Flavor Hierarchies from a Minimal U(2) Symmetry

Anders Eller Thomsen

Based on work with S. Antusch, A. Greljo, and B. Stefanek
[2309.11547] and [2311.09288]

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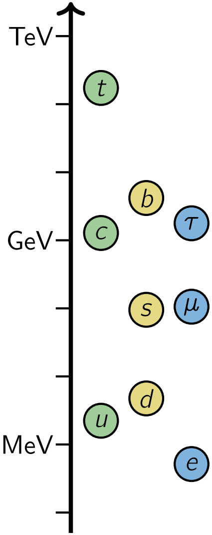
The Flavor Puzzle

What can approximate symmetries tell us?

The Flavor Puzzle



$V_{\mathrm{CKM}} \sim$ 

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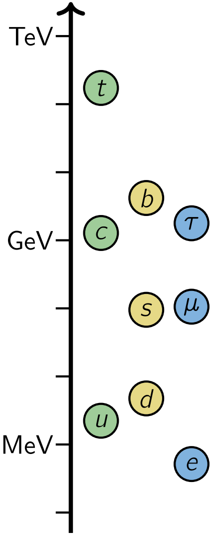

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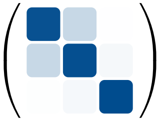
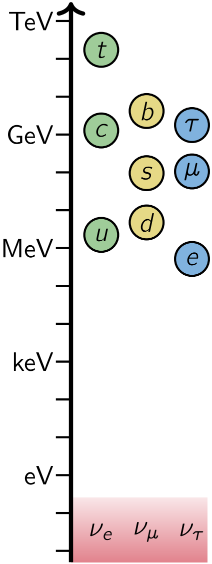


$$\mathcal{L}_{\text{SM}} \supset -Y_u^{pr}\, \overline{q}^p \widetilde{H} u^r - Y_d^{pr}\, \overline{q}^p H d^r - Y_e^{pr}\, \overline{\ell}^p H e^r$$

- Small Yukawas are natural in the sense of ‘t Hooft
- Why are they hierarchical if they all enter at the same level?

The Flavor Puzzle



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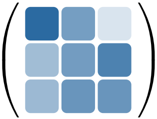
$V_{\mathrm{PMNS}} \sim$ 

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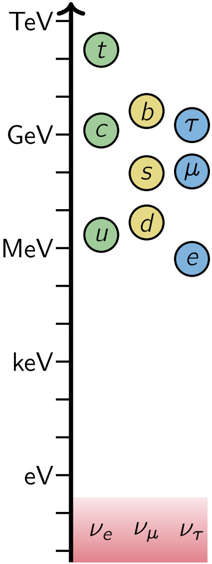

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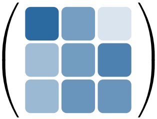
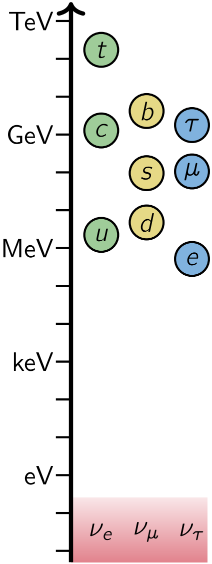
$V_{\mathrm{PMNS}} \sim$ 

$$\mathcal{L}_{\mathrm{SMEFT}} \supset -\frac{C^{pr}}{\Lambda}\bar{\ell}_p \widetilde{H}\widetilde{H}^{\intercal} \ell_r^C$$

- Smallness of the neutrino masses? $\rightarrow$ Heavy NP
- Why is the PMNS so radically different from the CKM?

The Flavor Puzzle



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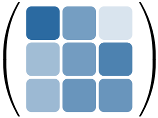
$V_{\mathrm{PMNS}} \sim$ 

What about explanations?

