Fermion masses from a flavorful Peccei-Quinn Froggatt-Nielsen U(1) symmetry

Leon MG de la Vega

Based on: Flavored axion in the UV-complete Froggatt–Nielsen models
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Leon M. G. de la Vega, Newton Nath, Stefan Nellen, Eduardo Peinado

Outline

- Mass hierarchies in the SM
- Froggatt-Nielsen approach
- Froggatt-Nielsen UV completion
- Peccei-Quinn symmetry & flavored axion
- Flavor non-diagonal axion couplings
- Flavor non-diagonal Higgs couplings

$$m_u \sim 10^{-3} m_c \sim 10^{-5} m_t$$
$$m_d \sim 10^{-1} m_s \sim 10^{-3} m_b$$
$$m_e \sim 10^{-3} m_\mu \sim 10^{-4} m_t$$

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2			Quarks spin =1/2		
Flavor	Mass GeV/c^2	Electric charge	Flavor	Approx. Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-0.8)\times 10^{-9}$	0	**u** up	0.0022	2/3
e electron	0.000511	–1	**d** down	0.0047	–1/3
ν_M middle neutrino*	$(0.009-0.8)\times 10^{-9}$	0	**c** charm	1.27	2/3
μ muon	0.1057	–1	**s** strange	0.0934	–1/3
ν_H heaviest neutrino*	$(0.05-0.8)\times 10^{-9}$	0	**t** top	172.7	2/3
τ tau	1.777	–1	**b** bottom	4.18	–1/3

CPEP SM poster

Mass Hierarchies in the SM

Fermion mass matrix elements

$$\mathcal{L}_{FN} \sim \frac{\mathcal{C}_{ij}}{\Lambda^N}\overline{\psi}_{iL} H \psi_{jR} \phi^N$$

FN Effective Lagrangian

$$m^{\psi}_{ij} = \frac{\mathcal{C}_{ij}}{\Lambda^N}\langle H \rangle \langle \phi \rangle^N$$

$$\varepsilon = \frac{\langle \phi \rangle}{\Lambda}$$

CKM: $\varepsilon \sim 0.2$

Froggatt-Nielsen approach to hierarchies

	Q_{iL}	u_{iR}	d_{iR}	H_u	H_d	σ
$SU(2)_L \times U(1)_Y$	(2, 1/6)	(1, 2/3)	(1, -1/3)	(2, -1/2)	(2, 1/2)	(1, 0)
$U(1)_{PQ}$	(9/2, -5/2, 1/2)	(-9/2, 5/2, -1/2)	(-9/2, 5/2, -1/2)	1	1	1

Note: Two Higgses 👀

$$\mathcal{L} \supset \frac{C^u_{11}}{\Lambda^8}\overline{Q}_{1L}H_u u_{1R}\sigma^8 + \frac{C^u_{12}}{\Lambda}\overline{Q}_{1L}H_u u_{2R}\sigma + \frac{C^u_{13}}{\Lambda^4}\overline{Q}_{1L}H_u u_{3R}\sigma^4 + \frac{C^u_{21}}{\Lambda}\overline{Q}_{2L}H_u u_{1R}\sigma + \frac{C^u_{22}}{\Lambda^4}\overline{Q}_{2L}\widetilde{H}_d u_{2R}\sigma^{*4}$$
$$+ \frac{C^u_{23}}{\Lambda}\overline{Q}_{2L}\widetilde{H}_d u_{3R}\sigma^* + \frac{C^u_{31}}{\Lambda^4}\overline{Q}_{3L}H_u u_{1R}\sigma^4 + \frac{C^u_{32}}{\Lambda}\overline{Q}_{3L}\widetilde{H}_d u_{2R}\sigma^* + y^u_{33}\overline{Q}_{3L}H_u u_{3R} \,,$$

