A Realistic U(2) Model of Flavor

Robert Ziegler (KIT)

mainly based on arXiv: 1805.07341 with M. Linster & work in progress with M. Linster & J. Lopez-Pavon

arXiv:1308.1090 with E. Dudas, G. v.Gersdorff, S. Pokorski } SUSY

arXiv:1509.01249 with A. Falkowksi, M. Nardecchia
arXiv:1904.04121 with R. Barbieri } B-anomalies

Outline

Realistic extension of U(2) models by Barbieri & al.

(viable CKM, neutrinos included, no SUSY)

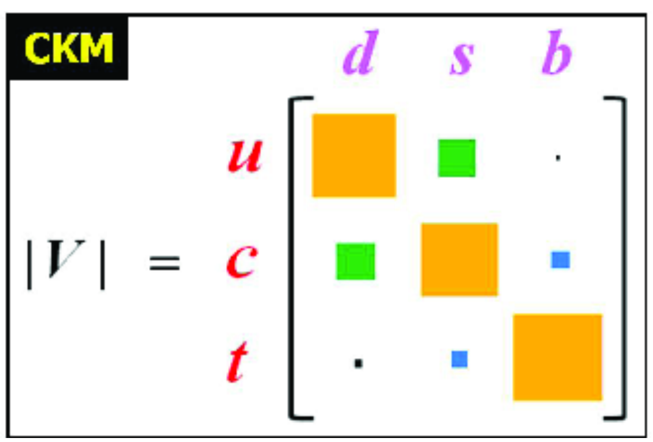
R. Barbieri, G. Dvali, L. Hall '96
R. Barbieri, L. Hall, A. Romanino '97....

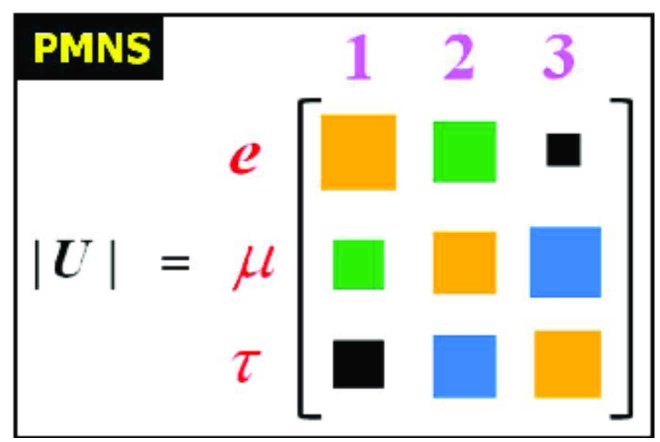
$$m_{\{u,d,e,\nu\}} \sim \begin{pmatrix} 0 & \varepsilon^2 & 0 \\ \varepsilon^2 & \varepsilon^2 & \{\varepsilon, \varepsilon^2, \varepsilon, \varepsilon^2\} \\ 0 & \{\varepsilon, \varepsilon, \varepsilon^2, \varepsilon^2\} & \{1, \varepsilon, \varepsilon, \varepsilon^2\} \end{pmatrix}$$

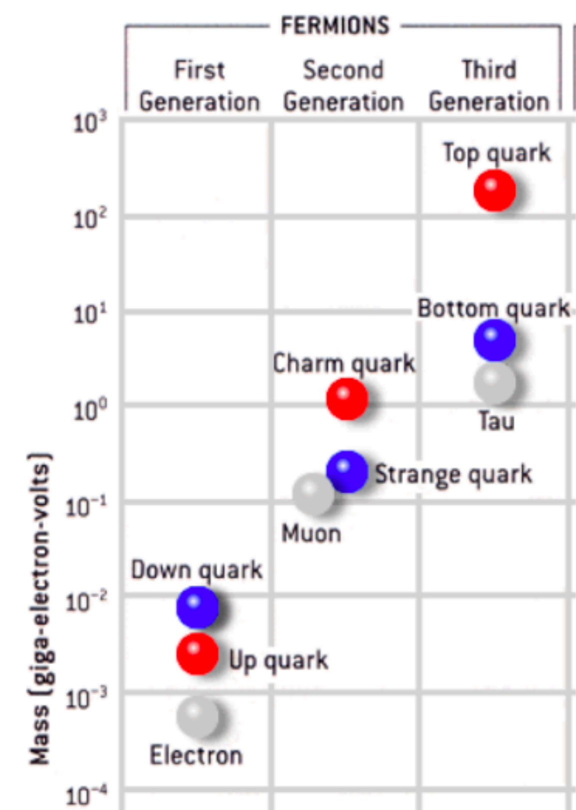
$\epsilon \sim V_{cb}$

The SM Flavor Puzzle

Explain large hierarchies in fermion masses and mixings







Here: **Approximate Flavor Symmetries**

Flavor Symmetries

SM fields charged under flavor symmetry group G, spontaneously broken by VEVs of "**flavon**" fields Φ_A

Effective Yukawa Lagrangian requires flavon insertions in order to be invariant under G

from G selection rules

$$\mathcal{L}_{\text{yuk}} = \lambda_{ij} \left(\frac{\Phi_A}{\Lambda_F} \right)^{x_{ij}^{A}} \bar{q}_i u_j h$$

"O(1)" coefficients

UV scale

Yukawas given by powers of small parameters $\epsilon_A = \langle \Phi_A \rangle / \Lambda_F$

Prototype Example: U(1)

