# Revisiting the Flavor Puzzle

AG, Thomsen; 2309.11547
Antusch, AG, Stefanek, Thomsen; 2311.09288

Admir Greljo

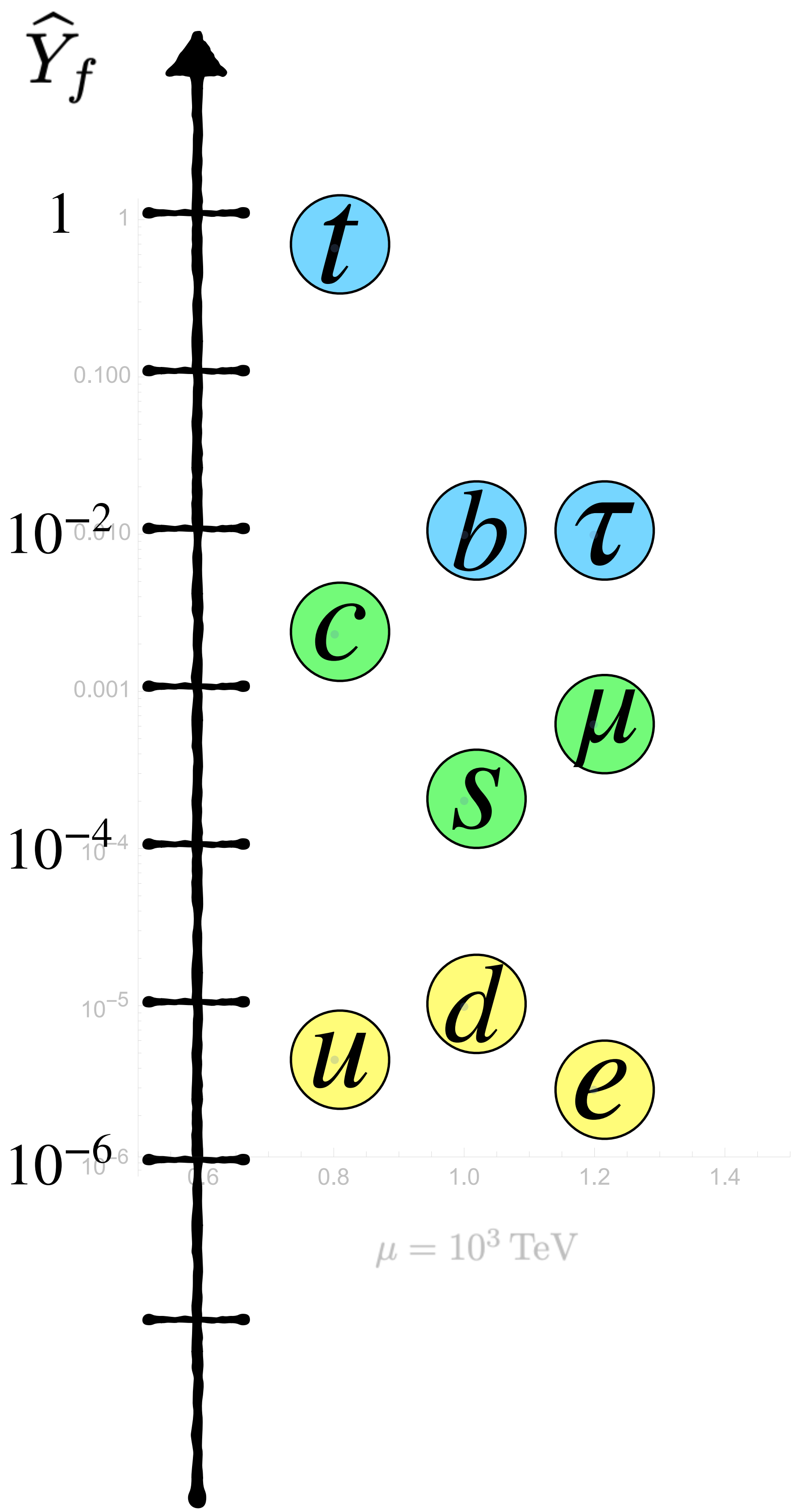
University of Basel

Swiss National Science Foundation
Eccellenza, Project-186866

06.03.2024, La Thuile

# The Flavour Puzzle

Empirical

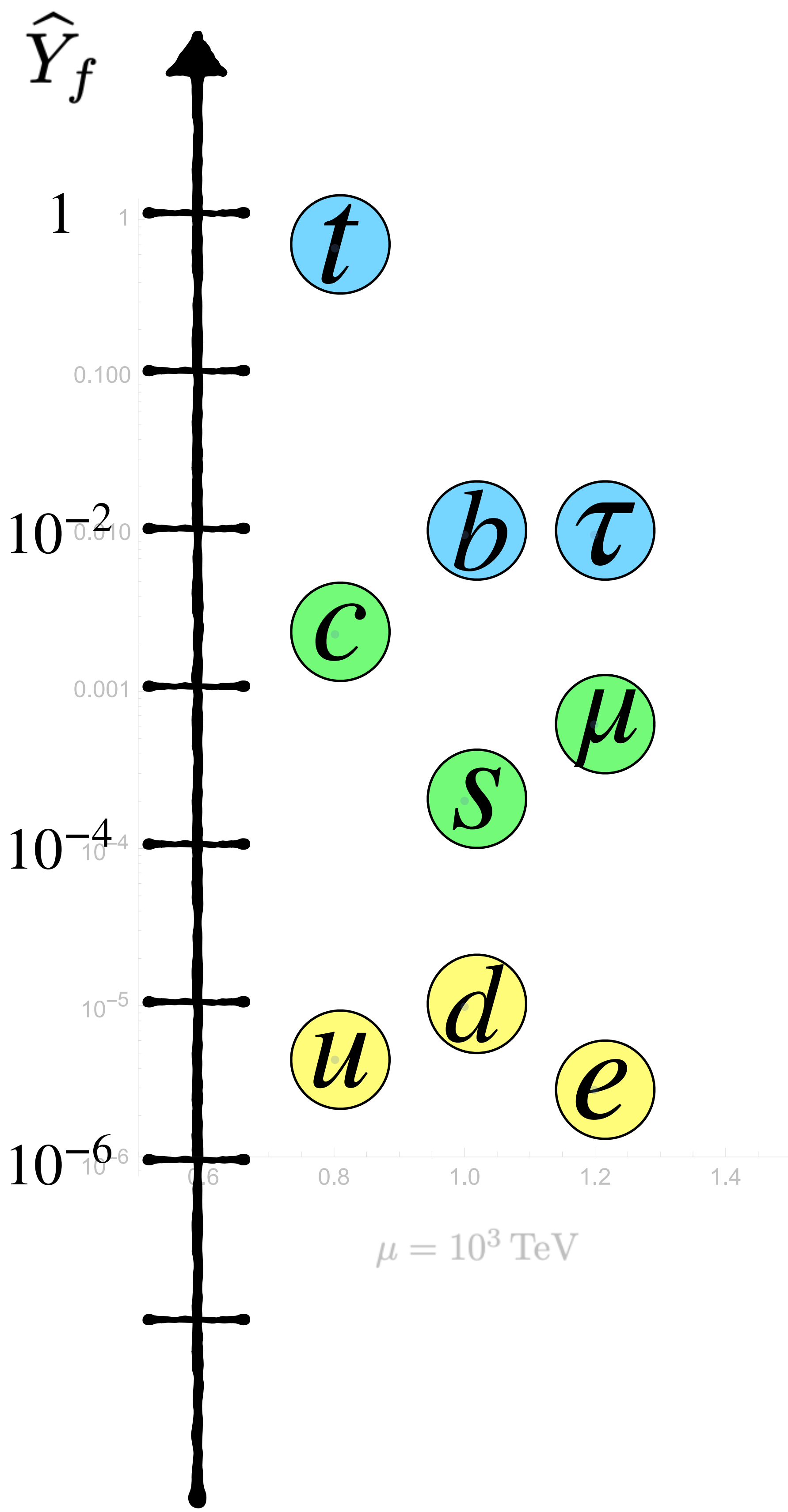



?

$$V_{\rm CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.2^3 \\ 0.2 & 1 & 0.2^2 \\ 0.2^3 & 0.2^2 & 1 \end{pmatrix}$$

# The Flavour Puzzle

Empirical




?

$$V_{\text{CKM}} \sim \begin{pmatrix} 1 & 0.2 & 0.2^3 \\ 0.2 & 1 & 0.2^2 \\ 0.2^3 & 0.2^2 & 1 \end{pmatrix}$$

$$-\mathcal{L}_{\text{SM}} \supset \bar{q}_i Y_u^{ij} u_j \tilde{H} + \bar{q}_i Y_d^{ij} d_j H + \bar{\ell}_i Y_e^{ij} e_j H$$

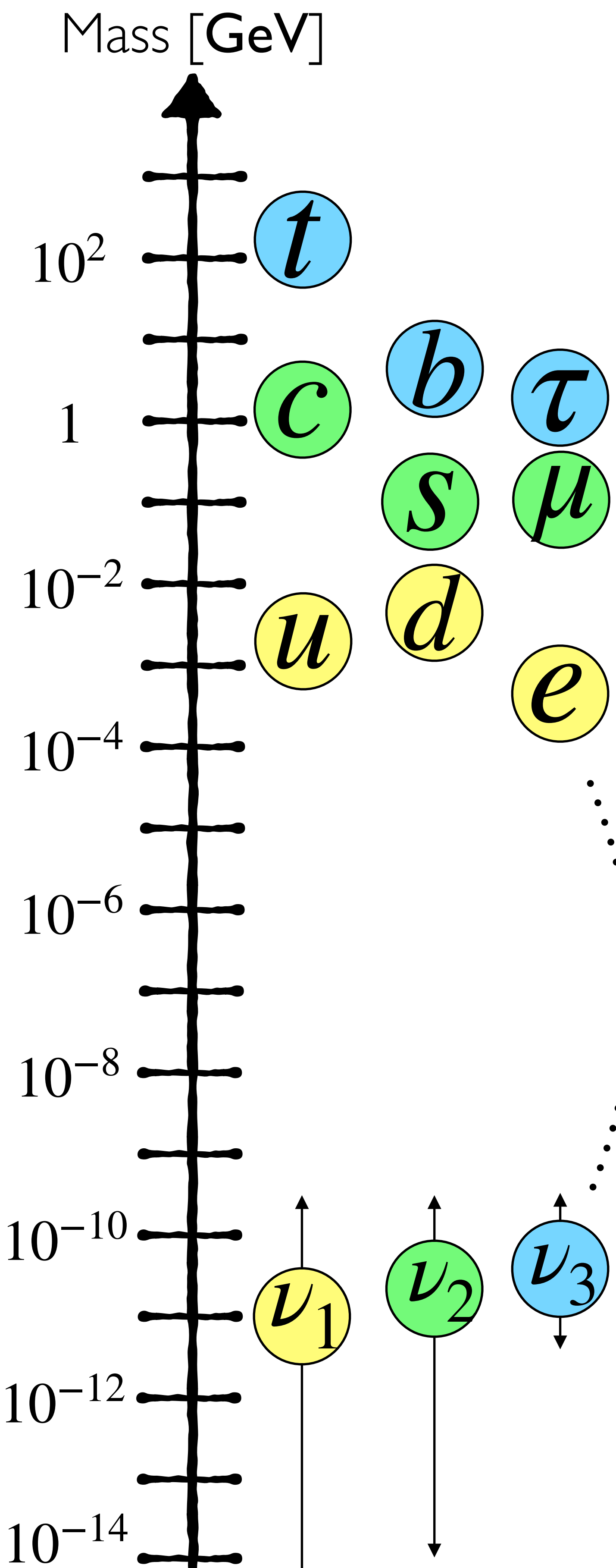
SVD: $Y_f = L_f \widehat{Y}_f R_f^\dagger$

$$V_{\text{CKM}} = L_u^\dagger L_d$$

- Small $y_f$ — natural a la t' Hooft.
- Enter the theory in the same way. **Why hierarchies???**

# The Flavour Puzzle

Empirical




The neutrino sector is different

$$-\mathcal{L}_{\rm SMEFT} \supset \frac{1}{\Lambda_\nu} \ell_i Y_\nu^{ij} \ell_j H H$$

1) High-scale $\Lambda_\nu$ predicts a mass gap!