FN Effective Lagrangian

$$M_{u/d} = \begin{pmatrix} 0 & C^{u/d}_{12}\varepsilon v_{u/d} & 0 \\ C^{u/d}_{21}\varepsilon v_{u/d} & 0 & C^{u/d}_{23}\varepsilon v_{d/u} \\ 0 & C^{u/d}_{32}\varepsilon v_{d/u} & y^{u/d}_{33} v_{u/d} \end{pmatrix}$$

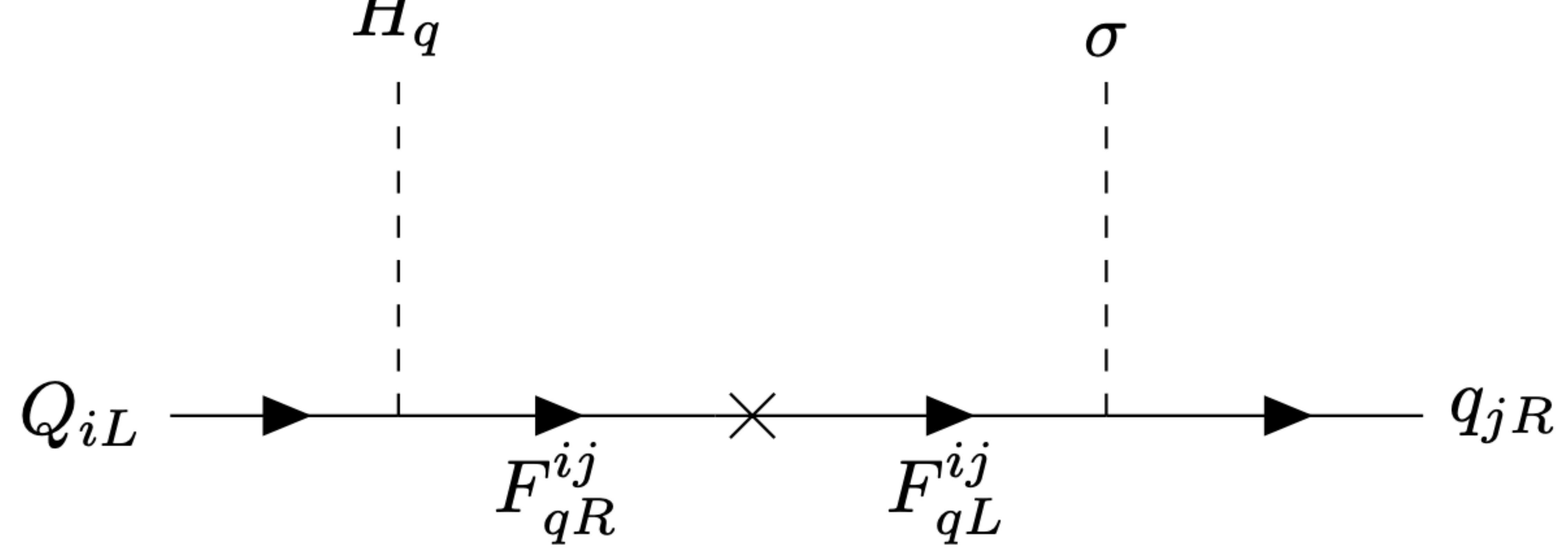
Leading order
Fermion mass matrix elements