- Many different BSM mechanisms: Froggatt–Nielsen, (gauged) flavor symmetries, accidental flavor, radiative mass models, multi-Higgs models, multi-scale flavor, warped compactification, clockwork, modular symmetries...
- UV completions of the models are often complex

Flavor symmetries

It is instructive to consider flavor in terms of symmetries:

SM Kinetic terms: $\mathcal{L} \supset i\overline{q}^p \not{D} q^p + i\overline{u}^p \not{D} u^p + i\overline{d}^p \not{D} d^p + i\overline{\ell}^p \not{D} \ell^p + i\overline{e}^p \not{D} e^p$

$\hookrightarrow$ Flavor symmetry: $\mathrm{U}(3)^5 = \mathrm{U}(3)_q \times \mathrm{U}(3)_u \times \mathrm{U}(3)_d \times \mathrm{U}(3)_\ell \times \mathrm{U}(3)_e$

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Minimal Flavor Violation (MFV): D'Ambrosio *et al.* [hep-ph/0207036]

the only breaking of $\mathrm{U}(3)^5$ is due to the spurions

$$Y_u \sim (\mathbf{3}, \bar{\mathbf{3}}, \mathbf{1}, \mathbf{1}, \mathbf{1}), \qquad Y_d \sim (\mathbf{3}, \mathbf{1}, \bar{\mathbf{3}}, \mathbf{1}, \mathbf{1}), \qquad Y_e \sim (\mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{3}, \bar{\mathbf{3}})$$

- ✗ The symmetry does not explain flavor! *(nor was it meant too)*
- ✗ $y_t \sim 1$ is large: there is no order parameter
- ✓ Selection rules allow for multi-TeV scale NP

$Y_u \sim$ 

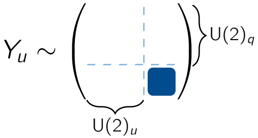
An approximate symmetry of the SM: U(2)^5

The leading violation of $\mathrm{U}(3)^5$:

$Y_u \sim$ 

An approximate symmetry of the SM: $U(2)^5$

The leading violation of $U(3)^5$:



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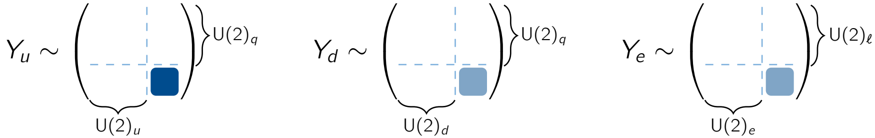

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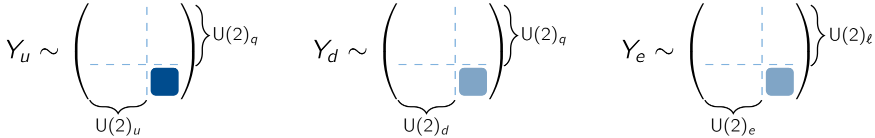

$U(2)^5$ symmetry: small spurions break $U(2)^5$ further

Kagan *et al.* [0903.1794]; Barbieri *et al.* [1105.2296]; Blankenburg *et al.* [1204.0688]; Fuentes-Martín *et al.* [1909.02519], ...

$$\Delta_u,\, \Delta_d,\, \Delta_e \ll V_q,\, V_\ell \ll 1$$

can be 0

$$Y_u = \begin{pmatrix} \Delta_u & x_t V_q \\ & 1 \end{pmatrix}, \qquad Y_d = y_b \begin{pmatrix} \Delta_d & x_b V_q \\ & 1 \end{pmatrix}, \qquad Y_e = y_\tau \begin{pmatrix} \Delta_e & x_\tau V_\ell \\ & 1 \end{pmatrix}$$

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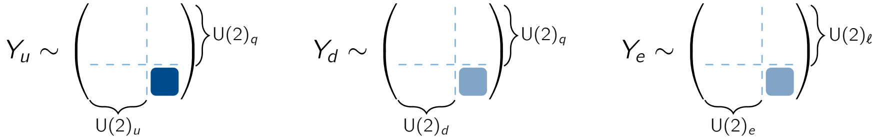