2) Large/Anarchic mixing!

$$V_{\rm PMNS} \sim \begin{pmatrix} 0.8 & 0.6 & 0.15 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

The success of the SM(EFT)?

# *A unifying picture of flavor…*

**?**

… generate **hierarchies** in the charged sector while keeping neutrinos **anarchic**

# *A unifying picture of flavor…*

**?**

… generate **hierarchies** in the charged sector while keeping neutrinos **anarchic**

Approximate global U(2)

Barbieri et al; hep-ph/9512388, hep-ph/9605224, hep-ph/9610449, …

Our revision:
Antusch, AG, Stefanek, Thomsen; 2311.09288

# $\bar{f}_L^i \, Y^{ij} f_R^j$ ***Hierarchies from*** $\mathrm{U(2)_L}$

$\mathrm{U(2)} \equiv \mathrm{SU(2)} \times \mathrm{U(1)}$ IRREPs $\begin{bmatrix} f_L^1 \\ f_L^2 \end{bmatrix} \sim \mathbf{2}_{+1}$ $f_L^3 \,, f_R^i \sim \mathbf{1}_0$

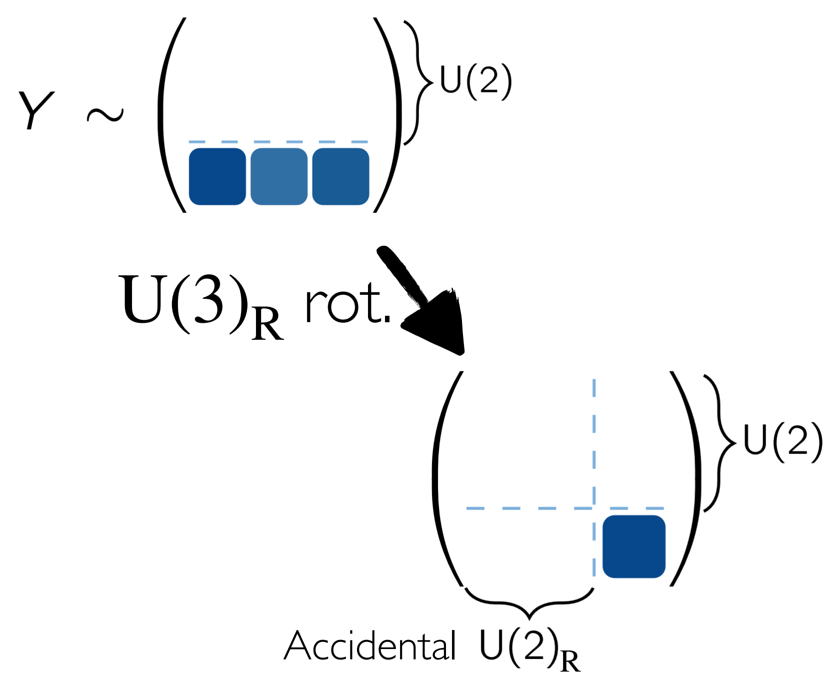
# $\bar{f}^i_L\, Y^{ij} f^j_R$ *Hierarchies from* $\mathrm{U(2)_L}$

$$\mathrm{U(2)} \equiv \mathrm{SU(2)} \times \mathrm{U(1)}$$

IRREPs $\begin{bmatrix} f^1_L \\ f^2_L \end{bmatrix} \sim \mathbf{2}_{+1}$ $\qquad f^3_L\,, f^i_R \sim \mathbf{1}_0$

Step A

Exact symmetry limit



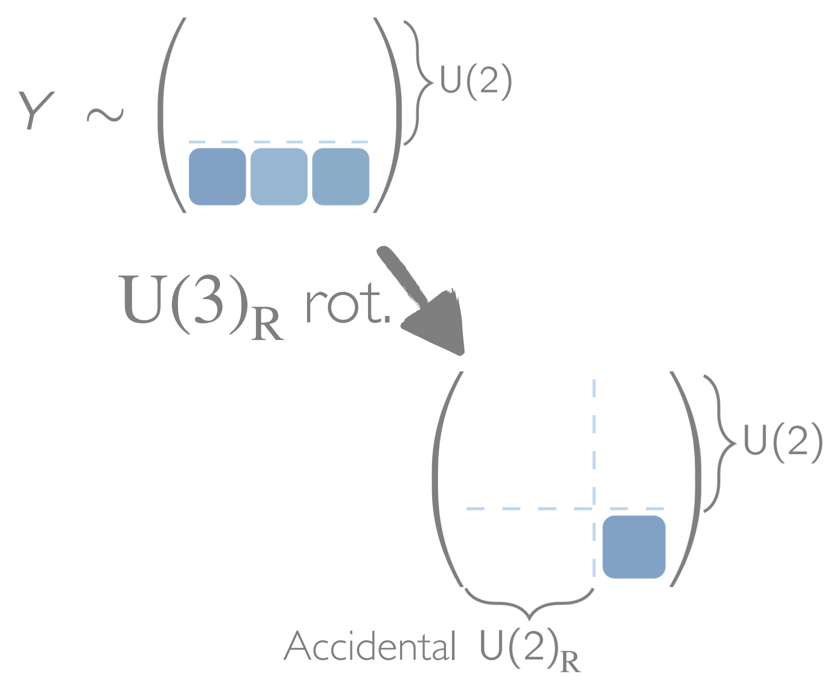

$$m_3 \neq 0\,, m_{1,2} = 0$$

# $\bar{f}^i_L \, Y^{ij} f^j_R$ Hierarchies from $\mathrm{U}(2)_\mathrm{L}$

$\mathrm{U}(2) \equiv \mathrm{SU}(2) \times \mathrm{U}(1)$ IRREPs $\begin{bmatrix} f^1_L \\ f^2_L \end{bmatrix} \sim \mathbf{2}_{+1}$ $f^3_L \,, f^i_R \sim \mathbf{1}_0$

Step A

Exact symmetry limit




$m_3 \neq 0 \,, m_{1,2} = 0$

Step B

Leading (small) breaking

$$V_2 = \begin{pmatrix} 0 \\ a \end{pmatrix} \sim \mathbf{2}_{+1} \qquad \bar{f}_L V \sim \mathbf{1}_0$$

$$\mathrm{U}(2) \rightarrow \mathrm{U}(1)$$

$$1 \gg a > 0$$

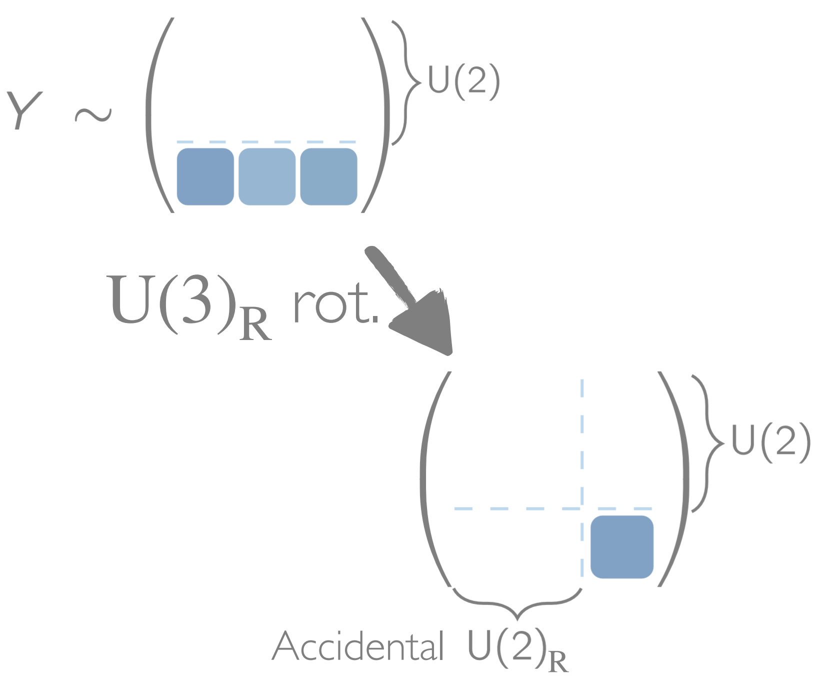
$m_3 \gg m_2 > 0 \,, m_1 = 0$

# $\bar{f}_L^i \, Y^{ij} f_R^j$ Hierarchies from $\mathrm{U}(2)_\mathrm{L}$

$\mathrm{U}(2) \equiv \mathrm{SU}(2) \times \mathrm{U}(1)$ IRREPs $\begin{bmatrix} f_L^1 \\ f_L^2 \end{bmatrix} \sim \mathbf{2}_{+1}$ $f_L^3 \,, f_R^i \sim \mathbf{1}_0$

## Step A

Exact symmetry limit




$m_3 \neq 0 \,, m_{1,2} = 0$

## Step B

Leading (small) breaking

$$V_2 = \begin{pmatrix} 0 \\ a \end{pmatrix} \sim \mathbf{2}_{+1}$$

$\bar{f}_L V \sim \mathbf{1}_0$

$$\mathrm{U}(2) \to \mathrm{U}(1)$$

$$1 \gg a > 0$$

$m_3 \gg m_2 > 0 \,, m_1 = 0$

## Step C

Subleading breaking

$$V_1 = \begin{pmatrix} b \\ 0 \end{pmatrix} \sim \mathbf{2}_{+1}$$

$$\to 0$$

$$1 \gg a \gg b > 0$$

$m_3 \gg m_2 \gg m_1$

# $U(2)_L$: *Singular value decomposition*

$$Y \equiv L_f \hat{Y} R_f^\dagger$$

$$Y \sim \begin{bmatrix} b & b & b \\ a & a & a \\ 1 & 1 & 1 \end{bmatrix}$$

$1 \gg a \gg b$

# $U(2)_L$: *Singular value decomposition*

$$Y \equiv L_f \, \hat{Y} \, R_f^\dagger$$

$$Y \sim \begin{bmatrix} b & b & b \\ a & a & a \\ 1 & 1 & 1 \end{bmatrix} \xrightarrow{R_f^{(0)} \sim \mathcal{O}(1) \text{ rot.}} Y^{(1)} \sim \begin{bmatrix} b & b & b \\ 0 & a & a \\ 0 & 0 & 1 \end{bmatrix}$$

$1 \gg a \gg b$

# $U(2)_L$: *Singular value decomposition*

$$Y \equiv L_f \, \hat{Y} \, R_f^\dagger$$

$$Y \sim \begin{bmatrix} b & b & b \\ a & a & a \\ 1 & 1 & 1 \end{bmatrix} \xrightarrow{R_f^{(0)} \sim \mathcal{O}(1) \text{ rot.}} Y^{(1)} \sim \begin{bmatrix} b & b & b \\ 0 & a & a \\ 0 & 0 & 1 \end{bmatrix}$$

$$1 \gg a \gg b$$

Perturbative diagonalisation: $Y^{(1)} = L_f^{(0)} \, \hat{Y} \, R_f^{(1)\dagger}$

$$\hat{Y} \sim \begin{bmatrix} b & 0 & 0 \\ 0 & a & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad L_f^{(0)} \sim \begin{bmatrix} 1 & b/a & b \\ & 1 & a \\ & & 1 \end{bmatrix}$$

# $U(2)_R$ ?

$$\begin{bmatrix} f_R^1 \\ f_R^2 \end{bmatrix} \sim \mathbf{2}_{+1} \qquad f_R^3, f_L^i \sim \mathbf{1}_0$$

$$Y \sim \begin{bmatrix} b & a & 1 \\ b & a & 1 \\ b & a & 1 \end{bmatrix} \xrightarrow{L_f^{(0)} \sim \mathcal{O}(1)\text{ rot.}} Y^{(1)} \sim \begin{bmatrix} b & 0 & 0 \\ b & a & 0 \\ b & a & 1 \end{bmatrix}$$

$1 \gg a \gg b$

Perturbative diagonalisation: $Y^{(1)} = L_f^{(1)}\, \hat{Y}\, R_f^{(0)\dagger}$

$$\hat{Y} \sim \begin{bmatrix} b & 0 & 0 \\ 0 & a & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad R_f^{(0)} \sim \begin{bmatrix} 1 & b/a & b \\ & 1 & a \\ & & 1 \end{bmatrix}$$

How can this be applied to the SM flavor puzzle?