Froggatt-Nielsen with texture zeroes in the quark sector

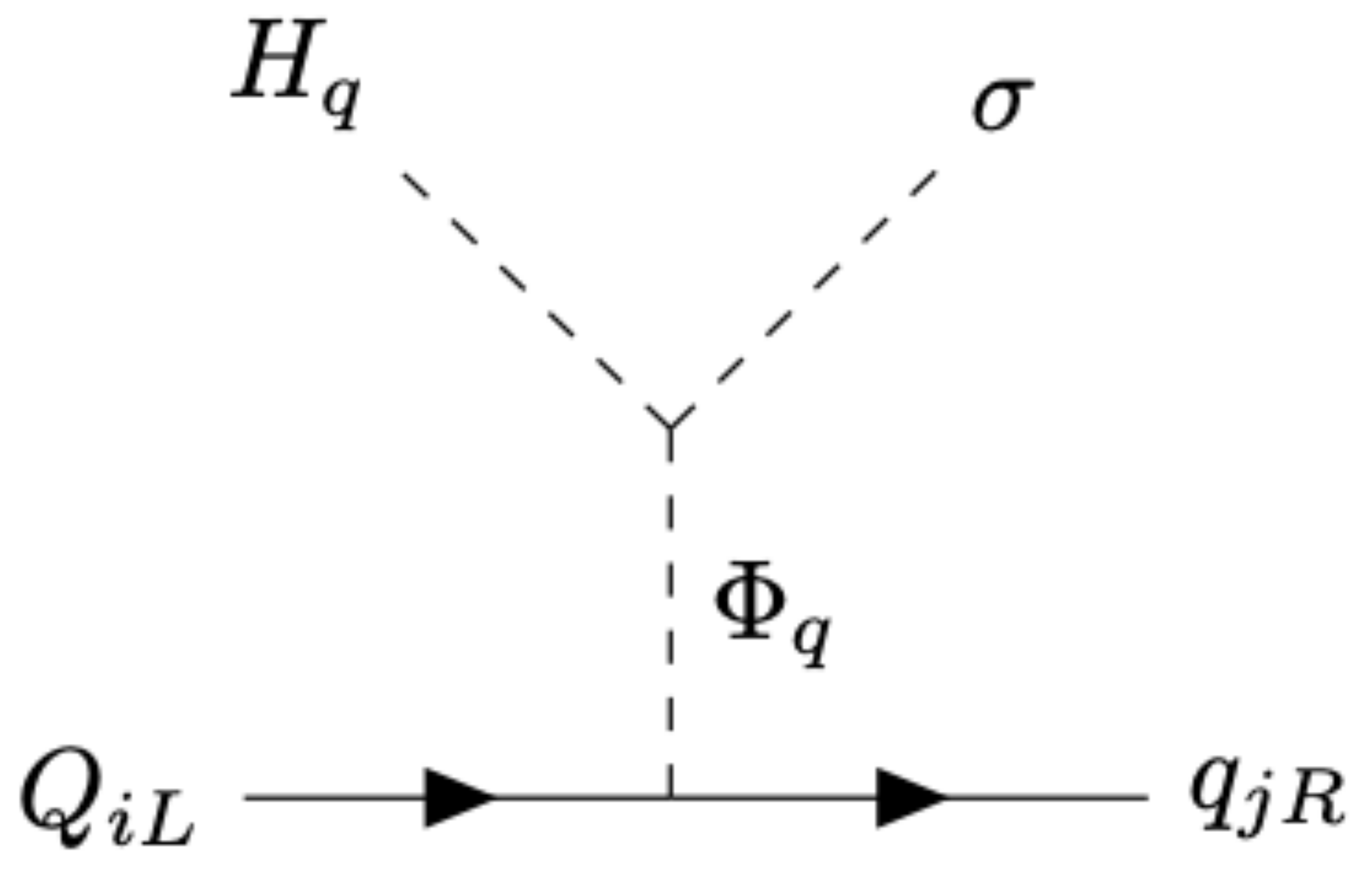
	F_{uC}^{12}	F_{uC}^{21}	F_{uC}^{23}	F_{uC}^{32}	F_{dC}^{12}	F_{dC}^{21}	F_{dC}^{23}	F_{dC}^{32}
$U(1)_Y$	2/3	2/3	2/3	2/3	-1/3	-1/3	-1/3	-1/3
$U(1)_{PQ}$	7/2	-7/2	-3/2	3/2	7/2	-7/2	-3/2	3/2