Froggatt, Nielsen '79

	Φ	$\bar{q}_i$	u_i	h
$U(1)_F$	-1	q_i	u_i	0

$$\longrightarrow \quad y^u_{ij} = \lambda^u_{ij} \epsilon^{q_i + u_j}$$

(same as in Partial Compositeness)

Can easily reproduce all Yukawa hierarchies, **e.g.**

$$q_i = (3, 2, 0)$$

$$u_i = (4, 2, 0)$$

$$y_u \sim \begin{pmatrix} \epsilon^{3+4} & \epsilon^{3+2} & \epsilon^{3+0} \\ \epsilon^{2+4} & \epsilon^{2+2} & \epsilon^{2+0} \\ \epsilon^{0+4} & \epsilon^{0+2} & \epsilon^{0+0} \end{pmatrix}$$

Diagonalized by $V_{ij} \sim \epsilon^{|f_i - f_j|} \longrightarrow V_{us} \sim \epsilon^{|q_1 - q_2|} \sim \epsilon$

not so small order parameter:
charge assignment not unique

2 charge diff's for 3 CKM angles: postdict $V_{ub} \sim V_{us} V_{cb}$

A U(2) Model of Flavor

$$U(2)_F \equiv SU(2)_F \times U(1)_F$$

SM quantum numbers

- compatible with SU(5) GUT
  $\mathbf{10} = Q, U, E \quad \overline{\mathbf{5}} = L, E$
- generations transform as **2+1**
  $\mathbf{10}_i = \mathbf{10}_a + \mathbf{10}_3$
- need to specify 4 $U(1)_F$ charges
  $X_{10_3} = 0 \quad X_{10_a} = X_{\bar{5}_a} = X_{\bar{5}_3} = 1$

U(2) breaking

- 2 flavons in **2+1** with charge -1
  $\phi = \mathbf{2}_{-1} \qquad \chi = \mathbf{1}_{-1}$
- VEVs slightly below cutoff Λ
  $\langle\phi\rangle = \begin{pmatrix} \varepsilon_\phi \Lambda \\ 0 \end{pmatrix} \qquad \langle\chi\rangle = \varepsilon_\chi \Lambda$

$\epsilon_\phi \sim 0.03 \qquad \epsilon_\chi \sim 0.01$

	$\mathbf{10}_a$	$\overline{\mathbf{5}}_a$	$\mathbf{10}_3$	$\overline{\mathbf{5}}_3$	H	ϕ_a	χ
$SU(2)_F$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$
$U(1)_F$	1	1	0	1	0	-1	-1

Linster, RZ '18
[old models: SO(10)]

Up-Quark Sector

Invariant Yukawa Lagrangian needs Flavon insertions

$$\mathcal{L}_u = \frac{\lambda_{11}^u}{\Lambda^6}\chi^4(\phi_a^* Q_a)(\phi_b^* U_b)H + \frac{\lambda_{12}^u}{\Lambda^2}\chi^2\epsilon_{ab}Q_a U_b H + \frac{\lambda_{13}^u}{\Lambda^3}\chi^2(\phi_a^* Q_a)U_3 H$$
$$+ \frac{\lambda_{22}^u}{\Lambda^2}(\epsilon_{ab}\phi_a Q_b)(\epsilon_{cd}\phi_c U_d)H + \frac{\lambda_{23}^u}{\Lambda}(\epsilon_{ab}\phi_a Q_b)U_3 H + \frac{\lambda_{31}^u}{\Lambda^3}\chi^2 Q_3(\phi_a^* U_a)H$$
$$+ \frac{\lambda_{32}^u}{\Lambda}Q_3(\epsilon_{ab}\phi_a U_b)H + \lambda_{33}^u Q_3 U_3 H\,,$$

Flavon vevs generate hierarchical Yukawa structure

$$Y_u \approx \begin{pmatrix} \lambda_{11}^u\varepsilon_\phi^2\varepsilon_\chi^4 & \lambda_{12}^u\varepsilon_\chi^2 & \lambda_{13}^u\varepsilon_\phi\varepsilon_\chi^2 \\ -\lambda_{12}^u\varepsilon_\chi^2 & \lambda_{22}^u\varepsilon_\phi^2 & \lambda_{23}^u\varepsilon_\phi \\ \lambda_{31}^u\varepsilon_\phi\varepsilon_\chi^2 & \lambda_{32}^u\varepsilon_\phi & \lambda_{33}^u \end{pmatrix} \approx \begin{pmatrix} 0 & \lambda_{12}^u\varepsilon_\chi^2 & 0 \\ -\lambda_{12}^u\varepsilon_\chi^2 & \lambda_{22}^u\varepsilon_\phi^2 & \lambda_{23}^u\varepsilon_\phi \\ 0 & \lambda_{32}^u\varepsilon_\phi & \lambda_{33}^u \end{pmatrix}$$

drop sub-leading corrections $\mathcal{O}(\epsilon_\phi^2) \sim 10^{-4}$

reproduce holomorphic 0's in SUSY models

Quarks and Charged Leptons

U(1) charge of RH_3 +1

$$Y_u \approx \begin{pmatrix} 0 & \lambda^u_{12}\varepsilon_\chi^2 & 0 \\ -\lambda^u_{12}\varepsilon_\chi^2 & \lambda^u_{22}\varepsilon_\phi^2 & \lambda^u_{23}\varepsilon_\phi \\ 0 & \lambda^u_{32}\varepsilon_\phi & \lambda^u_{33} \end{pmatrix}, \qquad Y_d \approx \begin{pmatrix} 0 & \lambda^d_{12}\varepsilon_\chi^2 & 0 \\ -\lambda^d_{12}\varepsilon_\chi^2 & \lambda^d_{22}\varepsilon_\phi^2 & \lambda^d_{23}\varepsilon_\phi\varepsilon_\chi \\ 0 & \lambda^d_{32}\varepsilon_\phi & \lambda^d_{33}\varepsilon_\chi \end{pmatrix}$$