# Quarks

Impose $\mathrm{U}(2)_q$ : $\begin{pmatrix} q_L^1 \\ q_L^2 \end{pmatrix} \sim \mathbf{2}_{+1}$ all other singlets

→

- Both $\hat{\mathrm{Y}}_u$ and $\hat{\mathrm{Y}}_d$ hierarchical
- $V_{\mathrm{CKM}} \approx \mathrm{L}_u^{(0)\dagger} \mathrm{L}_d^{(0)}$ hierarchical

Imposing $\mathrm{U}(2)_q \implies$
$\mathrm{U}(2)_u \times \mathrm{U}(2)_d$ is *accidental* at dim-4

# Quarks

Impose $\mathrm{U}(2)_q$ : $\begin{pmatrix} q_L^1 \\ q_L^2 \end{pmatrix} \sim \mathbf{2}_{+1}$ all other singlets

→

- Both $\hat{\mathrm{Y}}_u$ and $\hat{\mathrm{Y}}_d$ hierarchical
- $V_{\mathrm{CKM}} \approx \mathrm{L}_u^{(0)\dagger} \mathrm{L}_d^{(0)}$ hierarchical

Imposing $\mathrm{U}(2)_q \implies$ $\mathrm{U}(2)_u \times \mathrm{U}(2)_d$ is *accidental* at dim-4

# Leptons

Impose $\mathrm{U}(2)_e$ : $\begin{pmatrix} e_R^1 \\ e_R^2 \end{pmatrix} \sim \mathbf{2}_{+1}$ all other singlets

→

- Hierarchical $\hat{\mathrm{Y}}_e$ and $L_l^{(0)} \sim \mathcal{O}(1)$.
- No selection rules on the dim-5 Weinberg operator!
  PMNS $\sim \mathcal{O}(1)$

# *A single* $\mathrm{U}(2)$ *to rule them all?*

$$\mathrm{U}(2)_{q+e}$$

**U(2) is Right for Leptons and Left for Quarks**

Stefan Antusch, Admir Greljo, Ben A. Stefanek, Anders Eller Thomsen (Nov 15, 2023)

e-Print: 2311.09288 [hep-ph]

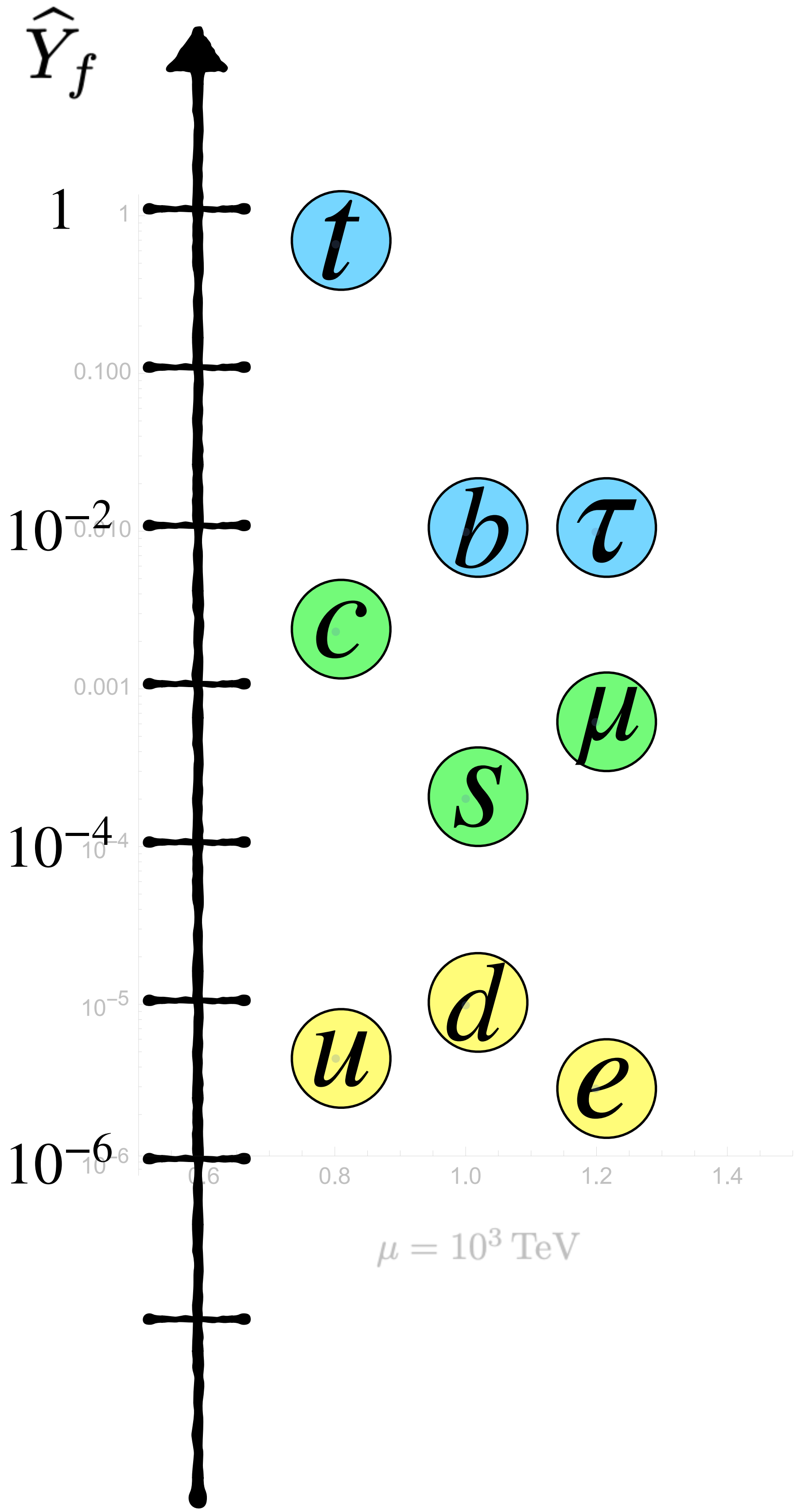
- Nine hierarchies in terms of two small parameters:

$$1 \gg a \gg b \gg a^2 \implies$$

$$y_f^3 \gg y_f^2 \gg y_f^1 \;(\times\, 3 \text{ for } f = u, d, e)$$

$$1 \gg |V_{us}| \gg |V_{cb}| \gg |V_{ub}|$$

# Refining the picture



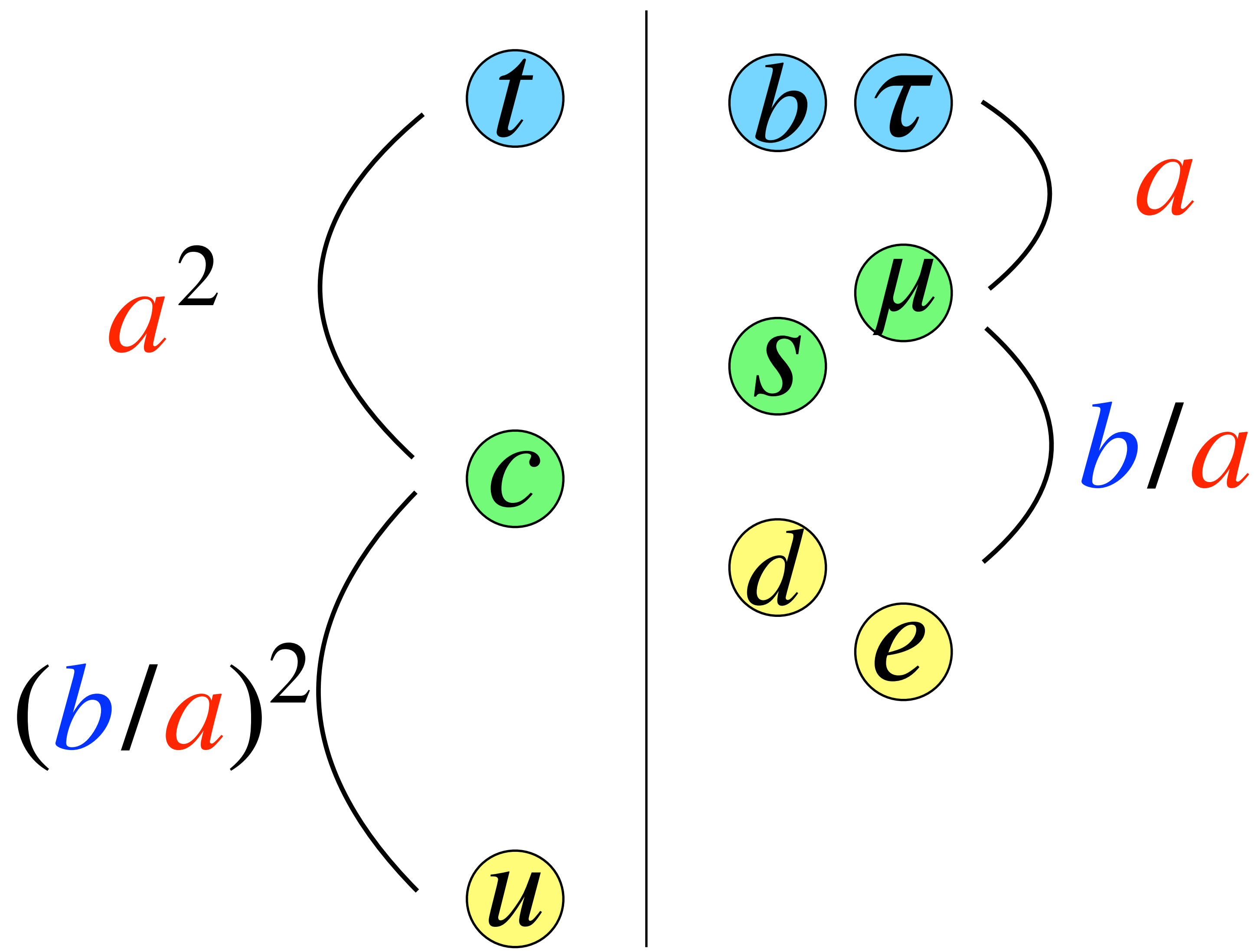

- What about $y_b\,, y_\tau \sim 10^{-2}$ ?
- $d^i$ & $e^i$ spectrum seems ***compressed*** compared with $u^i$.

# $\mathbf{U(2)}_{q+e^c+u^c}$

- Up-quarks also charged under the $\mathrm{U(2)}$:

$$Y_u = \begin{pmatrix} z_{u1} b^2 & z_{u2} ab & z_{u3} b \\ y_{u1} ab & y_{u2} a^2 & y_{u3} a \\ x_{u1} b & x_{u2} a & x_{u3} \end{pmatrix}$$

- Double **suppression** in the up-quark spectrum!