$$\begin{aligned}\mathcal{L}_u^{UV} \supset\ & \mathcal{Y}_{12}^u \overline{Q}_{1L} H_u F_{uR}^{12} + \mathcal{M}_{12}^u \overline{F_{uR}^{12}} F_{uL}^{12} + \mathcal{Y'}_{12}^u\ \overline{F_{uL}^{12}} \sigma u_{2R} \\ & + \mathcal{Y}_{21}^u \overline{Q}_{2L} H_u F_{uR}^{21} + \mathcal{M}_{21}^u \overline{F_{uR}^{21}} F_{uL}^{21} + \mathcal{Y'}_{21}^u \overline{F_{uL}^{21}} \sigma u_{1R} \\ & + \mathcal{Y}_{23}^u \overline{Q}_{2L} \widetilde{H}_d F_{uR}^{23} + \mathcal{M}_{23}^u \overline{F_{uR}^{23}} F_{uL}^{23} + \mathcal{Y'}_{23}^u\ \overline{F_{uL}^{23}} \sigma^* u_{3R} \\ & + \mathcal{Y}_{32}^u \overline{Q}_{3L} \widetilde{H}_d F_{uR}^{32} + \mathcal{M}_{32}^u \overline{F_{uR}^{32}} F_{uL}^{32} + \mathcal{Y'}_{32}^u \overline{F_{uL}^{32}} \sigma^* u_{2R}\ .\end{aligned}$$

Type-I seesaw UV completion



$$\mathcal{L}_u^{UV} \supset \mathcal{Y}_{12}^u \overline{Q}_{1L} \Phi_u u_{2R} + \mathcal{Y}_{21}^u \overline{Q}_{2L} \Phi_u u_{1R} + \kappa_u H_u \Phi_u^\dagger \sigma$$
$$+ \mathcal{Y}_{23}^u \overline{Q}_{2L} \widetilde{\Phi}_d u_{3R} + \mathcal{Y}_{32}^u \overline{Q}_{3L} \widetilde{\Phi}_d u_{2R} + \kappa_d \widetilde{H}_d \Phi_d \sigma^*$$



$$v_{\Phi_{u/d}} \approx -\frac{\kappa_{u/d} v_\sigma v_{u/d}}{M^2_{\Phi_{u/d}}}$$

$$m_{u/d} = \begin{pmatrix} 0 & \mathbf{A}_{u/d} & 0 \\ \mathbf{B}_{u/d} & 0 & \mathbf{C}_{u/d} \\ 0 & \mathbf{D}_{u/d} & \mathbf{E}_{u/d} \end{pmatrix}$$
$$= \begin{pmatrix} 0 & A_{u/d} & 0 \\ B_{u/d}\, e^{-i\alpha_{u/d}} & 0 & C_{u/d}\, e^{-i\alpha_{u/d}} \\ 0 & D_{u/d}\, e^{-i\beta_{u/d}} & E_{u/d}\, e^{-i\beta_{u/d}} \end{pmatrix}$$

Type-II UV completion

Mass Matrix reparametrization

	L_{iL}	ℓ_{iR}	N_i	σ'
$SU(2)_L \times U(1)_Y$	(2, -1/2)	(1, -1)	(1, 0)	(1, 0)
$U(1)_{PQ}$	(1,-3, 0)	(0, -2, -1)	(0, -2, -1)	2

Type-I seesaw

$$m_\nu = \begin{pmatrix} 0 & \times & 0 \\ \times & \times & \times \\ 0 & \times & \times \end{pmatrix}$$

$$= \begin{pmatrix} 0 & a\,e^{i\phi_a} & 0 \\ a\,e^{i\phi_a} & b\,e^{i\phi_b} & c\,e^{i\phi_c} \\ 0 & c\,e^{i\phi_c} & d\,e^{i\phi_d} \end{pmatrix}$$

