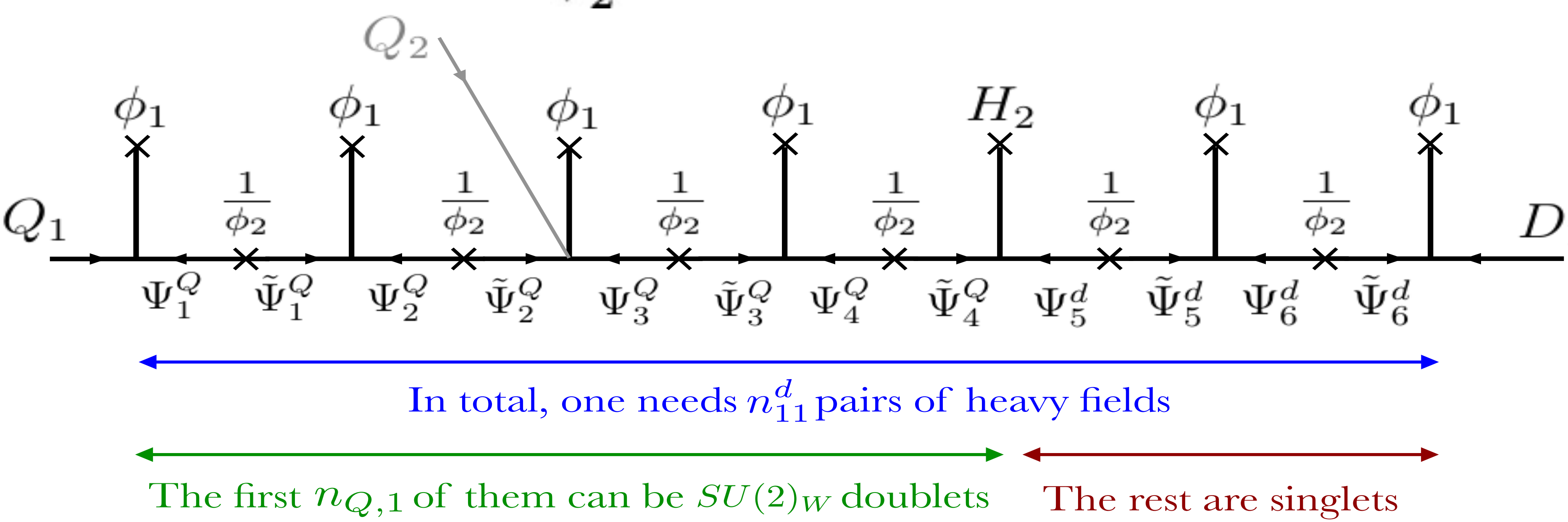
Use one flavon Φ_1, second field for fixing heavy fermion masses $M = \langle \Phi_2 \rangle$

$$\mathcal{L}_{Yuk} = y^u_{ij} \left(\frac{\Phi_1}{\Phi_2} \right)^{\frac{q_i + u_j + h_2}{X_2 - X_1}} Q_i U^c_i h_2 + \cdots$$

with $\frac{V_1}{V_2} \sim \sin \theta_c \sim 0.22$



The model has a physical axion

$$\Phi_i = (V_i + r_i)\, e^{\frac{i a_i}{V_i}} \quad \longrightarrow$$

$$a_{PQ} \sim X_2 V_2 a_1 - X_1 V_1 a_2$$

PQ symmetry is accidental, protected by the gauge symmetry

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The low-energy couplings to gauge fields are determined both by heavy and light fermions :

Couplings to gauge fields

$$\frac{C_a}{C_{q_i}} = \frac{A_a^{SM}}{q_i} \frac{X_1^2 V_1^2 + X_2^2 V_2^2}{X_1 V_1^2 + X_2 V_2^2}$$