U(1) charge of LH_3 +1

$$Y_e \approx \begin{pmatrix} 0 & \lambda^e_{12}\varepsilon_\chi^2 & 0 \\ -\lambda^e_{12}\varepsilon_\chi^2 & \lambda^e_{22}\varepsilon_\phi^2 & \lambda^e_{23}\varepsilon_\phi \\ 0 & \lambda^e_{32}\varepsilon_\phi\varepsilon_\chi & \lambda^e_{33}\varepsilon_\chi \end{pmatrix}.$$

SM Flavor Structure

$$Y_u \approx \begin{pmatrix} 0 & \lambda^u_{12}\varepsilon^2_\chi & 0 \\ -\lambda^u_{12}\varepsilon^2_\chi & \lambda^u_{22}\varepsilon^2_\phi & \lambda^u_{23}\varepsilon_\phi \\ 0 & \lambda^u_{32}\varepsilon_\phi & \lambda^u_{33} \end{pmatrix}, \qquad Y_d \approx \begin{pmatrix} 0 & \lambda^d_{12}\varepsilon^2_\chi & 0 \\ -\lambda^d_{12}\varepsilon^2_\chi & \lambda^d_{22}\varepsilon^2_\phi & \lambda^d_{23}\varepsilon_\phi\varepsilon_\chi \\ 0 & \lambda^d_{32}\varepsilon_\phi & \lambda^d_{33}\varepsilon_\chi \end{pmatrix}$$

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1-2 mixing angles **smallish,** related to light masses

$$\theta_{12} \sim \epsilon^2_\chi/\epsilon^2_\phi \sim \sqrt{m_1/m_2}$$

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2-3 angles **large** for **RH d-quarks** and **LH leptons**

$\theta^{DR}_{23} \sim \theta^{EL}_{23} \sim \epsilon_\phi/\epsilon_\chi \sim \mathcal{O}(1)$

SM Flavor Structure

$$Y_u \approx \begin{pmatrix} 0 & \lambda^u_{12}\varepsilon^2_\chi & 0 \\ -\lambda^u_{12}\varepsilon^2_\chi & \lambda^u_{22}\varepsilon^2_\phi & \lambda^u_{23}\varepsilon_\phi \\ 0 & \lambda^u_{32}\varepsilon_\phi & \lambda^u_{33} \end{pmatrix}, \qquad Y_d \approx \begin{pmatrix} 0 & \lambda^d_{12}\varepsilon^2_\chi & 0 \\ -\lambda^d_{12}\varepsilon^2_\chi & \lambda^d_{22}\varepsilon^2_\phi & \lambda^d_{23}\varepsilon_\phi\varepsilon_\chi \\ 0 & \lambda^d_{32}\varepsilon_\phi & \lambda^d_{33}\varepsilon_\chi \end{pmatrix}$$

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Other **2-3** angles are **small**

$\theta^{\rm rest}_{23} \sim \epsilon_\phi \sim V_{cb}$

SM Flavor Structure

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1-2 mixing angles **smallish,** related to light masses — $\theta_{12} \sim \epsilon^2_\chi/\epsilon^2_\phi \sim \sqrt{m_1/m_2}$

2-3 angles **large** for **RH d-quarks** and **LH leptons** — $\theta^{DR}_{23} \sim \theta^{EL}_{23} \sim \epsilon_\phi/\epsilon_\chi \sim \mathcal{O}(1)$

Other **2-3** angles are **small** — $\theta^{\rm rest}_{23} \sim \epsilon_\phi \sim V_{cb}$

1-3 angles given by **1-2** and **2-3** angles — $\theta_{13} \sim \theta_{12} \times \theta_{23}$

CKM Relations

Texture zeros accurately relate masses and mixing angles

$$|V_{us}| \approx \left| \sqrt{\frac{m_d}{m_s}} \sqrt{c_{23}^{Rd}} - e^{i(\phi_2 - \phi_1)} \sqrt{\frac{m_u}{m_c}} \right|$$

$$|V_{td}| \approx \sqrt{\frac{m_d}{m_s}} \sqrt{c_{23}^{Rd}} \left| |V_{cb}| - e^{i\phi_2} \frac{s_{23}^{Rd}}{c_{23}^{Rd}} \frac{m_s}{m_b} \right|$$

$$|V_{ub}| \approx \left| \sqrt{\frac{m_u}{m_c}} |V_{cb}| - e^{i\phi_1} \sqrt{\frac{m_d}{m_s}} \sqrt{c_{23}^{Rd}} \frac{s_{23}^{Rd}}{c_{23}^{Rd}} \frac{m_s}{m_b} \right|$$

2-3 mixing angle in RH down sector

free phases

In original U(2) models $s_{23}^{Rd} \sim V_{cb}$ ⟶ $|V_{ub}/V_{cb}| \approx \sqrt{m_u/m_c}$

Off by more than 3σ: need $s_{23}^{Rd} \sim 1$

Roberts, Ross, Romanino, Velasco-Sevilla '01

Numerical Fit

Fit parameters $\{\lambda_{ij}^{u,d,e}, \varepsilon_\phi, \varepsilon_\chi\}$ with SM observables