A2 texture zero matrix

Lepton sector FN

Quark sector

Parameter	Best fit
$A_u/(10^{-2}\,\mathrm{GeV})$	1.519
$B_u/(10^{-2}\,\mathrm{GeV})$	−5.368
$C_u/\,\mathrm{GeV}$	−3.004
$D_u/(10^{1}\,\mathrm{GeV})$	3.562
$E_u/(10^{2}\,\mathrm{GeV})$	1.679
$A_d/(10^{-2}\,\mathrm{GeV})$	−1.233
$B_d/(10^{-2}\,\mathrm{GeV})$	1.228
$C_d/(10^{-1}\,\mathrm{GeV})$	−3.074
$D_d/(10^{-1}\,\mathrm{GeV})$	−4.782
$E_d/\,\mathrm{GeV}$	−2.793
$\alpha_u/^\circ$	96.56
$\beta_u/^\circ$	98.23

Numerical fit to fermion masses and mixings

Observable	Global-fit value		Model best-fit
	Best-fit value	1σ range	
$\theta^q_{12}/^\circ$	13.09	13.06 → 13.12	12.988
$\theta^q_{13}/^\circ$	0.207	0.202 → 0.213	0.2000
$\theta^q_{23}/^\circ$	2.32	2.29 → 2.37	2.381
$\delta^q/^\circ$	68.53	66.06 → 71.10	68.720
$m_u/(10^{-3}\,\mathrm{GeV})$	1.288	0.766 → 1.550	1.2743
$m_c/(10^{-1}\,\mathrm{GeV})$	6.268	6.076 → 6.459	6.2592
$m_t/\,\mathrm{GeV}$	171.68	170.17 → 173.18	171.687
$m_d/(10^{-3}\,\mathrm{GeV})$	2.751	2.577 → 3.151	2.7330
$m_s/(10^{-2}\,\mathrm{GeV})$	5.432	5.153 → 5.728	5.4311
$m_b/\,\mathrm{GeV}$	2.854	2.827 → 2.880	2.8501
χ^2_q			1.0901

Lepton sector

Numerical fit to fermion masses and mixings

Parameter	Best fit
$a/(10^{-3}\ \text{eV})$	9.933
$b/(10^{-2}\ \text{eV})$	2.646
$c/(10^{-2}\ \text{eV})$	2.475
$d/(10^{-2}\ \text{eV})$	2.264
$\phi_a/°$	29.87
$\phi_b/°$	91.88
$\phi_c/°$	3.03
$\phi_d/°$	−109.97

Observable	Global-fit value		Model best-fit
	Best-fit value	1σ range	
$\theta^l_{12}/°$	34.5	$33.5 \to 35.7$	34.85
$\theta^l_{13}/°$	8.45	$8.31 \to 8.61$	8.432
$\theta^l_{23}/°$	47.7	$46.0 \to 48.9$	48.11
$\delta^l/°$	218	$191 \to 256$	258.8
$\alpha/°$			65.27
$\beta/°$			265.08
$\Delta m^2_{21}/(10^{-5}\ \text{eV}^2)$	7.55	$7.39 \to 7.75$	7.571
$\Delta m^2_{32}/(10^{-3}\ \text{eV}^2)$	2.424	$2.394 \to 2.454$	2.4221
$\sum m_\nu/(10^{-2}\ \text{eV})$			6.453
$m_e/\ \text{MeV}$	0.4865763	$0.4865735 \to 0.4865789$	–
$m_\mu/\ \text{GeV}$	0.10271897	$0.10271866 \to 0.10271931$	–
$m_\tau/\ \text{GeV}$	1.74618	$1.74602 \to 1.74633$	–
χ^2_l			2.0053