# $\mathbf{U(2)_{q+e^c+u^c} \times \mathbb{Z}_2}$

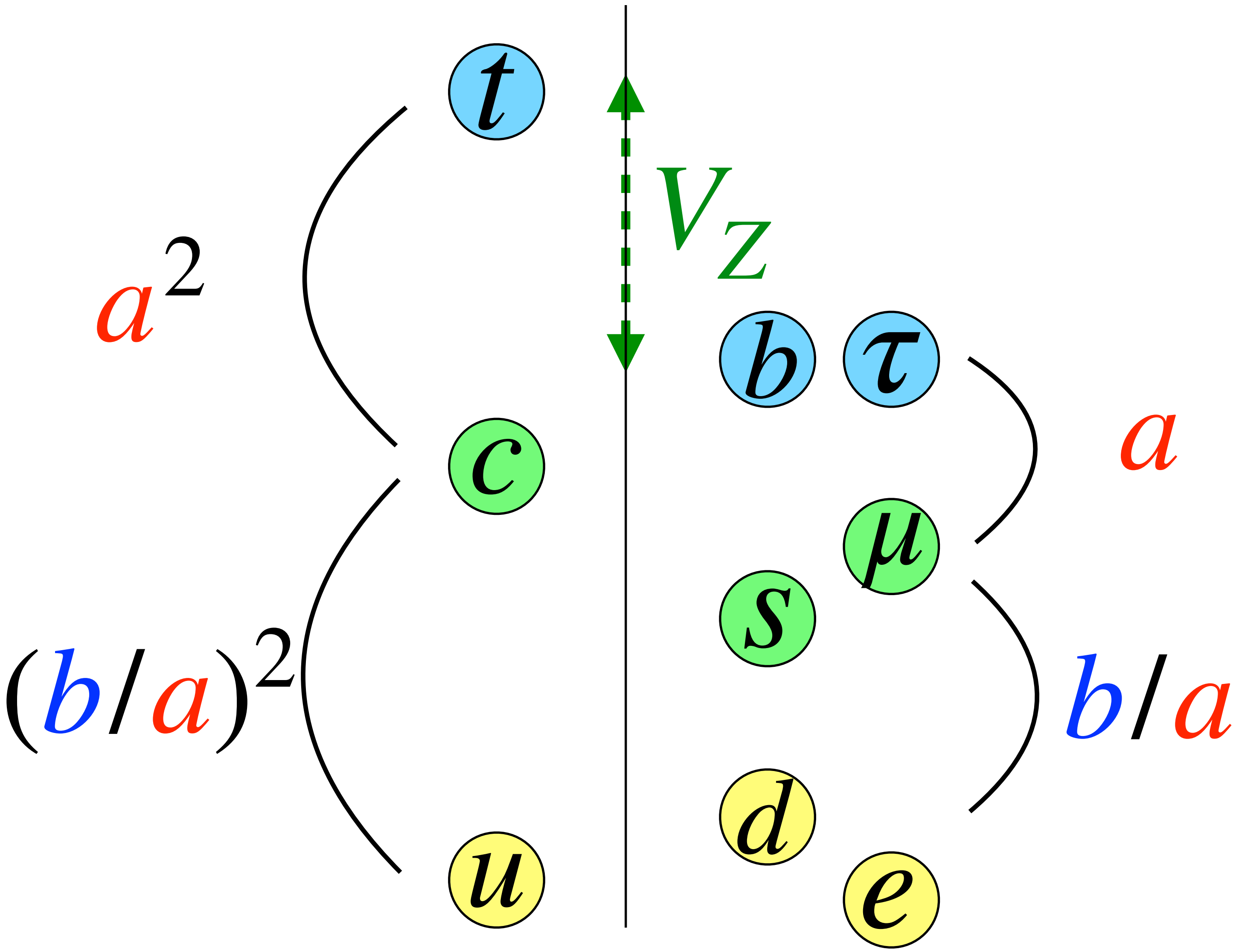
- $l_L^i, d_R^i$ are $Z_2$-odd

$$Y_d = V_Z \begin{pmatrix} z_{d1} b & z_{d2} b & z_{d3} b \\ & y_{d2} a & y_{d3} a \\ & & x_{d3} \end{pmatrix}$$

$$Y_e = V_Z \begin{pmatrix} z_{\ell 1} b & & \\ z_{\ell 2} b & y_{\ell 2} a & \\ z_{\ell 3} b & y_{\ell 3} a & x_{\ell 3} \end{pmatrix}$$

- $V_Z$ — $Z_2$ spurion
- 2HDM-II $\tan^{-1}\beta$ (SUSY?)

$$\langle H_u \rangle \gg \langle H_d \rangle$$



$$\mathbf{U(2)_{q+e^c+u^c} \times \mathbb{Z}_2}$$

Fixing three spurions,

$$(V_Z, a, b) = (0.01, 0.03, 0.002)$$

predicts the order of magnitudes for all flavor parameters (neutrinos++).

Fit of $\mathcal{O}(1)$ parameters:

$$\begin{aligned}
z_{\ell 1} &= 0.14 & y_{\ell 2} &= 2.0 & x_{\ell 3} &= 1.0 \\
z_{u1} &= 1.1 & y_{u2} &= 2.5 & x_{u3} &= 0.67 \\
z_{d1} &= 0.50 & y_{d2} &= 0.66 & x_{d3} &= 1.0 \\
z_{d2} &= 2.2 e^{i\alpha} & z_{d3} &= 1.8 e^{i(\beta-1.2)} & y_{d3} &= 1.3 e^{i(\beta-\alpha)}
\end{aligned} \qquad \text{(A9)}$$



Antusch, AG, Stefanek, Thomsen; 2311.09288

$$\boxed{\mathbf{U(2)}_{q+e^c+u^c} \times \mathbb{Z}_2}$$

Q: Why do $q, u, e$ feel $\mathbf{U(2)}$ flavor but $l, d$ don't?

A: $\mathbf{SU(5)}$ GUT…

$$\bar{\mathbf{5}} \to (\bar{3},1)_{\frac{1}{3}} \oplus (1,2)_{-\frac{1}{2}} \qquad d^c \text{ and } \ell$$

$$\mathbf{10} \to (3,2)_{\frac{1}{6}} \oplus (\bar{3},1)_{-\frac{2}{3}} \oplus (1,1)_1 \qquad q, u^c \text{ and } e^c$$

$$\boxed{\mathrm{U}(2)_{10} \equiv \mathrm{U}(2)_{q+e^c+u^c}}$$



Revisiting SUSY GUT predictions, [wip]

# The UV origin of approximate **U(2)**

# *The UV origin of* $\mathrm{U}(2)$

- Gauge the $\mathbf{SU(2)}$ part!

$\mathrm{SU}(2)_{q+l}$

anomaly-free

AG, Thomsen; 2309.11547

*Neutrinos need an elaborate structure

$\mathrm{SU}(2)_{q+e}$

anomalons

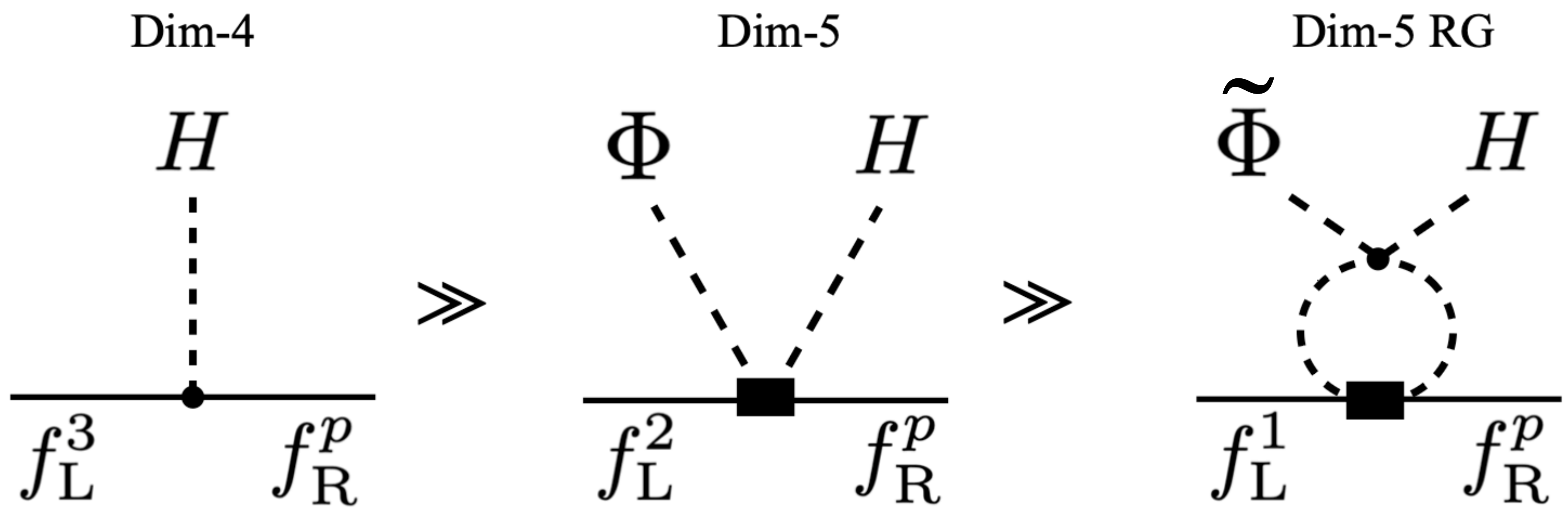
Antusch, AG, Stefanek, Thomsen; 2311.09288

$\mathrm{SU}(2)_{q+e^c+u^c}$

anomaly-free

wip

# $\mathrm{SM} \times \mathrm{SU}(2)_{q+l}$ ***gauged***

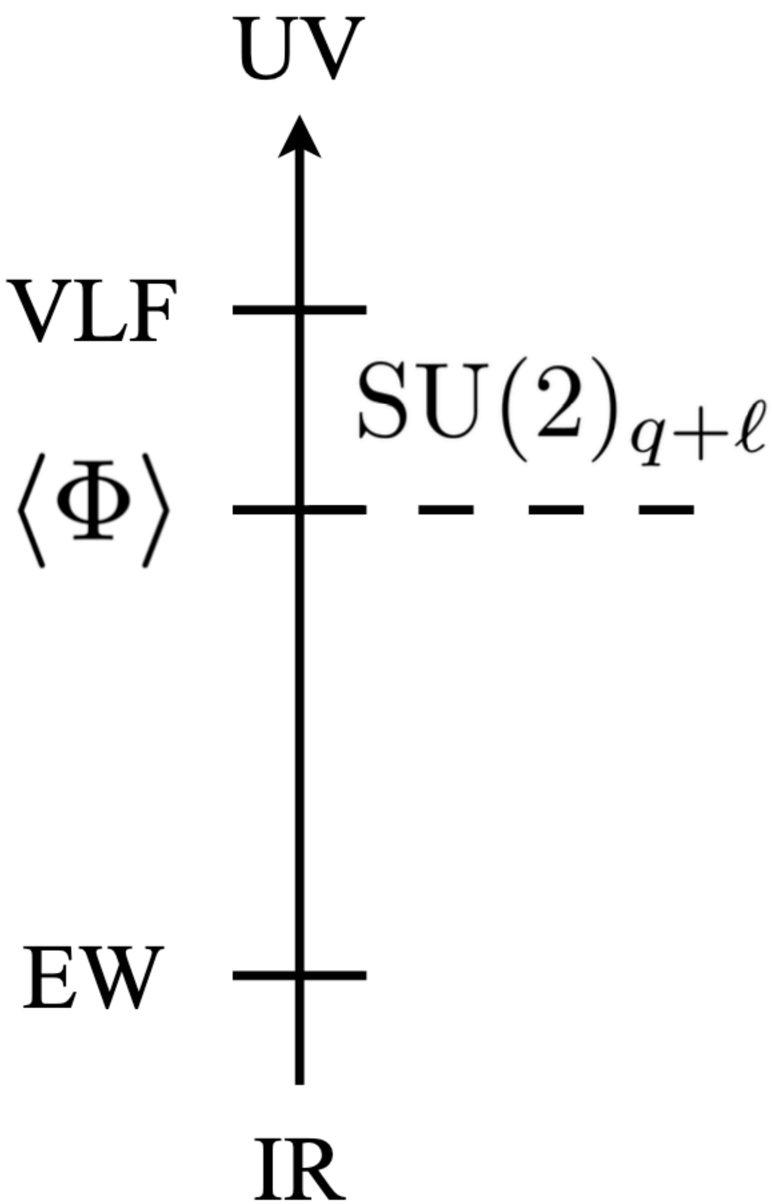



AG, Thomsen; 2309.11547

- The SM-singlet scalar $\mathbf{\Phi} \sim \mathbf{2}$ of flavor: $\langle \Phi^\alpha \rangle = \begin{pmatrix} 0 \\ v_\Phi \end{pmatrix}$ $\qquad \tilde{\Phi}^\alpha = \varepsilon^{\alpha\beta} \Phi^*_\beta$