Couplings to quarks

contribution heavy fermions

Usual flavorful axion couplings correspond to $X_2 = 0$

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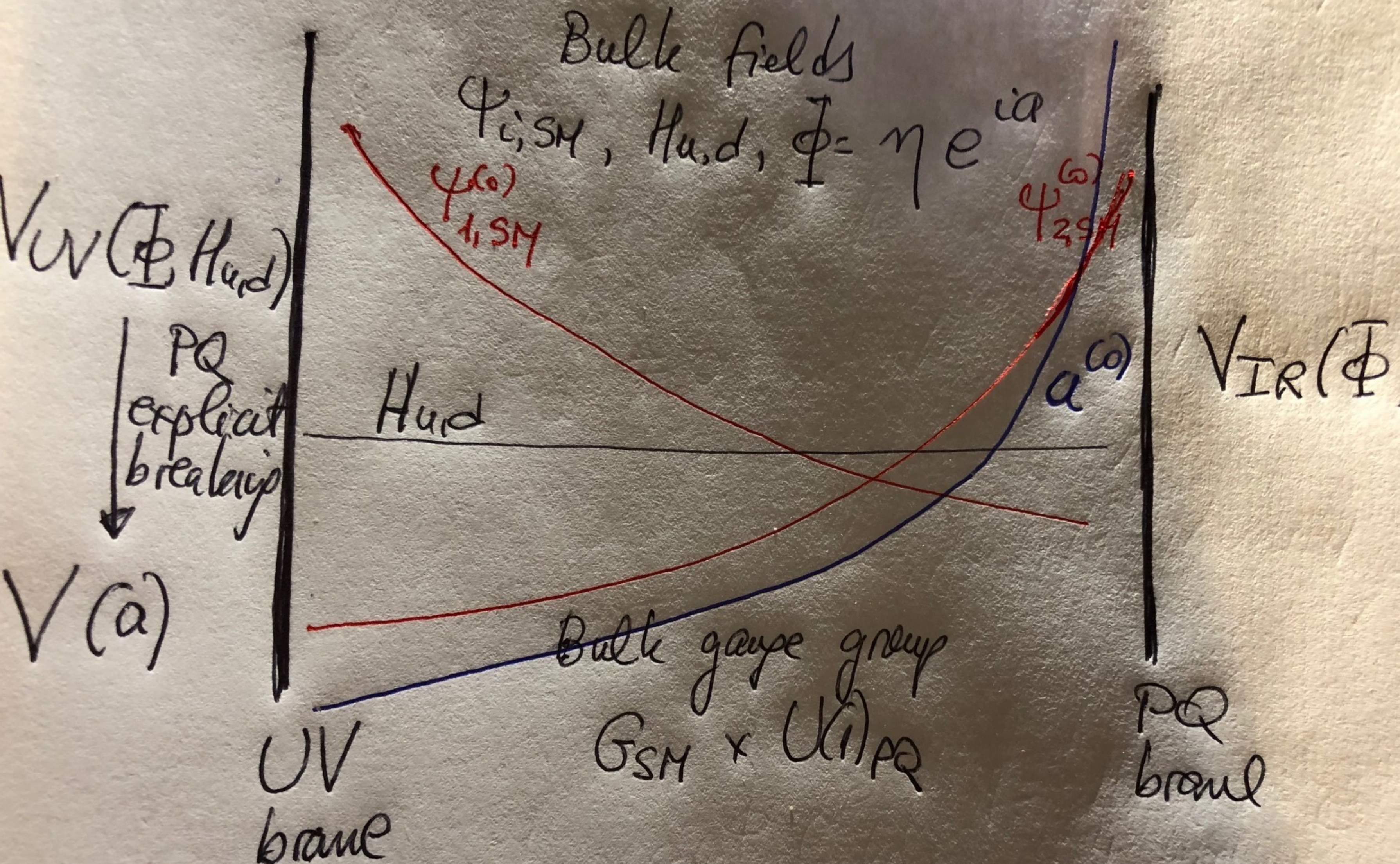
- Holographic axion (see also talk E.Kiritsis)

5d setup with AdS_5 geometry,
UV (Planck) and IR (PQ) branes

- Bulk gauge group $G = G_{SM} \times U(1)_{PQ}$
- SM fields, two Higgses $H_{u,d}$, one singlet Φ
- Gauged PQ symmetry, broken explicitly UV brane
- Fields localized towards UV : elementary
- Fields localized towards IR: composites
- 4d Yukawas, axion couplings : overlap integrals


Bulk fields
Ψ_{i,SM}, H_{u,d}, Φ = η e^{ia}
V_{UV}(Φ, H_{u,d})
PQ explicit breaking
V(a)
Ψ^{(0)}_{1,SM}
Ψ^{(0)}_{2,SM}
H_{u,d}
a^{(0)}
V_{IR}(Φ)
Bulk gauge group
G_{SM} × U(1)_{PQ}
UV brane
PQ brane

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Due to the non-trivial profile of the fermions and the axion, axion-fermion couplings are flavor non-diagonal

matrices diagonalizing quark masses

$$\frac{1}{(F_u^{V,A})_{ij}} \equiv \frac{(c_u^{V,A})_{ij}}{F_a} = X_{H_u} \int_{z_{UV}}^{z_{IR}} \frac{dz}{(kz)^4}\, \widehat{f}^{\,0}_{aX} \Big((A_R^u)_{ik} (f^0_{U_{kR}})^2 (A_R^{u\,\dagger})_{kj} \mp (A_L^u)_{ik} (f^0_{Q_{kL}})^2 (A_L^{u\,\dagger})_{kj} \Big)$$