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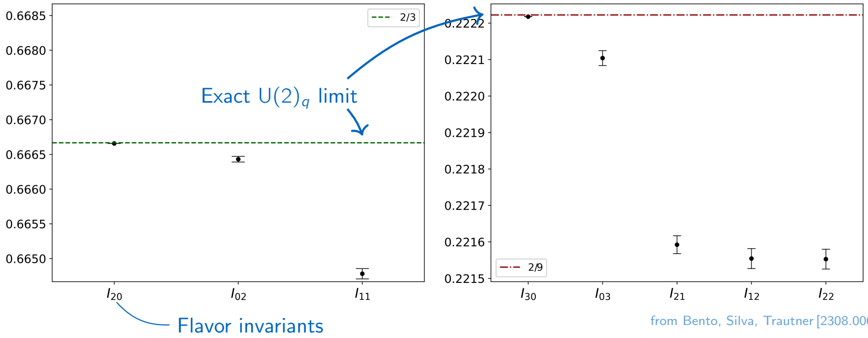
- ✓ Hierarchical charged fermion masses + CKM matrix
- ✗ Complicated symmetry and breaking pattern
- ✗ Suggests a hierarchical PMNS matrix
- ✓ Selection rules allow for multi-TeV NP

How good is the $U(2)_q$ symmetry?

Flavor invariants, e.g., $I_{21} = \mathrm{Tr}\left[H_u^2 H_d\right]/(y_t^4 y_b^2)$, $H_f = Y_f Y_f^\dagger - \frac{1}{3}\mathrm{Tr}\left[Y_f Y_f^\dagger\right]$



from Bento, Silva, Trautner [2308.00019]

Very good!

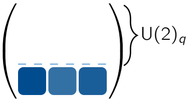
U(2) is Right for Leptons and Left for Quarks

All flavor structure from a single U(2)

One U(2) symmetry

Assume the existence of a $\mathrm{U}(2)_q$ flavor symmetry:

$Y_u \sim$



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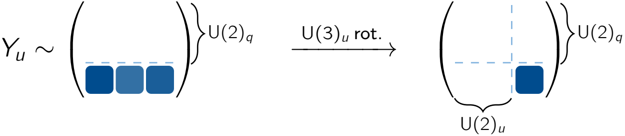

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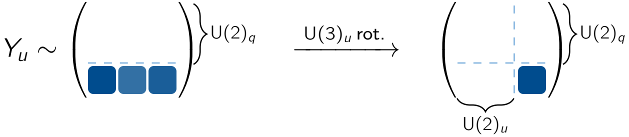

Causing accidental symmetries in the SM Yukawa couplings

$$\mathrm{U}(2)_q \xrightarrow{\text{accidental}} \mathrm{U}(2)_u \times \mathrm{U}(2)_d$$
$$\mathrm{U}(2)_e \xrightarrow{\text{accidental}} \mathrm{U}(2)_\ell$$

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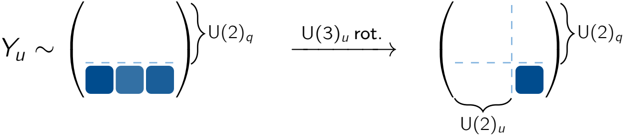

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No selection rules on Weinberg operator (or NP) from the accidental SM symmetries

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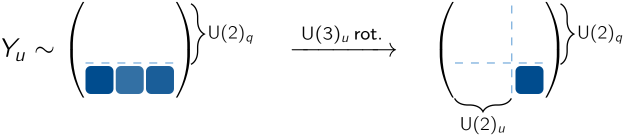

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Assuming a **$\mathrm{U}(2)_{q+e}$ flavor symmetry**

- ✓ hierarchy between the 3rd and light generation charged fermions
- ✓ anarchic PMNS matrix