*2nd family $\qquad$ *1st family

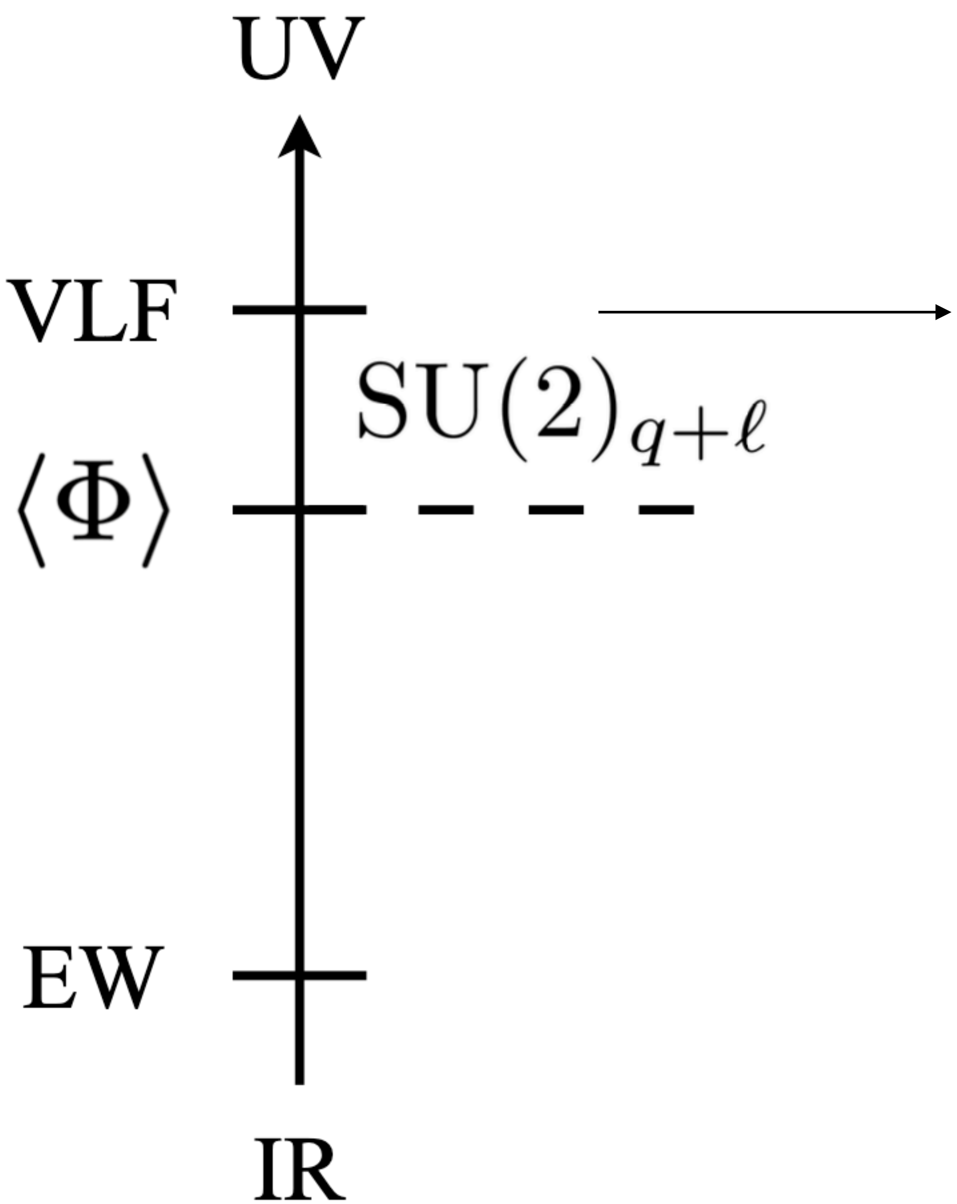
# *Gauged flavor*

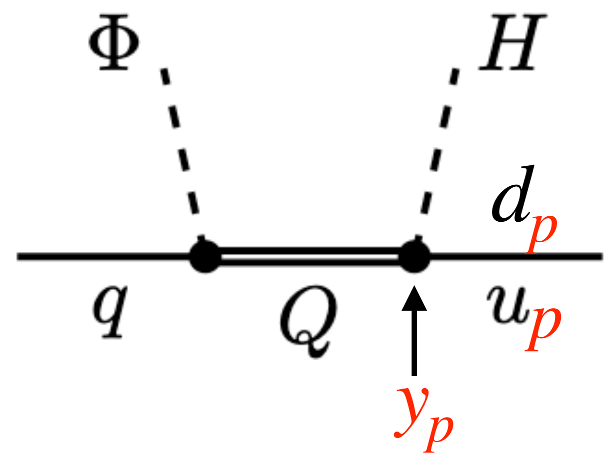


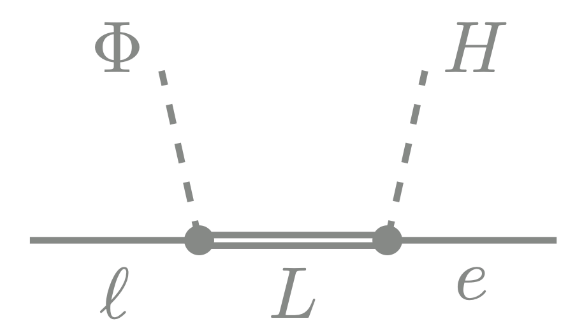

$$a = \frac{v_\Phi}{m_F}$$

AG, Thomsen; 2309.11547

# *Gauged flavor*




PS unification $m_Q = m_L$, wip

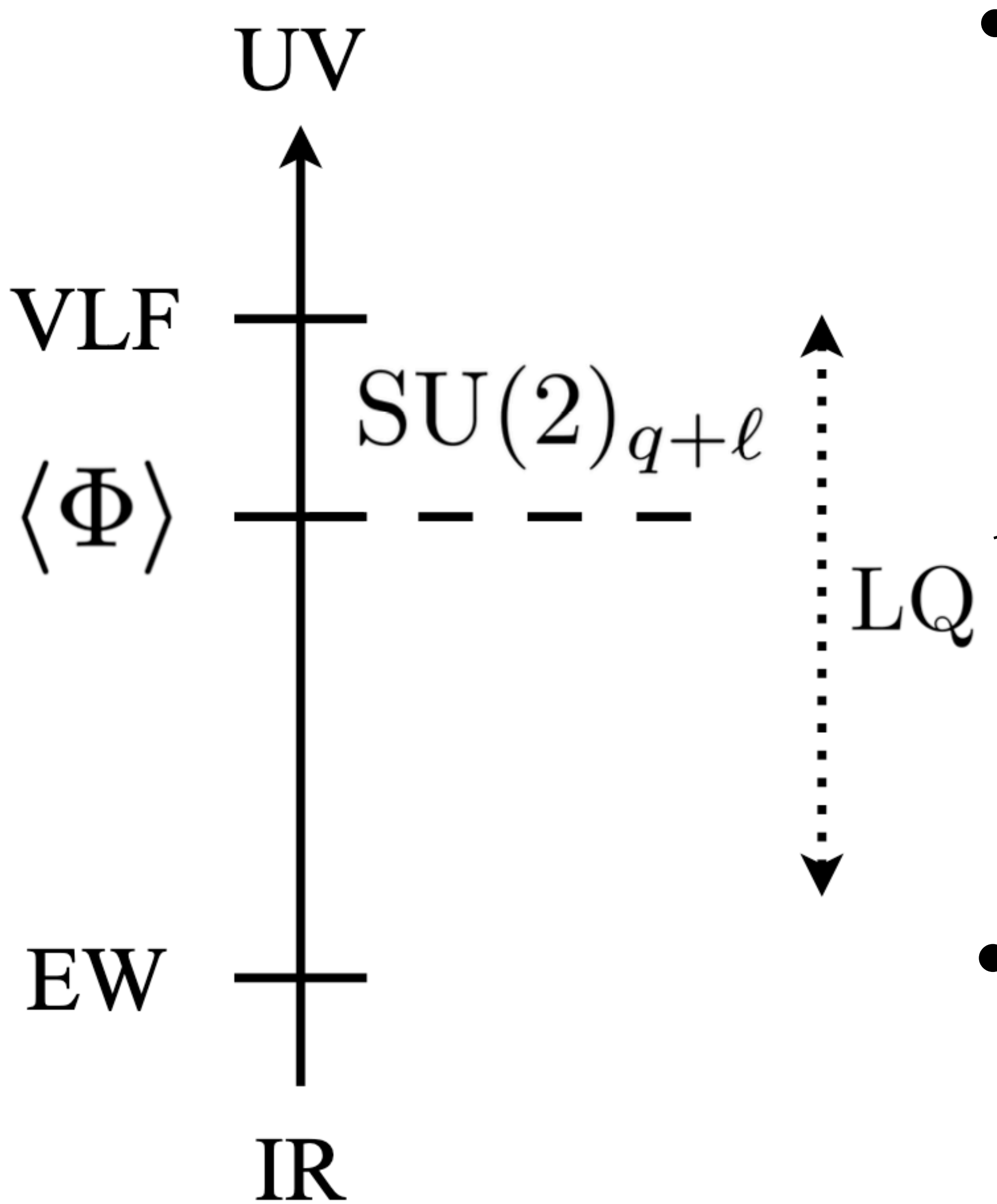
- A *single* VLQ $\Longrightarrow$ Y is **Rank 2**

$$\mathrm{Y} \propto \begin{bmatrix} y^p \\ y^p \\ 1^p \end{bmatrix} \begin{matrix} \longleftarrow \tilde{\Phi} \\ \longleftarrow \Phi \\ \phantom{x} \end{matrix}$$

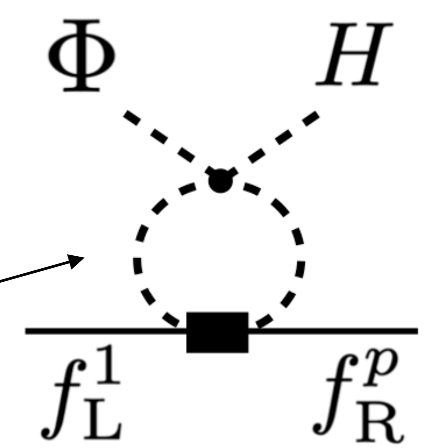
- Accidental $\mathrm{U}(1)$:
  Massless 1st family!

AG, Thomsen; 2309.11547

# *Gauged flavor*



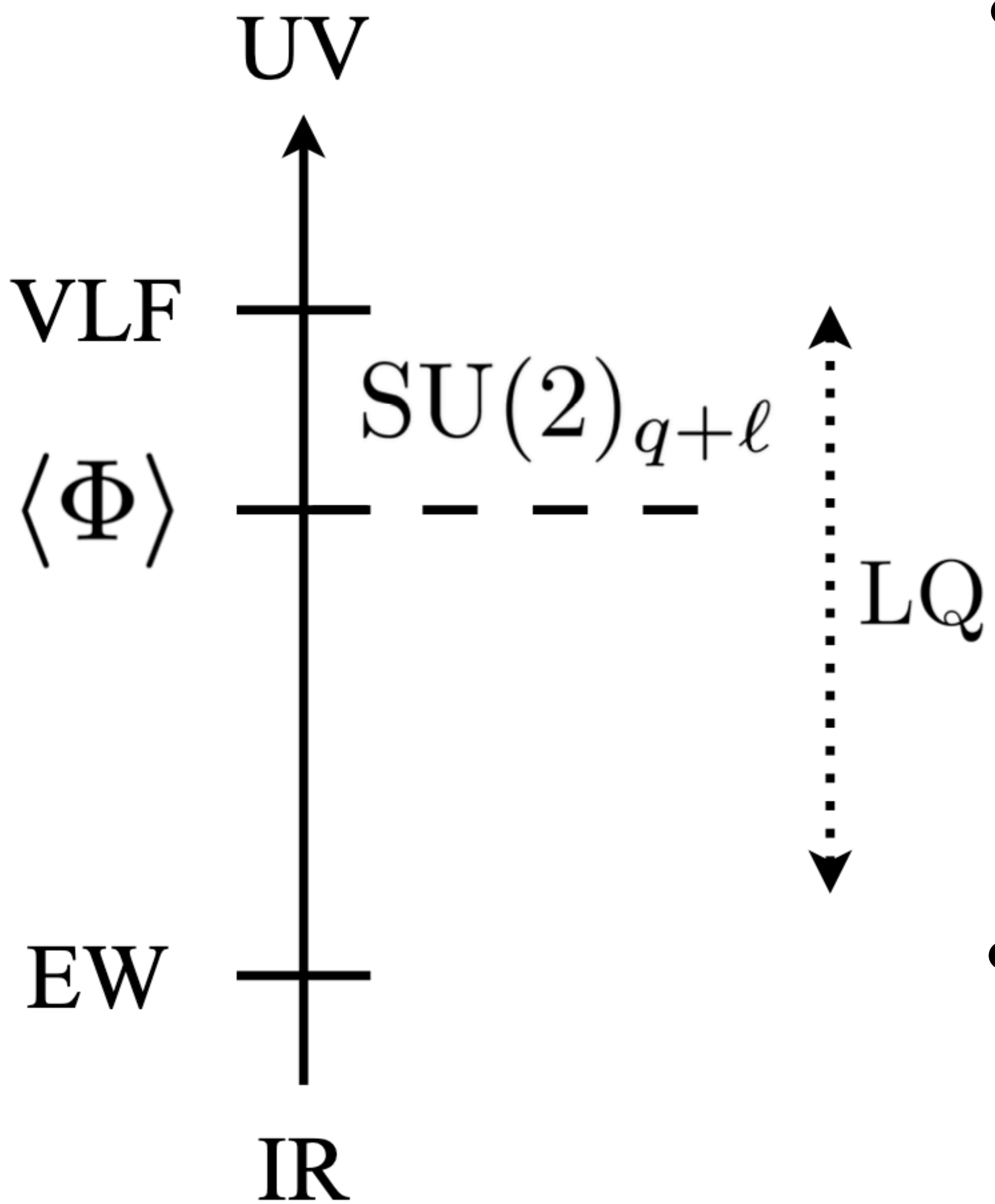

- Instead of new UV states, introduce IR states.