axion profile

quark profiles

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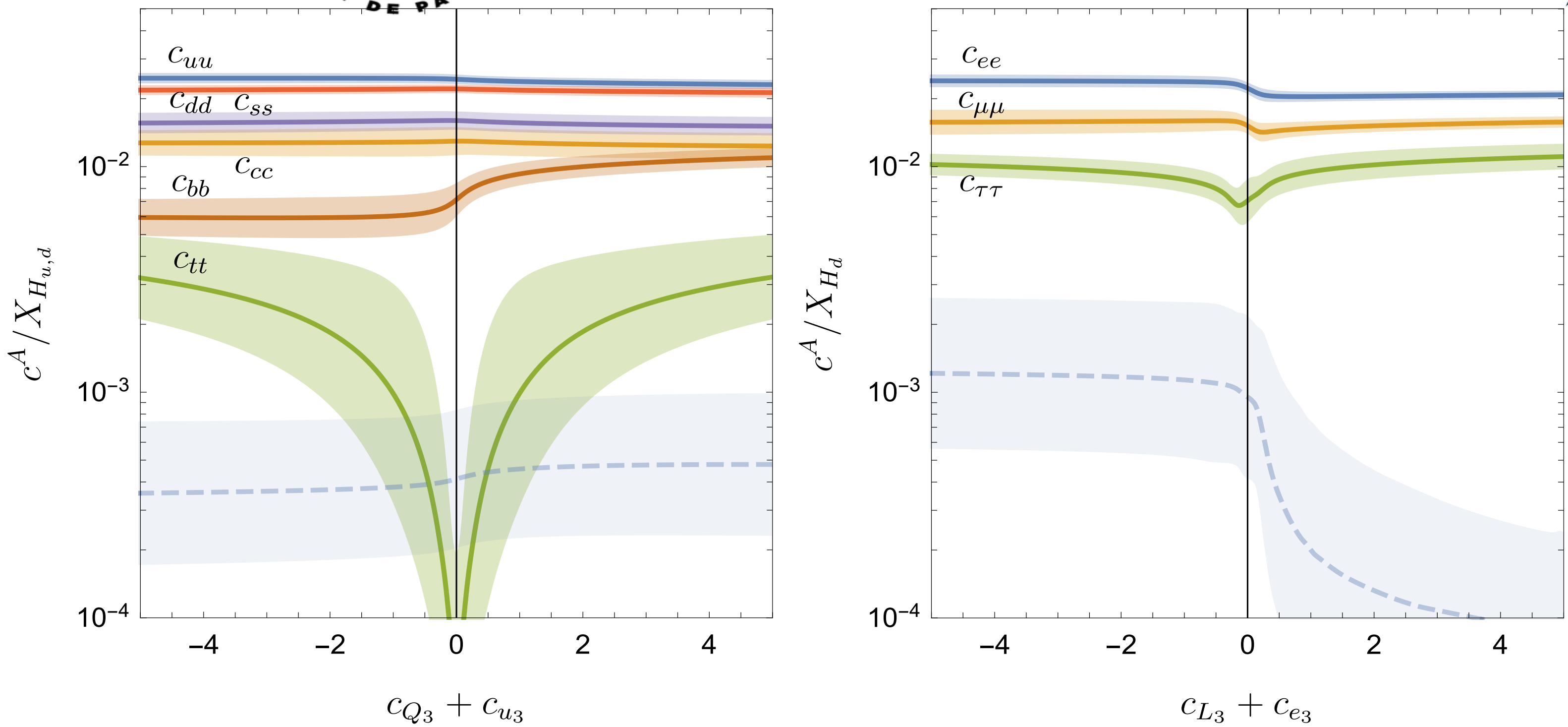

Figure 4: Left: absolute values of the diagonal axion-quark couplings c^A_{uu} (blue), c^A_{cc} (orange) and c^A_{tt} (green) in units of X_{H_u}, and c^A_{dd} (red), c^A_{ss} (purple) and c^A_{bb} (tan) in units of X_{H_d} as functions of $c_{Q_3}+c_{u_3}$. Right: absolute values of the diagonal axion-charged lepton couplings c^A_{ee} (blue), $c^A_{\mu\mu}$ (orange) and $c^A_{\tau\tau}$ (green) in units of X_{H_d} as functions of $c_{L_3}+c_{e_3}$. We fix $kz_{\rm IR}=10^{10}, g_5^2k=1, \Delta=10$ and $\sigma_0=3$, corresponding to $F_a\simeq 10^9\,$GeV. The curves and bands depict the mean and standard deviation of $\log_{10}F^V$ obtained from a scan over anarchic 5D Yukawa couplings. The dashed line shows (left) c^A_{uc} and (right) $c^A_{e\mu}$ for reference.