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

$$q^p = q^\alpha \oplus q^3 \sim \mathbf{2}_1 \oplus \mathbf{1}_0, \qquad e^p = e^\alpha \oplus e^3 \sim \mathbf{2}_1 \oplus \mathbf{1}_0, \qquad V^\alpha_{1,2} \sim \mathbf{2}_1$$

Spurions $V^\alpha_{1,2}$ break $\mathrm{U}(2)_{q+e}$ giving light generation masses:

$$\begin{aligned}\mathcal{L} \supset &- \left(x^p_u \overline{q}^3 + y^p_u \overline{q}_\alpha V^\alpha_2 + z^p_u \overline{q}_\alpha V^\alpha_1\right) \widetilde{H} u^p \\ &- \left(x^p_d \overline{q}^3 + y^p_d \overline{q}_\alpha V^\alpha_2 + z^p_d \overline{q}_\alpha V^\alpha_1\right) H d^p \\ &- \overline{\ell}^p H \left(x^p_e e^3 + y^p_e V^*_{2\alpha} e^\alpha + z^p_e V^*_{1\alpha} e^\alpha\right)\end{aligned}$$

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The effective SM Yukawa matrices take the form, e.g.,

$$Y_u = \begin{pmatrix} z_{u1} b & z_{u2} b & z_{u3} b \\ & y_{u2} a & y_{u3} a \\ & & x_{u3} \end{pmatrix} = L_u \widehat{Y}_u R_u^\dagger, \qquad \begin{cases} V_2^\alpha = (0,\ a) \\ V_1^\alpha = (b,\ 0) \\ 1 \gg a \gg b > 0 \end{cases}$$

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✓ hierarchy between the 1st and 2nd generation charged fermions

✓ hierarchical (close to identity) CKM matrix

✗ selection rules do not allow for TeV-scale NP *but the phenomenology is interesting*

Numerical benchmark

The down rotation dominates $V_{\text{CKM}} = L_u^\dagger L_d$ due to a compressed mass hierarchy:

$$L_d \simeq \begin{pmatrix} 1 & \frac{m_d}{m_s}\frac{z_{d2}}{z_{d1}} & \frac{m_d}{m_b}\frac{z_{d3}}{z_{d1}} \\ -\frac{m_d}{m_s}\frac{z_{d2}^*}{z_{d1}} & 1 & \frac{m_s}{m_b}\frac{y_{d3}}{y_{d2}} \\ \frac{m_d}{m_b}\left(\frac{y_{d3}^* z_{d2}^*}{y_{d2} z_{d1}} - \frac{z_{d3}^*}{z_{d1}}\right) & -\frac{m_s}{m_b}\frac{y_{d3}^*}{y_{d2}} & 1 \end{pmatrix}$$

$$L_u \simeq \begin{pmatrix} 1 & \frac{m_u}{m_c}\frac{z_{u2}}{z_{u1}} & \frac{m_u}{m_t}\frac{z_{u3}}{z_{u1}} \\ -\frac{m_u}{m_c}\frac{z_{u2}^*}{z_{u1}} & 1 & \frac{m_c}{m_t}\frac{y_{u3}}{y_{u2}} \\ \frac{m_u}{m_t}\left(\frac{y_{u3}^* z_{u2}^*}{y_{u2} z_{u1}} - \frac{z_{u3}^*}{z_{u1}}\right) & -\frac{m_c}{m_t}\frac{y_{u3}^*}{y_{u2}} & 1 \end{pmatrix}$$