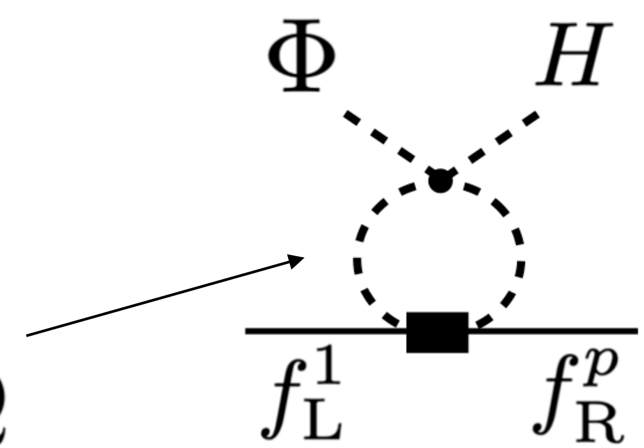

- The obtained Yukawas are mainly ***insensitive*** to their masses! $\sim \log m_\mathrm{F}/m_\mathrm{S}$

AG, Thomsen; 2309.11547

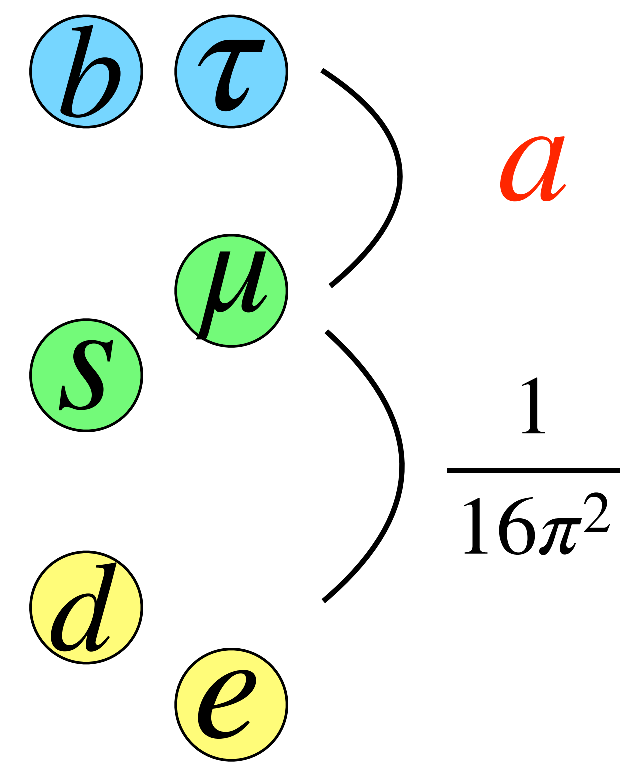
# *Gauged flavor*




- Instead of new UV states, introduce IR states.




- The obtained Yukawas are mainly ***insensitive*** to their masses! $\sim \log m_F/m_S$




$$b \sim a/16\pi^2$$

A single parameter!

$$a = v_\Phi/m_F$$

AG, Thomsen; 2309.11547

# Phenomenology

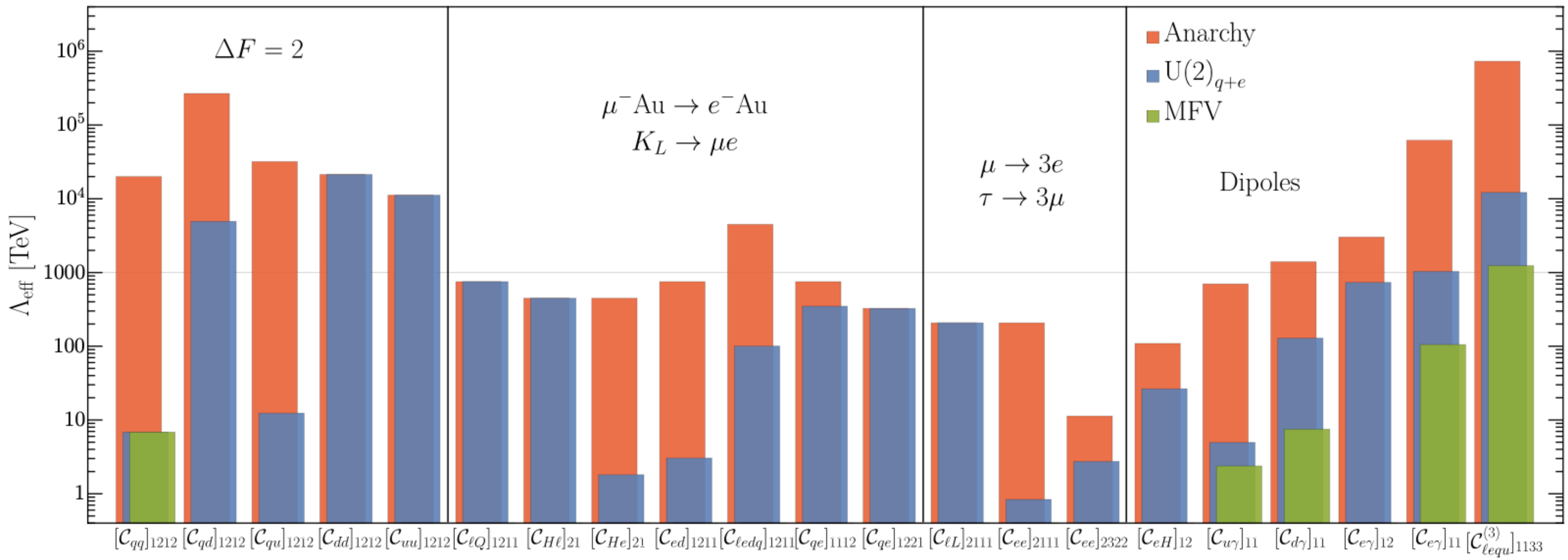



FIG. 1. Comparative constraints on SMEFT operators from flavor and CP violation: Minimally-broken $\mathrm{U}(2)_{q+e}$ (Blue), MFV (Green), Flavor Anarchy (Red). Here, $Q = q, u, d$ and $L = \ell, e$. See Section 3 for details.

- SMEFT as a proxy for short-distance physics: $\mathrm{U}(2) \Longrightarrow$ selection rules.
- A pattern of deviations emerges; distinct from MFV and anarchy.
- Determine the chirality of operators to test it!

# Conclusions

- An approximate $\mathrm{U}(2)_{q+e}$ (or $\mathrm{U}(2)_{q+e^c+u^c}$) flavor symmetry:

$\Longrightarrow$ hierarchies in the charged fermion sector (masses + CKM) while simultaneously large (anarchic) neutrino mixing.

- Gauged $\mathbf{SU}(2)$ flavor:

$\Longrightarrow$ offers an elegant UV completion of the approximate $\mathbf{U}(2)$ paradigm

Alhambra of Granada

# *Thank you*

University of Basel

https://physik.unibas.ch/en/persons/admir-greljo/

admir.greljo@unibas.ch

# The Model

- Rank 1

| Field | $SU(3)_c$ | $SU(2)_L$ | $U(1)_Y$ | $SU(2)_{q+\ell}$ |
|---|---|---|---|---|
| $q_L^\alpha$ | **3** | **2** | 1/6 | **2** |
| $q_L^3$ | **3** | **2** | 1/6 | **1** |
| $u_R^p$ | **3** | **1** | 2/3 | **1** |
| $d_R^p$ | **3** | **1** | -1/3 | **1** |
| $\ell_L^\alpha$ | **1** | **2** | -1/2 | **2** |
| $\ell_L^3$ | **1** | **2** | -1/2 | **1** |
| $e_R^p$ | **1** | **1** | -1 | **1** |
| $H$ | **1** | **2** | 1/2 | **1** |
| $\Phi$ | **1** | **1** | 0 | **2** |

$$\mathcal{L} \supset -x_u^p\, \overline{q}^3 \widetilde{H} u^p - x_d^p\, \overline{q}^3 H d^p - x_e^p\, \overline{\ell}^3 H e^p + \text{H.c.}$$

$\widetilde{H}^i = \varepsilon^{ij} H_j^*$ $\qquad x_f^p = (0,\, 0,\, x_{f3}),$ $\qquad x_{f3} \in \mathbb{R}_0^+$

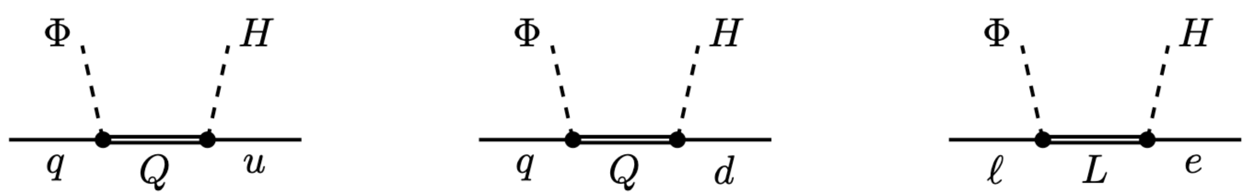
- Rank 2

| Field | $SU(3)_c$ | $SU(2)_L$ | $U(1)_Y$ | $SU(2)_{q+\ell}$ |
|---|---|---|---|---|
| $Q_{L,R}$ | **3** | **2** | 1/6 | **1** |
| $L_{L,R}$ | **1** | **2** | -1/2 | **1** |

$$\mathcal{L} \supset +\left(y_q \Phi^\alpha + \tilde{y}_q \widetilde{\Phi}^\alpha\right)\overline{q}_\alpha Q + \left(y_\ell \Phi^\alpha + \tilde{y}_\ell \widetilde{\Phi}^\alpha\right)\overline{\ell}_\alpha L - y_u^p\, \overline{Q}\widetilde{H} u^p - y_d^p\, \overline{Q} H d^p - y_e^p\, \overline{L} H e^p + \text{H.c.}\,.$$

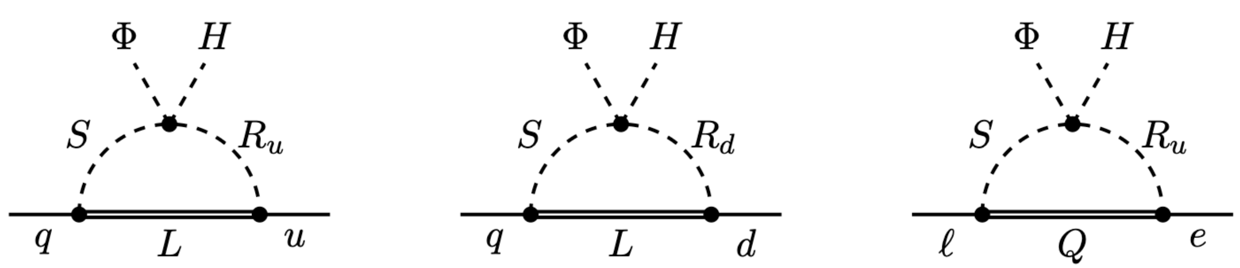
$\widetilde{\Phi}^\alpha = \varepsilon^{\alpha\beta}\Phi_\beta^*$ $\qquad y_f^p = (0,\, y_{f2},\, y_{f3}),$ $\qquad \tilde{y}_q = 0\,,$

$y_{f2},\, y_{d3},\, y_{e3},\, y_q,\, y_\ell,\, \tilde{y}_\ell \in \mathbb{R}_0^+,$ $\qquad y_{u3} \in \mathbb{C}$