Use quality measure for "O(1)-ness" of $\lambda_{ij}^{u,d,e}$

$$\chi^2_{\mathcal{O}(1)} = \sum_{\lambda_{ij}^p} \frac{\left(\log(|\lambda_{ij}^p|)\right)^2}{2\cdot 0.55^2} \longrightarrow \lambda_{ij}^{u,d,e} \text{ with 95\% prob. in [1/3, 3]}$$

e.g. for single parameter $\lambda = \{3, 5, 7, 10, 50, 100\}$

get contribution $\Delta\chi^2_{\mathcal{O}(1)} = \{2, 4, 6, 9, 25, 35\}$

Fit satisfactory if

$\chi^2_{\mathcal{O}(1)} \leq \#\text{pars}$

$\chi^2 \leq \#\text{obs}$

Fit	ε_ϕ	ε_χ	min $\lvert\lambda_{ij}^{u,d,\ell}\rvert$	max $\lvert\lambda_{ij}^{u,d,\ell}\rvert$	χ^2	$\chi^2_{\mathcal{O}(1)}$
$\text{QL1}_\mathbb{R}$	0.019	0.008	1/3.1	2.7	1.7	7.8
$\text{QL2}_\mathbb{R}$	0.023	0.008	1/2.7	2.8	12	5.4

Neutrino Sector

Majorana neutrinos don't work because leading order 1-2 entry in Weinberg operator vanishes due to SU(2) antisymmetrization

$\epsilon_{ab} L_a L_b H H = 0$

Can do Dirac Neutrinos with $N_i = N_a + N_3$ & $X_a^N = X_3^N$

$$m_\nu^D \approx v\, \varepsilon_\chi^{X_a^N - 1} \begin{pmatrix} 0 & \lambda_{12}^\nu \varepsilon_\chi^2 & 0 \\ -\lambda_{12}^\nu \varepsilon_\chi^2 & \lambda_{22}^\nu \varepsilon_\phi^2 & \lambda_{23}^\nu \varepsilon_\phi \varepsilon_\chi \\ 0 & \lambda_{32}^\nu \varepsilon_\phi \varepsilon_\chi & \lambda_{33}^\nu \varepsilon_\chi^2 \end{pmatrix}$$

get anarchic structure; smallness from largish U(1) charges

Neutrino Fit & Predictions

Good fit just for Normal Ordering

Fit	X_a^N	X_3^N	ε_ϕ	ε_χ	min $\lvert\lambda_{ij}^{u,d,e,\nu}\rvert$	max $\lvert\lambda_{ij}^{u,d,e,\nu}\rvert$	χ^2	$\chi^2_{\mathcal{O}(1)}$
QLν_D-1 (NO)	6	6	0.026	0.012	1/2.9	2.6	0.5	10
QLν_D-2 (NO)	6	6	0.024	0.013	1/2.6	2.2	18	9
QLν_D-3 (NO)	5	5	0.022	0.006	1/3.1	3.8	1.0	13
QLν_D-4 (NO)	5	5	0.021	0.006	1/2.5	2.4	18	9

Predict overall mass scale from scanning over succesful fits

Quantity	Range [meV]	Preferred values [meV]
$\sum m_i$	58 – 110	60 – 65
m_β	8 – 26	9 – 10

No chance for KATRIN

PLANCK bound automatically satisfied!

$m_\beta = \sqrt{\sum_i m_i^2 |U_{ei}|^2}$

Majorana Neutrinos from $D_6 \times U(1)$

Consider dihedral $D_6 = D_3 \times Z_2$ instead of SU(2)

	$\mathbf{10}_a$	$\overline{\mathbf{5}}_a$	$\mathbf{10}_3$	$\overline{\mathbf{5}}_3$	H	ϕ_a	χ
$D_3 \times Z_2$	$\mathbf{2}_-$	$\mathbf{2}_-$	$\mathbf{1}_+$	$\mathbf{1}_+$	$\mathbf{1}_+$	$\mathbf{2}_-$	$\mathbf{1}_+$
$U(1)_F$	1	1	0	1	0	-1	-1

$$(\psi \otimes \phi)_{\mathbf{1}} = \psi_1\phi_2 + \psi_2\phi_1$$

$$(\psi \otimes \phi \otimes \chi)_{\mathbf{1}} = \psi_1\phi_1\chi_1 + \psi_2\phi_2\chi_2$$

Mimics U(2) structure except for symmetric 1-2:
Weinberg operator fixed from charged lepton sector

2 1
1 0

$$m_u \approx v \begin{pmatrix} 0 & \lambda^u_{12}\varepsilon_\chi^2 & 0 \\ \lambda^u_{12}\varepsilon_\chi^2 & \lambda^u_{22}\varepsilon_\phi^2 & \lambda^u_{23}\varepsilon_\phi \\ 0 & \lambda^u_{32}\varepsilon_\phi & \lambda^u_{33} \end{pmatrix}, \qquad m_d \approx v \begin{pmatrix} 0 & \lambda^d_{12}\varepsilon_\chi^2 & 0 \\ \lambda^d_{12}\varepsilon_\chi^2 & \lambda^d_{22}\varepsilon_\phi^2 & \lambda^d_{23}\varepsilon_\phi\varepsilon_\chi \\ 0 & \lambda^d_{32}\varepsilon_\phi & \lambda^d_{33}\varepsilon_\chi \end{pmatrix}$$