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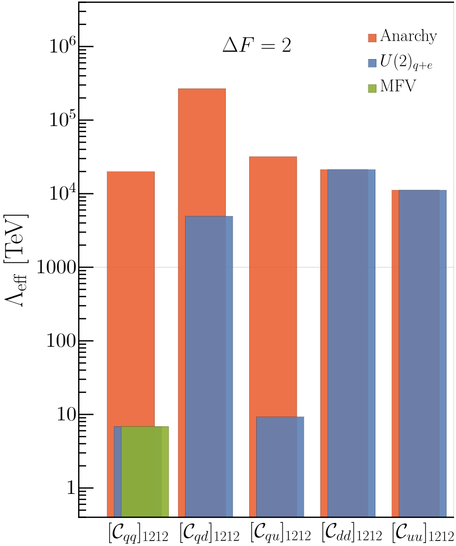
A realistic benchmark $\mu = 1\,\text{PeV}$ with $(a,\ b) = (3\cdot 10^{-3},\ 5\cdot 10^{-5})$ is

$$\begin{aligned} z_{\ell 1} &= 0.057 & y_{\ell 2} &= 0.20 & x_{\ell 3} &= 0.010 \\ z_{u1} &= 0.091 & y_{u2} &= 0.76 & x_{u3} &= 0.67 \\ z_{d1} &= 0.20 & y_{d2} &= 0.066 & x_{d3} &= 0.010 \\ z_{d2} &= 0.89 e^{i\alpha} & z_{d3} &= 0.72 e^{i(\beta - 1.2)} & y_{d3} &= 0.13 e^{i(\beta-\alpha)} \end{aligned}$$

* *The remaining parameters are largely unconstrained*

SMEFT bounds



EFT as a proxy for new physics:

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{1}{\Lambda_{\text{eff}}^2} \mathcal{O}_i + \ldots$$

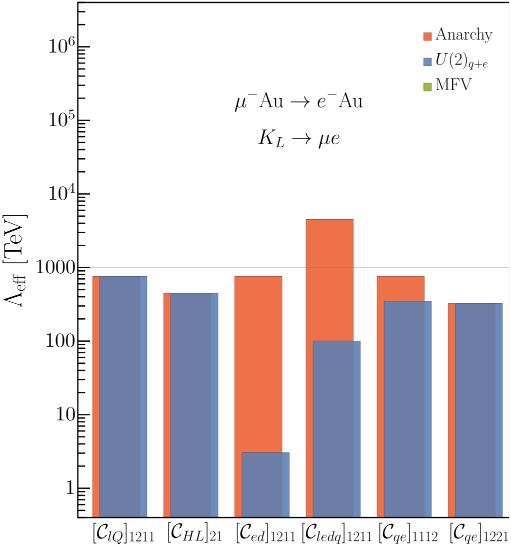
Interaction basis:

$$\mathcal{L}_{\text{SMEFT}} \supset -\frac{1}{\Lambda^2} (\overline{q}^3 \gamma_\mu q^3)(\overline{d}^1 \gamma_\mu d^2)$$

Down quark mass basis:

$$\mathcal{L}_{\text{SMEFT}} \supset -\frac{[L_d^*]_{31} [L_d]_{32}}{\Lambda^2} (\overline{q}^1 \gamma_\mu q^2)(\overline{d}^1 \gamma_\mu d^2)$$

SMEFT bounds



Interaction basis:

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Mass basis:

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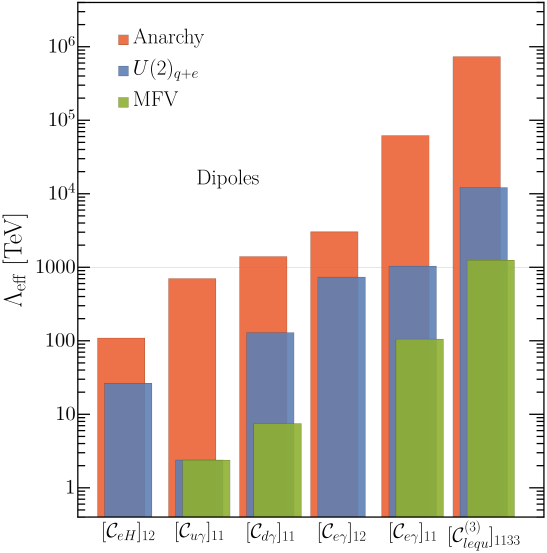
SMEFT bounds