- Rank 3

| Field | $SU(3)_c$ | $SU(2)_L$ | $U(1)_Y$ | $SU(2)_{q+\ell}$ |
|---|---|---|---|---|
| $R_u$ | **3** | **2** | 7/6 | **1** |
| $R_d$ | **3** | **2** | 1/6 | **1** |
| $S$ | **3** | **1** | 2/3 | **2** |




$$\mathcal{L} \supset -z_u^p\, \overline{L} u^p \widetilde{R}_u - z_d^p\, \overline{L} d^p \widetilde{R}_d - z_e^p\, \overline{Q} e^p R_u - z_q\, \overline{q}_\alpha L S^\alpha - z_\ell\, \overline{\ell}_\alpha Q \widetilde{S}^\alpha + \text{H.c.}\,,$$

$$V \supset \left(\lambda_u \Phi^\alpha + \tilde{\lambda}_u \widetilde{\Phi}^\alpha\right) S_\alpha^* R_u H^* + \left(\lambda_d \Phi^\alpha + \tilde{\lambda}_d \widetilde{\Phi}^\alpha\right) S_\alpha^* R_d \widetilde{H}^* + \text{H.c.}$$

$z_f^p = (z_{f1},\, z_{f2},\, z_{f3}),$ $\qquad z_{f1},\, z_q,\, \tilde{\lambda}_u,\, \tilde{\lambda}_d \in \mathbb{R}_0^+,$

$z_\ell,\, z_{f2},\, z_{f3},\, \lambda_u,\, \lambda_d,\, \kappa_f^p \in \mathbb{C}.$

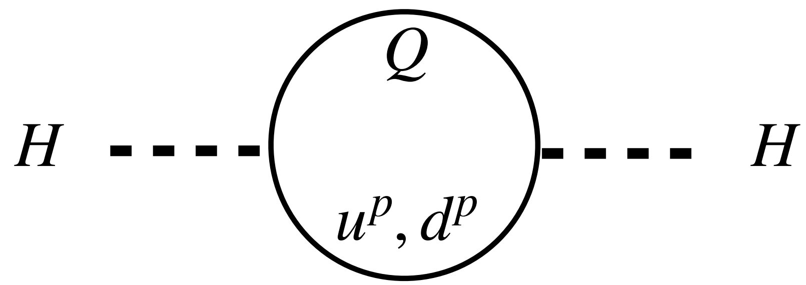
accidental $U(1)_B \times U(1)_L$ global symmetry

# Phenomenology

- Decoupling limit exits: Take the new mass thresholds substantially heavy while keeping $v_\Phi / M_{Q,L}$ fixed and $M_{S,R_u,R_d} \lesssim M_{Q,L}$.

- The low-scale variant of the model is interesting for experiments.

- Finite Higgs naturalness provides another motivation for low-scale $M_{Q,L}$




- Q1: What are the bounds on the new masses given the current data?

- Q2: Which observables and deviation patterns should be prioritized?

# *Z' effects*

- SSB of $SU(2)_{q+\ell}$ produced heavy, degenerate vector triplet.
- Integrating it out:

$$\mathcal{L}_{\rm SMEFT} \supset -\frac{1}{2v_\Phi^2}\left[\delta^\alpha{}_\delta\delta^\gamma{}_\beta - \frac{1}{2}\delta^\alpha{}_\beta\delta^\gamma{}_\delta\right]\left[(\bar{q}_\alpha\gamma^\mu q^\beta)(\bar{q}_\gamma\gamma^\mu q^\delta) + 2(\bar{q}_\alpha\gamma^\mu q^\beta)(\bar{\ell}_\gamma\gamma^\mu\ell^\delta) + (\bar{\ell}_\alpha\gamma^\mu\ell^\beta)(\bar{\ell}_\gamma\gamma^\mu\ell^\delta)\right].$$

$$\alpha, \beta, \ldots \in \{1,\, 2\}$$

- Suppressed bounds from 4-quark and 4-lepton FCNCs — Darme et al; 2307.09595

Eg. $\mathcal{L}_{\rm LEFT} \supset -\frac{1}{4v_\Phi^2}A_{sd}^2(\bar{s}_{\rm L}\gamma_\mu d_{\rm L})^2$ $\qquad A_{f_p f'_r} = \left[L_f^\dagger\,{\rm diag}(1,\,1,\,0)L_{f'}\right]_{pr}.$

- The strongest bounds involve 2q2l transitions:

*complementary, can not be tuned away simultaneously

$$\mathrm{BR}(K_L \to \mu^\pm e^\mp) = 5.9\cdot 10^{-12}\left(\frac{300\,\mathrm{TeV}}{v_\Phi}\right)^4 \left|A_{se}A_{\mu d} + A_{de}A_{\mu s}\right|^2.$$

$$\mathrm{CR}(\mu\mathrm{Au} \to e\mathrm{Au}) = 2\cdot 10^{-11}\cdot\left(\frac{300\,\mathrm{TeV}}{v_\Phi}\right)^4 \times \left|1.01\, s_{2\ell} - 0.25\, c_{2\ell}\right|^2.$$

$$v_\Phi \gtrsim 300\ \mathrm{TeV}$$

*Future MU2E and COMET will improve by an order of magnitude on the VEV

# Leptoquark phenomenology

- The flavor structure of the LQ couplings is fixed

$$\mathcal{L} \supset -\kappa_u^p\,\bar{\ell}^3 \widetilde{R}_u u^p - \kappa_d^p\,\bar{\ell}^3 \widetilde{R}_d d^p - \kappa_e^p\,\bar{q}^3 R_u e^p + \text{H.c.}$$

- Consistency criteria on the mass spectrum from the scalar potential:

$$V \supset (\lambda_u \Phi^\alpha + \tilde{\lambda}_u \widetilde{\Phi}^\alpha) S_\alpha^* R_u H^* + (\lambda_d \Phi^\alpha + \tilde{\lambda}_d \widetilde{\Phi}^\alpha) S_\alpha^* R_d \widetilde{H}^* + \text{H.c.}$$

[7] Consider a toy potential $V(x,y,z) = -v\,xyz + x^4 + y^4 + z^4$. In such a configuration all fields would develop a VEV: $\langle x \rangle = \langle y \rangle = \langle z \rangle = v/4$ (up to a tetrahedral symmetry). When one of the fields gets a mass $m \geq v/2$, the minimum of the potential moves to the origin, and no symmetry breaking will occur.

- A consistent mass spectrum allows for two interesting scenarios:

**Flavor**
- Scenario I: $M_S \gtrsim v_\Phi$ with $R_d$ and $R_u$ potentially lighter,

**Collider**
- Scenario II: $M_{R_d}, M_{R_u} \gtrsim v_\Phi$ with $S$ potentially lighter.

# Scenario I: $R_u$ leptoquark

- Induces chirality-enhanced dipoles at one-loop:

$$C_{e\gamma}^{pr} = -\frac{1}{16\pi^2}\frac{(L_e^{3p})^* \kappa_u^3 x_{3u} \kappa_e^r}{M_{R_u}^2} \log \frac{M_{R_u}^2}{m_t^2}$$

- The strongest bounds:

$\mu \to e\gamma$

$$|\kappa_u^3 x_{3u} \kappa_e^1| \frac{|L_e^{32}|}{0.1} \left(\frac{500\,\text{TeV}}{M_{R_u}}\right)^2 \frac{\log \frac{M_{R_u}}{m_t}}{8} < 0.017$$

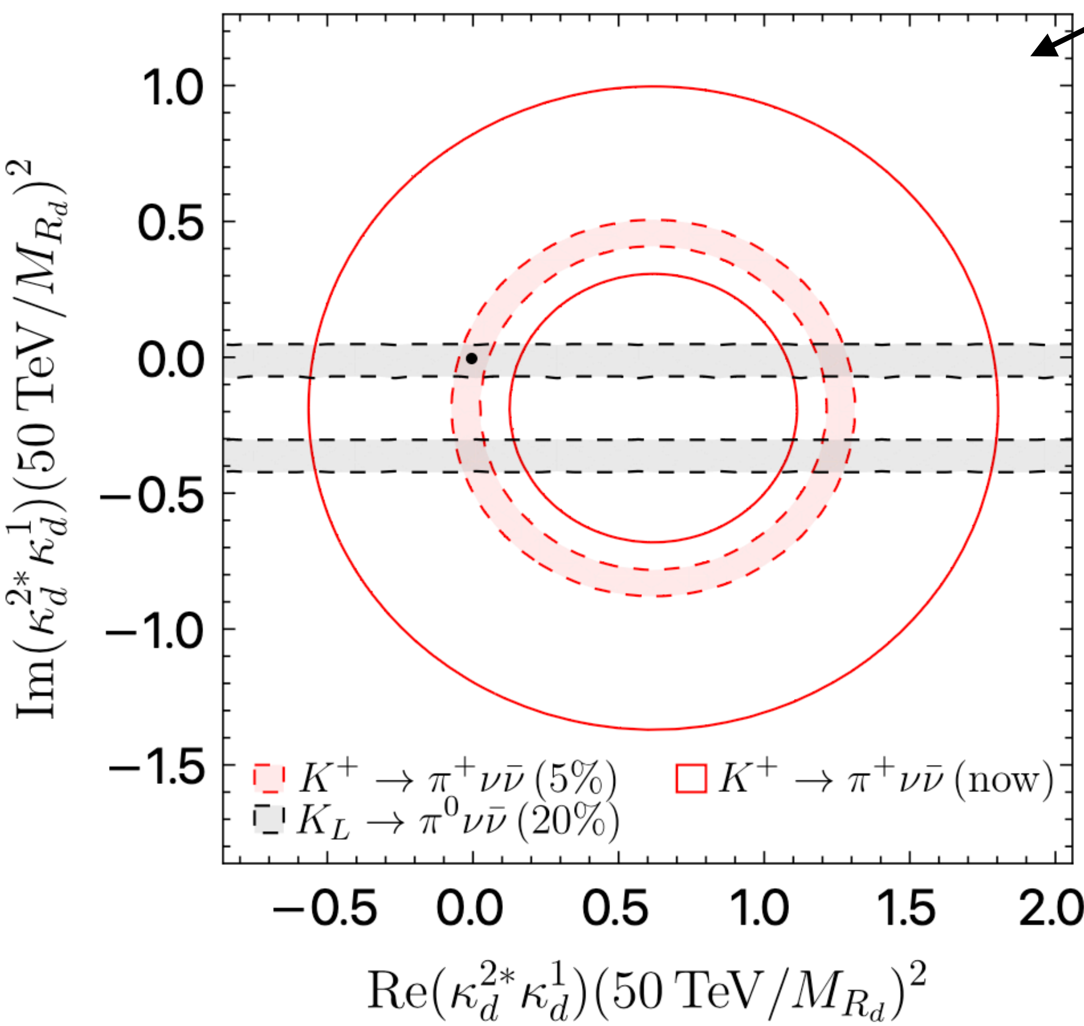
$e$**EDM**

$$\frac{|x_{3u}\,\text{Im}((L_e^{31})^* \kappa_u^1 \kappa_e^1)|}{10^{-3}} \left(\frac{500\,\text{TeV}}{M_{R_u}}\right)^2 \frac{\log \frac{M_{R_u}}{m_t}}{8} < 4 \cdot 10^{-3}$$

$M_{R_u} \gtrsim 500\,\text{TeV}$ when couplings $\mathcal{O}(0.3)$

# Scenario I: $R_d$ leptoquark

Kaon Physics




$K \to \pi\nu\nu$ : $\mathcal{L}_{\text{SMEFT}} \supset -\frac{\kappa_d^{p*}\kappa_d^r}{2M_{R_d}^2}(\bar{\ell}^3\gamma_\mu \ell^3)(\bar{d}^p\gamma^\mu d^r)$

$K - \bar{K}$ : $\mathcal{L}_{\text{SMEFT}} \supset -\frac{\kappa_d^{p*}\kappa_d^r\kappa_d^{s*}\kappa_d^t}{64\pi^2 M_{R_d}^2}(\bar{d}^p\gamma^\mu d^r)(\bar{d}^s\gamma^\mu d^t)$

$$\left|\mathrm{Re}\left[(\kappa_d^{2*}\kappa_d^1)^2\right]\right|\left(\frac{50\,\mathrm{TeV}}{M_{R_d}}\right)^2 \lesssim 1.0 \quad (\Delta m_K)\,,$$
$$\left|\mathrm{Im}\left[(\kappa_d^{2*}\kappa_d^1)^2\right]\right|\left(\frac{50\,\mathrm{TeV}}{M_{R_d}}\right)^2 \lesssim 3\cdot 10^{-3} \quad (\epsilon_K)\,.$$