2 2
1 1

2 1
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$$m_e \approx v \begin{pmatrix} 0 & \lambda^e_{12}\varepsilon_\chi^2 & 0 \\ \lambda^e_{12}\varepsilon_\chi^2 & \lambda^e_{22}\varepsilon_\phi^2 & \lambda^e_{23}\varepsilon_\phi \\ 0 & \lambda^e_{32}\varepsilon_\phi\varepsilon_\chi & \lambda^e_{33}\varepsilon_\chi \end{pmatrix}, \qquad m_\nu \approx \frac{v^2}{M} \begin{pmatrix} 0 & \lambda^\nu_{12}\varepsilon_\chi^2 & 0 \\ \lambda^\nu_{12}\varepsilon_\chi^2 & \lambda^\nu_{22}\varepsilon_\phi^2 & \lambda^\nu_{23}\varepsilon_\phi\varepsilon_\chi \\ 0 & \lambda^\nu_{23}\varepsilon_\phi\varepsilon_\chi & \lambda^\nu_{33}\varepsilon_\chi^2 \end{pmatrix}$$

2 2
2 2

Majorana Neutrino Fit

Neutrino mass matrix automatically anarchic: better fit with less parameters

Fit	ε_ϕ	ε_χ	min $\lvert\lambda_{ij}^{\mathrm{u,d},\ell}\rvert$	max $\lvert\lambda_{ij}^{\mathrm{u,d},\ell}\rvert$	χ^2	$\chi^2_{\mathcal{O}(1)}$	M [10^{11} GeV]
QLν_M-1	0.025	0.009	1/2.8	2.1	0.7	7.9	4.1
QLν_M-2	0.024	0.009	1/2.6	1.9	18	6.3	3.3

Predict overall mass scale from scanning over succesful fits

Quantity	Range [meV]	Preferred values [meV]
$\sum m_i$	$59 - 78$	60, 70
m_β	$8 - 15$	$9 - 10$, $11 - 12$
$m_{\beta\beta}^{\max}$	$3 - 16$	5, 9

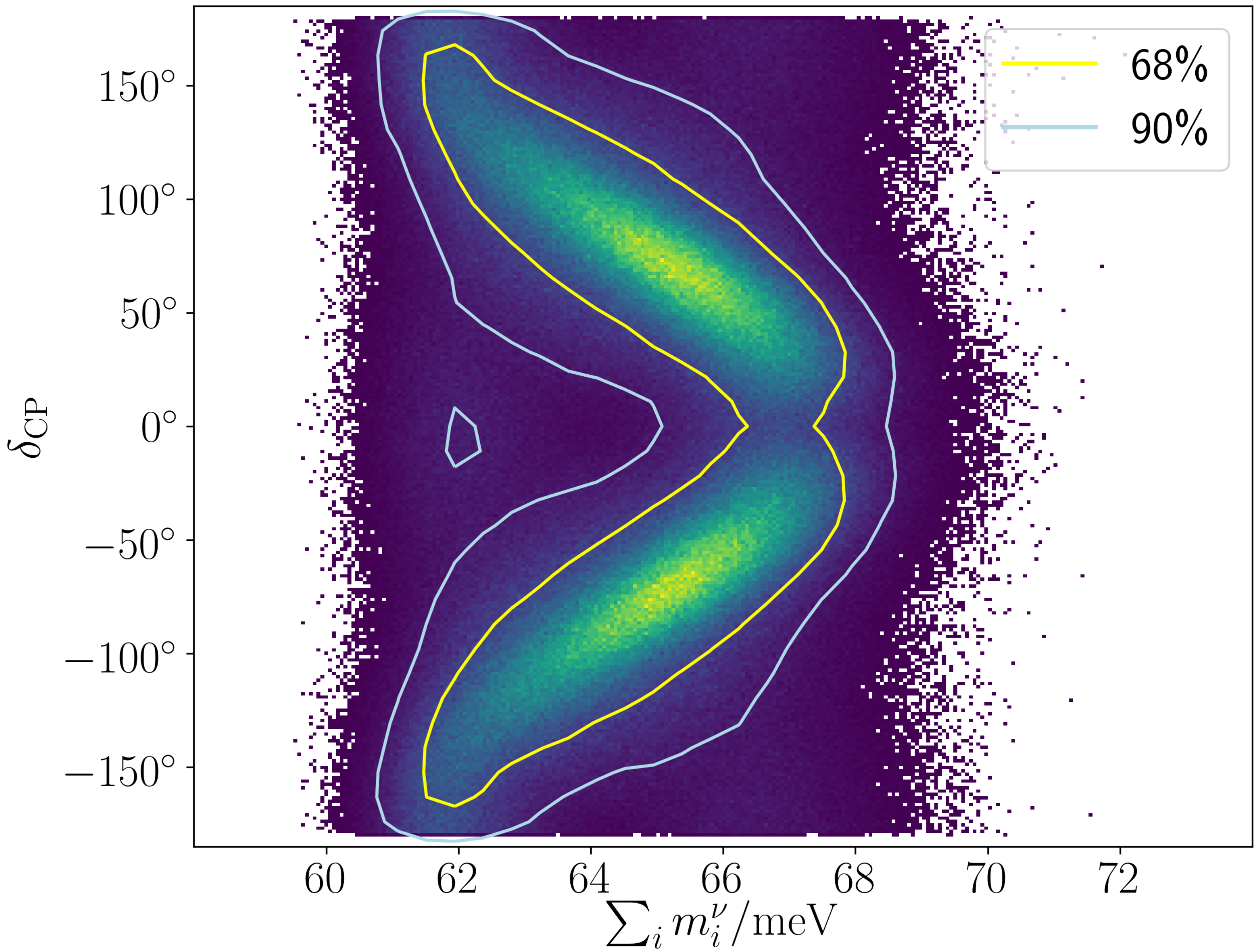
Similar to Dirac case, neutrinoless double beta decay hopeless