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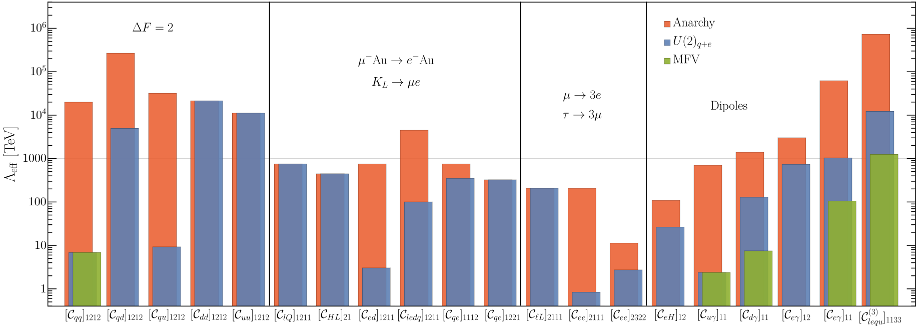

Antusch, Greljo, Stefanek, AET [2311.09288]

- cLFV observables are more competitive the with $\mathrm{U}(2)_{q+e}$ assumption
- Expect order-10 improvement in $\mu \to e$ conversion (Mu2e, COMET), electron EDM (ACME), and $\mu \to 3e$ (Mu3e)
- Gauged realizations of $\mathrm{SU}(2)_{q+e}$ produce $[C_{qe}]_{1211} \sim \langle \Phi \rangle^{-2}$ (the breaking scale): this is a smoking gun

Rising Through the Ranks

A UV realization of the U(2) idea

Aim for the UV realization

Rules of the "Game:"

- Explain hierarchy of charged fermion Yukawas, $Y_{u,d,e}$, and $V_{\text{CKM}} \sim \mathbb{1}$
- Marginal couplings are $\mathcal{O}(0.3)$ (couplings $\gtrsim 1$ tend to give Landau poles)
- Simple models are favored—no epicycles

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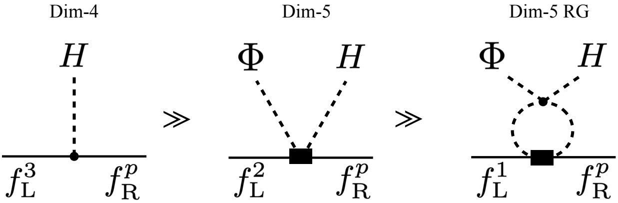


Starting point: gauged $\mathrm{SU}(2)_{q+\ell}$!

Babu, Mohapatra '91

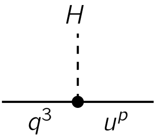
- $\mathrm{SU}(2)_{q+\ell}$ is non-anomalous: no chiral BSM fermions are needed
- Accidental $\mathrm{U}(2)_u \times \mathrm{U}(2)_d \times \mathrm{U}(2)_e$ ensures hierarchical Yukawas
- Neutrino masses left for model extension
- $\langle \Phi^\alpha \rangle = \binom{0}{v_\Phi}$ breaks $\mathrm{SU}(2)_{q+\ell}$, allowing light fermion masses

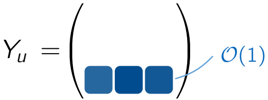
$$q^p = (q^\alpha, q^3) \sim (\mathbf{2}, \mathbf{1}), \qquad \ell^p = (\ell^\alpha, \ell^3) \sim (\mathbf{2}, \mathbf{1}), \qquad \Phi^\alpha \sim \mathbf{2}$$