- A low-scale benchmark:

$$M_{R_d} = 5\,\mathrm{TeV}$$
$$\kappa_d^2 \simeq 0.3 \qquad |\kappa_d^1| \simeq \mathcal{O}(0.01)$$

# Scenario I: $R_d$ leptoquark

B Physics

$B \to K\nu\nu$ : $\mathcal{L}_{\rm SMEFT} \supset -\frac{\kappa_d^{p*}\kappa_d^r}{2M_{R_d}^2}(\bar{\ell}^3\gamma_\mu\ell^3)(\bar{d}^p\gamma^\mu d^r)$

$B_s - \bar{B}_s$ : $\mathcal{L}_{\rm SMEFT} \supset -\frac{\kappa_d^{p*}\kappa_d^r\kappa_d^{s*}\kappa_d^t}{64\pi^2 M_{R_d}^2}(\bar{d}^p\gamma^\mu d^r)(\bar{d}^s\gamma^\mu d^t)$

$$\left|{\rm Re(Im)}[(\kappa_d^{2*}\kappa_d^3)^2]\right| \left(\frac{5\,{\rm TeV}}{M_{R_d}}\right)^2 \lesssim 0.35\,(0.12)$$

- Belle II 2023 anomaly: $R_K^\nu = 2.8 \pm 0.8$
- Consistency with mixing implies:

$$M_{R_d} \lesssim 5\,{\rm TeV}$$

- Collider limits: $\gtrsim 1.5\,{\rm TeV}$

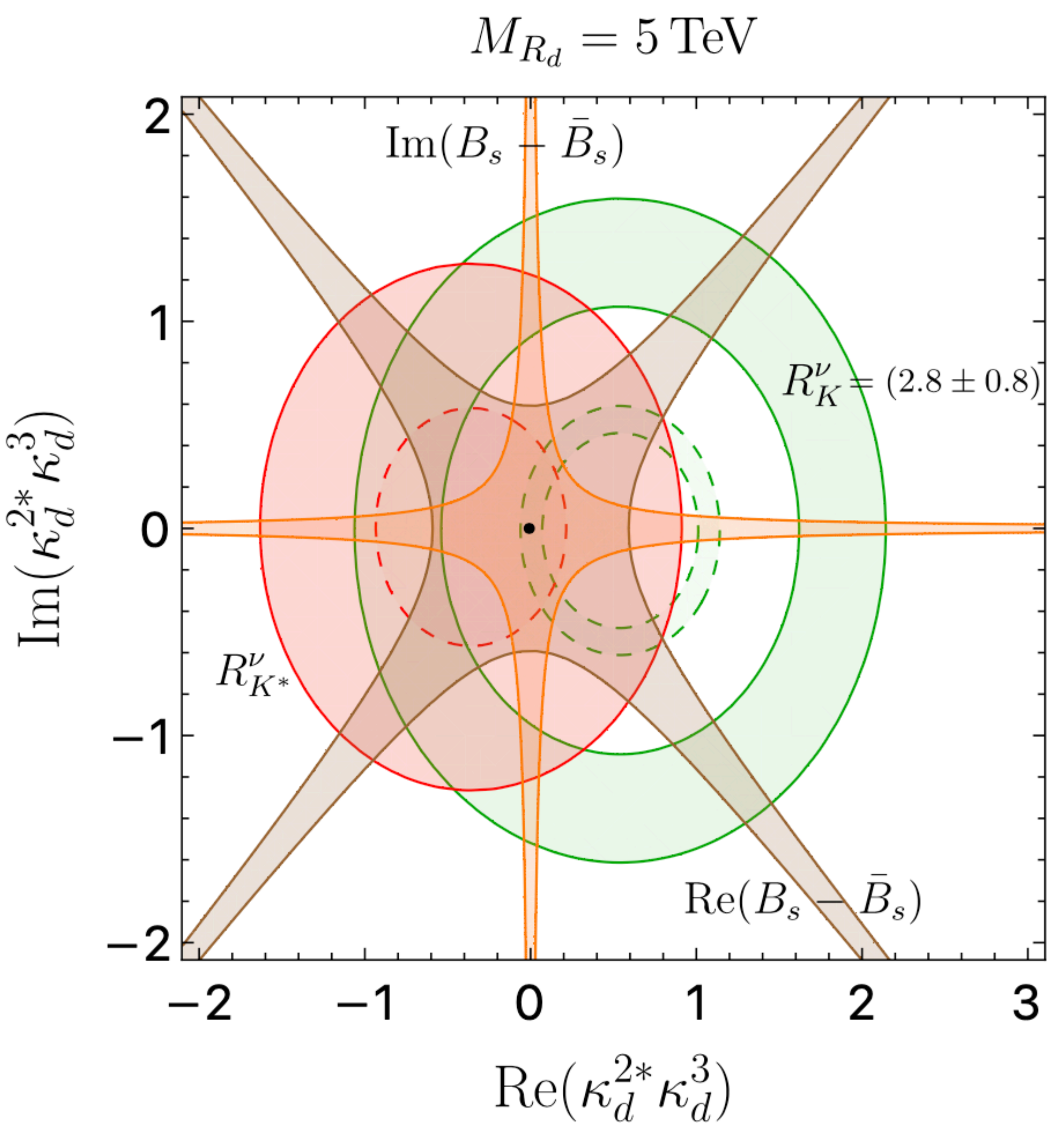



FIG. 6. Constraints on $R_d$ leptoquark from $B \to K^{(*)}\nu\bar{\nu}$ decays and $B_s - \bar{B}_s$ oscillations. The leptoquark mass is set to $M_{R_d} = 5\,$TeV. Shown with solid green is the latest $R_K^\nu$ average from Eq. (40), including the most recent Belle II measurement [86]. Solid red is for $R_{K^*}^\nu$ and satisfies Eq. (39). Brown and orange show the constraints from $B_s - \bar{B}_s$ oscillations, namely Eq. (45). The dashed lines show the future Belle II projections with $50\,{\rm ab}^{-1}$ [92].

# Scenario II: $S$ leptoquark

$$M_{R_d}, M_{R_u} \gtrsim v_\Phi$$

- No renormalisable couplings to SM fermions!

$$\frac{\lambda_u^* \kappa_e^p}{M_{R_u}^2} \bar{q}_3 S \Phi^\dagger H e^p \text{ and } \frac{y_e^p z_q}{M_L} \bar{q}_\alpha S^\alpha H e^p$$

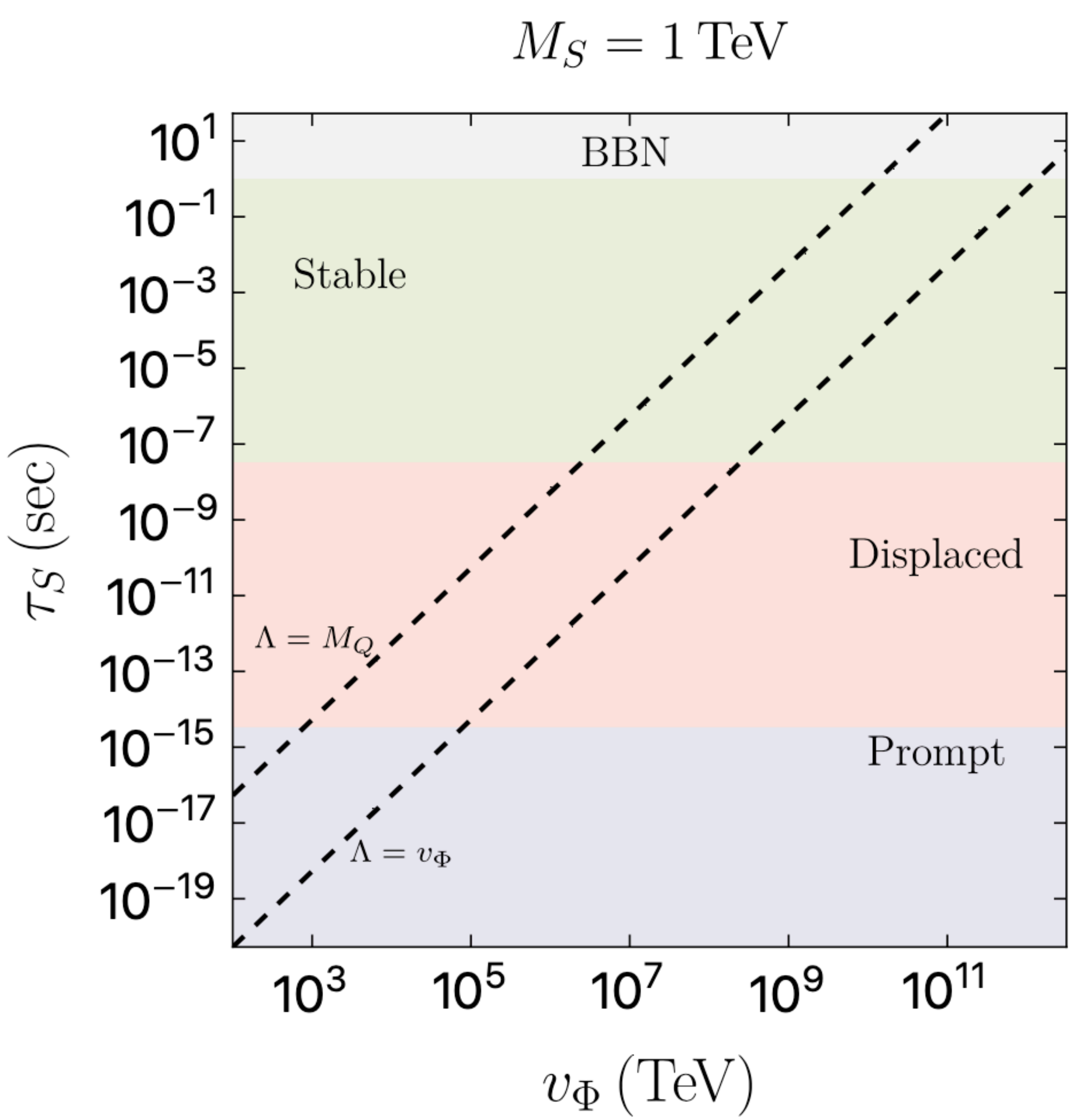
- Decays through the UV scale

$$\frac{\Gamma_S}{M_S} \approx \frac{1}{16\pi} \frac{v_{\rm EW}^2}{\Lambda^2}$$

- Interesting collider pheno if light: LLP!

- Signatures depend on the UV scale:

A discovery of a leptoquark via a distinct signature could indirectly shed light on the scale of flavor dynamics in the deep UV.



# Discussion

Q: How to fit neutrinos?

- Add 3 RHN and do high-scale seesaw:

$$m_{\nu_L} \simeq -M_D M_R^{-1} M_D^\intercal \simeq U^\intercal \hat{m}_{\nu_L} U$$

- The model predicts hierarchical $M_D$. Large PMNS require $M_R$ to also be hierarchical to "undo" the hierarchy in $M_D$. :(

A possible resolution comes from a mechanism to generate anarchic $Y_\nu$. To this end, we can extend the field content with a single vector-like fermion representation $N_{L,R} \sim (\mathbf{1}, \mathbf{1}, 0, \mathbf{2})$. When the mass of this field is comparable to $v_\Phi$, marginal interactions $\bar{\ell}_\alpha \widetilde{H} N^\alpha$ and $\overline{N}_\alpha \overset{(\sim)}{\Phi}{}^\alpha \nu_p$ wash out the hierarchy in $Y_\nu$. In this case, the required Majorana mass matrix $M_R$ is also anarchic. This is an elegant solution, provided one accepts the coincidence of scales $M_N \sim v_\Phi$.

# Outlook

## Pati-Salam unification

- All five scalar fields of the model fit into just two irreps!

$$H, R_u, R_d \subseteq \Sigma_H \sim (\mathbf{15},\ \mathbf{2},\ 1/2,\ \mathbf{1})$$

$$\Phi, S \subseteq \Sigma_\Phi \sim (\mathbf{15},\ \mathbf{1},\ 0,\ \mathbf{2})$$

$$\mathrm{SU}(4) \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)_\mathrm{R} \times \mathrm{SU}(2)_{q+\ell}$$

- Explains why $M_Q = M_L$. They unify into a single VLF!

$$\Psi_{\mathrm{L,R}} \sim (\mathbf{4},\ \mathbf{2},\ 0,\ \mathbf{1})$$

- Can one fit masses and mixings? Predictions from unification? w.i.p.