$m_{\beta\beta} = \lvert\sum U_{ei}^2 m_i\rvert$

Neutrino Sector Predictions

Correlation of Dirac phase and absolute mass scale

work in progress with J. Lopez-Pavon & M. Linster



just using neutrino mass textures and

$s^e_{12} \approx s^e_{13} \approx 0$

Testability

- Neutrino sector predictions
- Low-energy UV completion?
- Full-fledged SU(5) model?
- **The U(2) Axiflavon**

$U(1)_F$ spontaneously broken and has QCD anomaly:
Goldstone is QCD axion solving Strong CP ["axiflavon"]

Wilczek '82; Ema, Hamaguchi, Moroi, Nakayama '16; Calibbi, Goertz, Redigolo, RZ, Zupan '16

Predict flavor-violating axion couplings, fix cutoff by Axion DM

The U(2) Axiflavon

$$\mathcal{L}_a = \frac{\partial_\mu a}{2 f_a} \bar{f}_i \gamma^\mu \left[C^V_{f_i f_j} + C^A_{f_i f_j} \gamma_5 \right] f_j + \frac{E}{N} \frac{a(x)}{f_a} \frac{\alpha_{\rm em}}{8\pi} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

U(1)$_{\rm F}$ charges give anomaly coefficients

$$N_{\rm DW} = 2N = 9$$

$$E/N = 8/3 \quad \text{[SU(5)]}$$

Flavon breaking scale (~cutoff) sets mass scale

$$f_a \sim \sqrt{\epsilon_\chi^2 + \epsilon_\phi^2}\,\Lambda$$

$$m_a = 5.7\,\mu\text{eV} \left(\frac{10^{12}\,\text{GeV}}{f_a} \right)$$

Yukawa structure gives axion-fermion couplings

$$C^V_{f_i f_j} = (V_{fL})_{ki} X_{f_k} (V_{fL})^*_{kj}$$

$$C^A_{f_i f_j} = (V_{fR})^*_{ki} X_{f^c_k} (V_{fR})_{kj}$$

The U(2) Axiflavon

$$C^V_{u_iu_j} = \frac{\varepsilon^u_{L,ij} - \varepsilon^u_{R,ij}}{9}\,, \qquad C^A_{u_iu_j} = \frac{2\delta_{ij} - \varepsilon^u_{L,ij} - \varepsilon^u_{R,ij}}{9}\,,$$
$$C^V_{d_id_j} = \frac{\varepsilon^d_{L,ij}}{9}\,, \qquad C^A_{d_id_j} = \frac{2\delta_{ij} - \varepsilon^d_{L,ij}}{9}\,,$$
$$C^V_{e_ie_j} = -\frac{\varepsilon^e_{R,ij}}{9}\,, \qquad C^A_{e_ie_j} = \frac{2\delta_{ij} - \varepsilon^e_{R,ij}}{9}\,,$$

$$\varepsilon^u_L \sim \varepsilon^u_R \sim \varepsilon^d_L \sim \varepsilon^e_R \sim \begin{pmatrix} \lambda^6 & \lambda^5 & \lambda^3 \\ \lambda^5 & \lambda^4 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

SU(2)/D6 protects s-d transitions, strongest bound from SN

Coupling	$m_a^{\max}/C$ [eV]	$m_a^{\max,\mathrm{U}(2)}$ [eV]	$f_a^{\min,\mathrm{U}(2)}$ [GeV]	Constraint
C^V_{bs}	$9.1 \cdot 10^{-2}$	16	$3.6 \cdot 10^5$	$B^+ \to K^+ a$ [28]
C^V_{sd}	$1.7 \cdot 10^{-5}$	0.58	$9.8 \cdot 10^6$	$K^+ \to \pi^+ a$ [29]
C^A_{ee}	$3.1 \cdot 10^{-3}$	0.014	$4.1 \cdot 10^8$	WD Cooling [30]
C_N	$3.5 \cdot 10^{-3}$	0.0092	$6.2 \cdot 10^8$	SN1987A [31]

U(2) Axiflavon Phenomenology

U(1)$_F$ broken before inflation:

$$\Omega_{DM} h^2 \approx 0.12 \left(\frac{6\,\mu\text{eV}}{m_a}\right)^{1.165} \theta^2$$