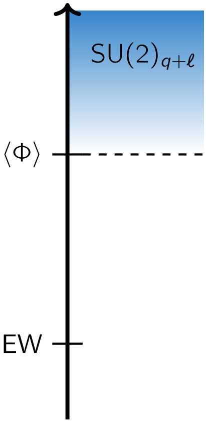
- Heavy, flavored gauge bosons, Z', of $\mathrm{U}(2)_{q+\ell}$ have phenomenological implications

Mechanism for flavor hierarchies

Rank-1 Yukawas: renormalizable interactions







$$m_t > 0, \qquad m_c = m_u = 0$$

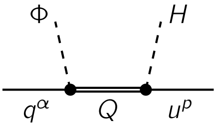
Field	$\mathrm{SU}(3)_c$	$\mathrm{SU}(2)_\mathrm{L}$	$\mathrm{U}(1)_Y$	$\mathrm{SU}(2)_{q+\ell}$
q_L^α	**3**	**2**	1/6	**2**
q_L^3	**3**	**2**	1/6	**1**
u_R^p	**3**	**1**	2/3	**1**
H	**1**	**2**	1/2	**1**
Φ	**1**	**1**	0	**2**

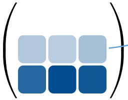
Greljo, AET [2309.11547]

A similar mechanism is behind masses for the down quarks and charged leptons

Mechanism for flavor hierarchies

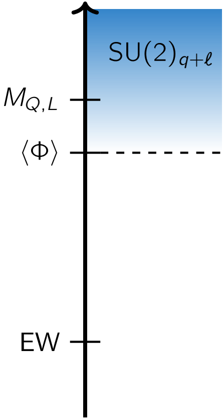
Rank-2 Yukawas: vector-like fermions



$Y_u =$  $\frac{\langle \Phi \rangle}{M_Q} \sim \frac{1}{100}$

$$m_t \gg m_c > 0, \qquad m_u = 0$$

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



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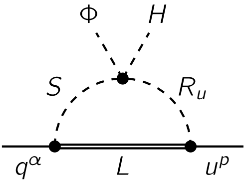
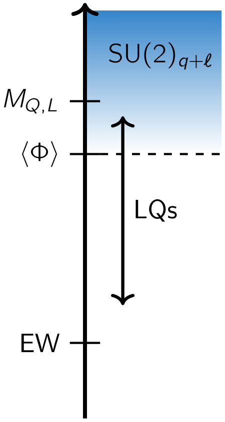
Mechanism for flavor hierarchies

Rank-3 Yukawas: scalar leptoquarks



$Y_u =$  $\frac{\langle\Phi\rangle}{M_L}\frac{\log(\mu/M_L)}{16\pi^2}$



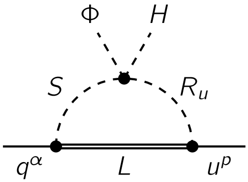
$$m_t \gg m_c \gg m_u > 0$$

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**

Greljo, AET [2309.11547]

A similar mechanism is behind masses for the down quarks and charged leptons

Rank-3 Yukawas: scalar leptoquarks



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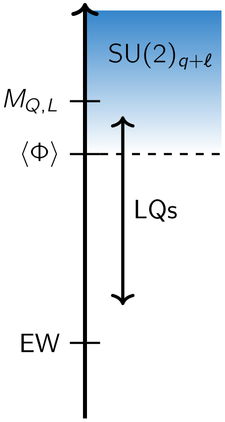

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Greljo, AET [2309.11547]

Benchmark at $\langle\Phi\rangle = M_{L,Q}/100 = 1\,\mathrm{PeV}$:

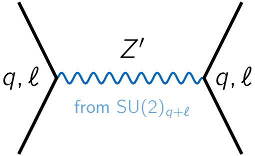
Most couplings in [.1, 1] (exception $y_{b,\tau} = 0.01$)

Perhaps a 2HDM variation?