SU(3)xSU(3)x U(1)PQ anomaly

axion

$$\sigma(x) = \frac{1}{\sqrt{2}}(\rho(x) + f_a)e^{ia(x)/f_a}.$$

Peccei-Quinn symmetry

$$g_{a\gamma} = \frac{\alpha_{EM}}{2\pi f_a}\left(\frac{E}{N} - 1{,}92\right), \quad g_{ag} = \frac{\alpha_s}{8\pi f_a}$$

Anomalous couplings to photons, gluons

$$\frac{|g_{a\gamma}^{SU(5)}|}{|g_{a\gamma}^{DFSZ}|} = 14$$

Anomalous couplings suppressed wrt SU(5) axions

$$\mathcal{L} \supset \frac{C^u_{11}}{\Lambda^8}\overline{Q}_{1L}H_u u_{1R}\sigma^8 + \frac{C^u_{12}}{\Lambda}\overline{Q}_{1L}H_u u_{2R}\sigma + \frac{C^u_{13}}{\Lambda^4}\overline{Q}_{1L}H_u u_{3R}\sigma^4 + \frac{C^u_{21}}{\Lambda}\overline{Q}_{2L}H_u u_{1R}\sigma + \frac{C^u_{22}}{\Lambda^4}\overline{Q}_{2L}\widetilde{H}_d u_{2R}\sigma^{*4}$$

$$+ \frac{C^u_{23}}{\Lambda}\overline{Q}_{2L}\widetilde{H}_d u_{3R}\sigma^* + \frac{C^u_{31}}{\Lambda^4}\overline{Q}_{3L}H_u u_{1R}\sigma^4 + \frac{C^u_{32}}{\Lambda}\overline{Q}_{3L}\widetilde{H}_d u_{2R}\sigma^* + y^u_{33}\overline{Q}_{3L}H_u u_{3R} \,,$$

Y. Ema, K. Hamaguchi, T. Moroi, K. Nakayama,
C.D.Carone,M.Merchand
L. Calibbi, F. Goertz, D. Redigolo, R. Ziegler, J. Zupan
F. Arias-Aragon, L. Merlo
M. Linster, R. Ziegler
F. Björkeroth, E.J. Chun, S.F. King
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Q. Bonnefoy, E. Dudas, S. Pokorski

“Flaxion”, “axiflavon”, “flavored axion”,…

$$K^+ \to \pi^+ a$$

$$\mathrm{BR}(K^+ \to \pi^+ a) = \frac{\Gamma(K^+ \to \pi^+ a)}{\Gamma_{Total}(K^+)} < 7.3 \times 10^{-11}$$