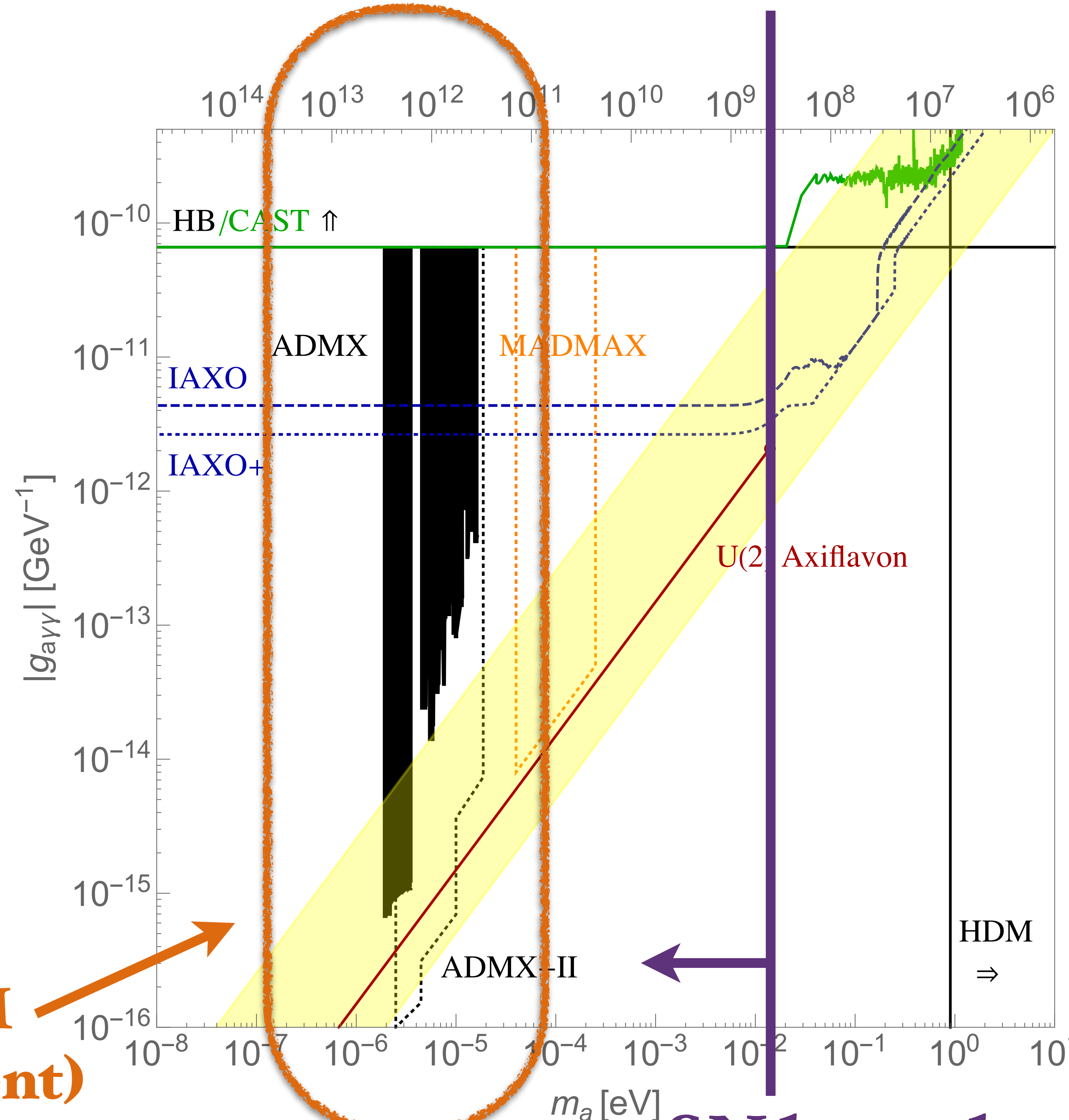
with misalignment angle

$$\theta \in [-\pi, \pi]$$

Axion DM gives preferred range for cutoff

$$\Lambda \sim (10^{13} \div 10^{15})\,\text{GeV}$$

Natural Axion DM window (misalignment)



SN bound

A U(2) Model of Flavor Anomalies

Vector Leptoquark model with U(2) governing all couplings

arxiv:1904.04121 with R. Barbieri

1) Vector Leptoquark couples only to heavy vector-like family

$$\mathcal{L}_{int} = g_V V_\mu^a (\bar{Q}_i^a \gamma_\mu L_i + \bar{D}_i^a \gamma_\mu E_i) + h.c.$$

$$V_\mu^a = (\mathbf{3}, 1)_{2/3}$$

2) Heavy vector-like family mixes with chiral fields

$$\mathcal{L}_{\text{mass}} = M_Q \overline{Q}_i Q_i + \overline{Q}_i (m_Q)_{ij} q_j + \overline{q}_i (\lambda_u)_{ij} u_j h + \ldots$$

3) Get Leptoquark couplings to light fields through mixing; fit CC and NC anomalies & constraints from loop $\Delta F = 2$

Mass Mixing

Take vectorlike quantum numbers $Q^c_a \sim q_a, Q^c_3 \sim q_3 \ldots$

[and SU(4) compatible charges instead of SU(5): $e^c \leftrightarrow \ell$]

Mixing sizable only for 3rd generation doublets!

$$m_q = \begin{pmatrix} \epsilon^2\epsilon'^4 & \epsilon'^2 & \epsilon\epsilon'^2 \\ -\epsilon'^2 & \epsilon^2 & \epsilon \\ \epsilon\epsilon'^2 & \epsilon & 1 \end{pmatrix} \qquad m_d = \begin{pmatrix} \epsilon^2\epsilon'^4 & \epsilon'^2 & \epsilon\epsilon'^3 \\ -\epsilon'^2 & \epsilon^2 & \epsilon\epsilon' \\ \epsilon\epsilon'^3 & \epsilon\epsilon' & \epsilon'^2 \end{pmatrix}$$

$$\mathcal{L}_{\rm LQ} \approx g_V s_{q3} s_{\ell 3} V^a_\mu (\overline{q}^a_3 \gamma^\mu \ell_3)$$

LQ couples only to 3rd generation in gauge basis

Effective Leptoquark Couplings

LQ couplings determined by LH Yukawa sector

$$\mathcal{L}_{int}^{physical} = g_V s_{q3} s_{l3} V_\mu^a (\bar{d}_{iL}^a \gamma_\mu F_{ij}^D e_{jL} + \bar{u}_{iL}^a \gamma_\mu F_{ij}^U \nu_{jL}) + h.c.$$

$$F_{ij}^D = D_{3i}^{L*} E_{3j}^L \qquad F_{ij}^U = U_{3i}^{L*} E_{3j}^L.$$

$$V_{ij} = \Sigma_k U_{ki}^{L*} D_{kj}^L$$

Good fit to B-anomalies with largish CL rotations only prevented by sign

$$\Delta R_D = 0.06 \left(\frac{\text{TeV}}{M_{\text{eff}}}\right)^2 \left[1 - \mathcal{R}e\left(\frac{D_{23}}{V_{cb}}\right)\right]$$