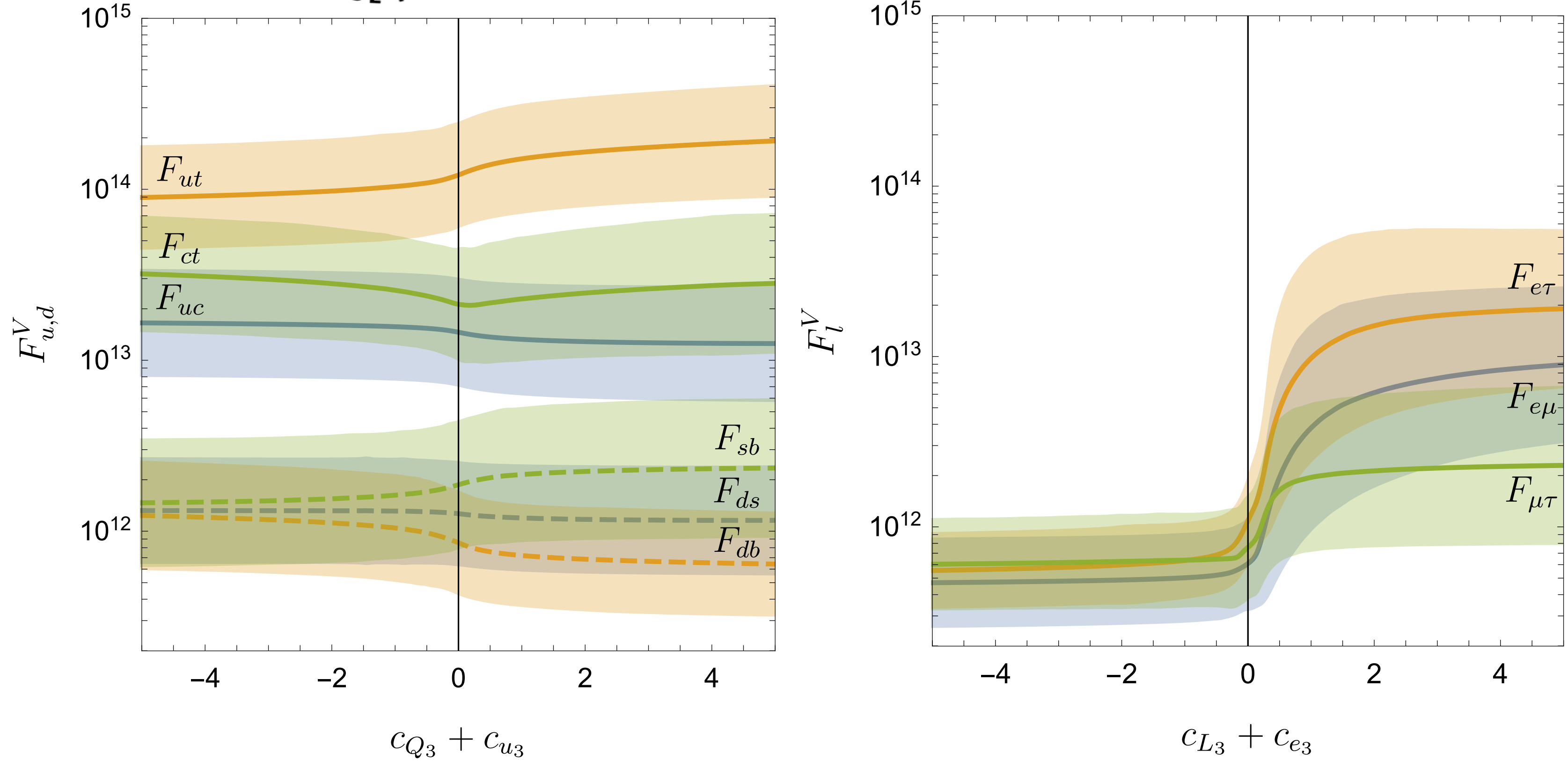

Figure 5: Absolute values of the off-diagonal elements of the axion-quark coupling matrix F^V_u (left, solid) and F^V_d (left, dashed) as functions of $c_{Q_3} + c_{u_3}$, and F^V_l (right) as a function of $c_{L_3} + c_{e_3}$. We fix $kz_{\rm IR} = 10^{10}, g_5^2 k = 1, \Delta = 10$ and $\sigma_0 = 3$, corresponding to $F_a \simeq 10^9$ GeV. The curves and bands depict the mean and standard deviation of $\log_{10} F^V$ obtained from a scan over anarchic 5D Yukawa couplings.

Conclusions

- Gauged FN models with chiral heavy fermions more natural: dynamical mass, cancelation anomalies, axion. Low-energy axion couplings slightly modified compared to the flavorful axion. Explicit examples, perturbativity in minimal setup favors large axion decay constants $f \geq 10^{14}\ GeV$

- Composite axion arises naturally in holographic setups. Flavor-dependent axion couplings to bulk fermions, if axion profile is not flat. One needs one-two more orders of magnitude improvement in the data to test such models.

THANK YOU

Backup slides