E949 limit on Kaon decay

$$f_a > 7 \times 10^9 \; GeV$$

Flavored axion couplings

$$h_0 \approx h_o^u \cos\alpha + h_o^d \sin\alpha$$

$$\mathscr{L} \supset h_0 \overline{u}_\alpha u_\beta$$

$$t \to hc \ , \ h \to bs$$

Higgs Flavor non-diagonal couplings

$$\mathrm{BR}(t \to hc)_{\mathrm{LHC}} < 1.1 \times 10^{-3},$$

Current constraint

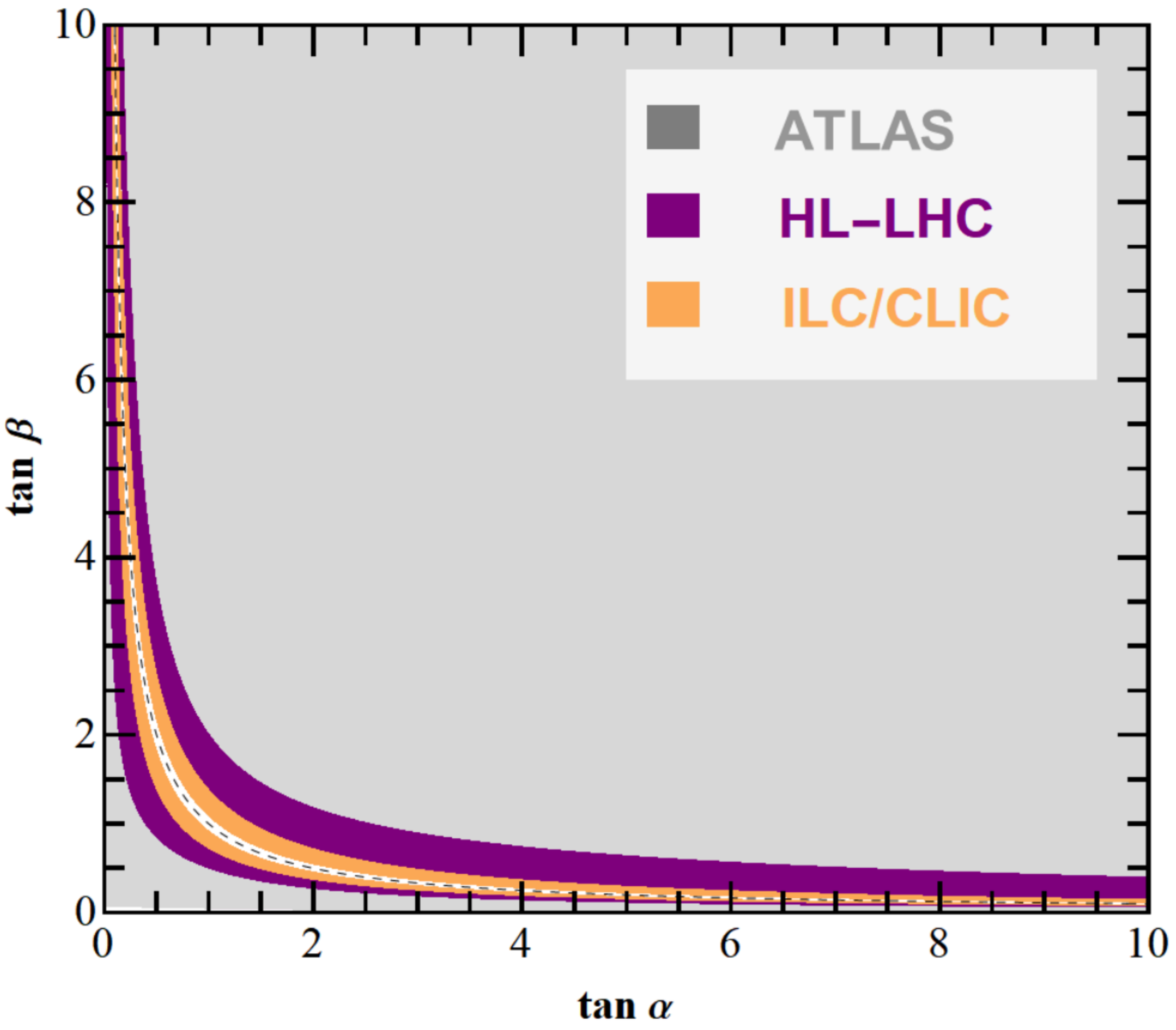
Projected constraints

$$\mathrm{BR}(t \to hc)_{\mathrm{HL-LHC}} < 2 \times 10^{-4},$$

$$\mathrm{BR}(t \to hc)_{\mathrm{ILC/CLIC}} < 10^{-5}.$$

$$\left| \frac{\cos\alpha}{\sin\beta} (1 - \tan\alpha \tan\beta) \right| \leq 17 \frac{\Gamma^{Exp}_{t\to hc}}{[GeV]}$$

$$\left|\frac{\cos\alpha}{\sin\beta}(1-\tan\alpha\tan\beta)\right| \leq 17\frac{\Gamma^{Exp}_{t\to hc}}{[GeV]}$$



Collider limits

Summary

- Fermion mass hierarchy from U(1) FN
- Axions from U(1)
- DM, Strong CP
- Axion pheno in rare meson decays
- Higgs pheno in colliders

Thank you