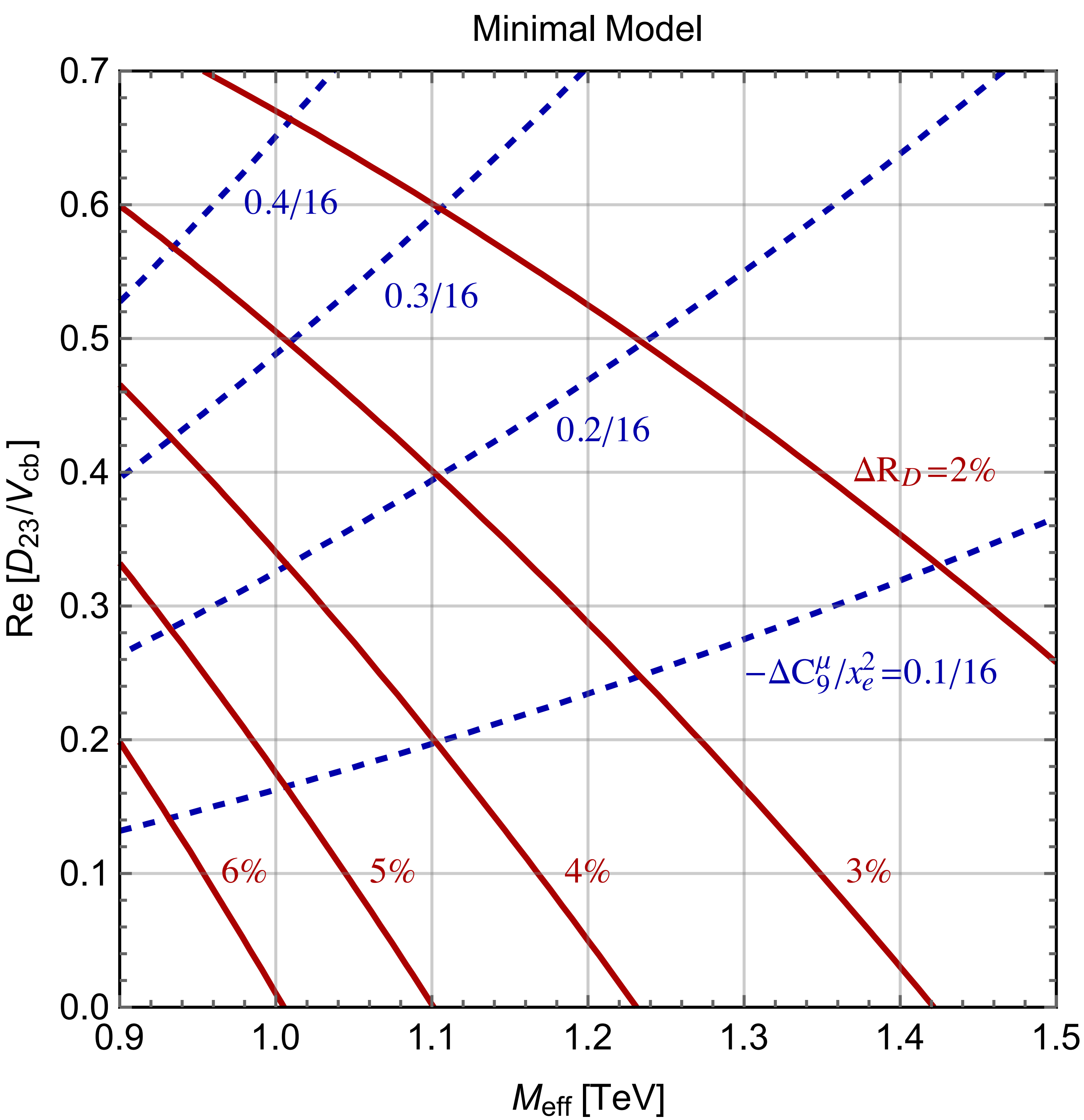
$$\Delta C_9^\mu = -0.04 \left(\frac{\text{TeV}}{M_{\text{eff}}}\right)^2 \left|\frac{E_{23}}{V_{cb}}\right|^2 \mathcal{R}e\left(\frac{D_{23}}{V_{cb}}\right)$$

$$\Delta R_D = (14 \pm 4)\,\%$$

$$\Delta C_9^\mu = -\,(0.53 \pm 0.09)$$

$$M_{\text{eff}} = \frac{M_V}{g_V s_{q3} s_{l3} c_{ql}}$$

Effective Leptoquark Couplings



$$x_e = |E_{23}/V_{cb}| \sim \mathcal{O}(1)$$

$$\Delta R_D = (14 \pm 4)\,\%$$

$$\Delta C_9^\mu = -\,(0.53 \pm 0.09)$$

Summary

- Simple and realistic model of flavor from U(2); viable CKM, non-SUSY, includes neutrinos

- Majorana Neutrinos are automatically anarchic; can predict absolute neutrino mass scale

- Naturally get QCD Axion as DM from $U(1)_F$; fixes flavor scale; SU(2) strongly suppresses flavor violation

- With leptoquark and vector-like fermions get too predictive model for flavor anomalies