Phenomenology of Z'

There is a GIM-like mechanism suppressing 4-quark and 4-lepton FCNCs from

Darmé, Deandrea, Mahmoudi [2307.09595]



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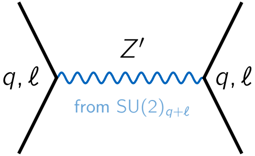

Leading constraints from ***q*-to-*ℓ* "flavor transfer"**:

Alignment of 2nd generation leptons and quarks

$$\mathrm{BR}\big(K_L \to \mu^\pm e^\mp\big) = 5.9 \cdot 10^{-12} \cdot \left(\frac{300\,\mathrm{TeV}}{\langle\Phi\rangle}\right)^4 \big(0.90\, c_{2\ell} + 0.44\, s_{2\ell}\big)^2 < 4.7 \cdot 10^{-12}$$

$$\mathrm{CR}(\mu\mathrm{Au} \to e\mathrm{Au}) = 2 \cdot 10^{-11} \cdot \left(\frac{300\,\mathrm{TeV}}{\langle\Phi\rangle}\right)^4 (1.01\, s_{2\ell} - 0.25\, c_{2\ell})^2 < 7 \cdot 10^{-13}$$

$$\hookrightarrow \langle\Phi\rangle \gtrsim 500\,\mathrm{TeV}$$

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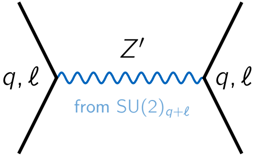

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Future sensitivity:
$\mathrm{CR}(\mu\mathrm{Al} \to e\mathrm{Al}) \lesssim 10^{-16}$
Mu2e and COMET

$$\hookrightarrow \langle \Phi \rangle \gtrsim 500\,\mathrm{TeV} \quad 5000\,\mathrm{TeV}$$

future sensitivity

Leptoquark phenomenology

Stability of the scalar potential admits two interesting scenarios:

I) $M_{R_u}, M_{R_d} \lesssim \langle \Phi \rangle \lesssim M_S \longrightarrow$ flavor physics

II) $M_S \ll \langle \Phi \rangle \lesssim M_{R_u}, M_{R_d} \longrightarrow$ collider physics

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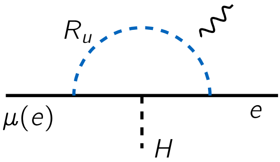
Light R_u? Not likely

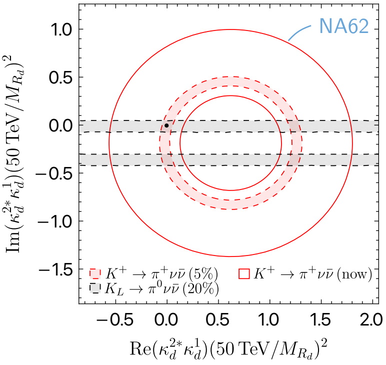


Lepton dipoles contributing to $\mu \to e\gamma$ and eEDM limits

$$M_{R_u} \gtrsim 500\,\mathrm{TeV}$$

Phenomenology of R_d: Kaon physics

$K \to \pi\nu\nu$



R_d interacts mainly with 3-generation leptons:

$$\mathcal{L}_{\mathrm{UV}} \supset -\kappa_d^p \,\bar{\ell}^3 \widetilde{R}_d d^p + \mathrm{H.c.}$$

Constraints from meson mixing (one loop)

$$\left|\mathrm{Re}\big[(\kappa_d^{2*}\kappa_d^1)^2\big]\right| \left(\frac{50\ \mathrm{TeV}}{M_{R_d}}\right)^2 \lesssim 1.0 \quad (\Delta m_K)$$

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

Low-scale scenario allowed:

$$M_{R_d} = 5\ \mathrm{TeV} \qquad |\kappa_d^2| \sim 0.3 \qquad |\kappa_d^1| \lesssim 0.01$$

Phenomenology of R_d: B physics

$$\mathcal{L}_{\rm UV} \supset -\kappa_d^p \,\bar{\ell}^3 \widetilde{R}_d d^p + \text{H.c.}$$

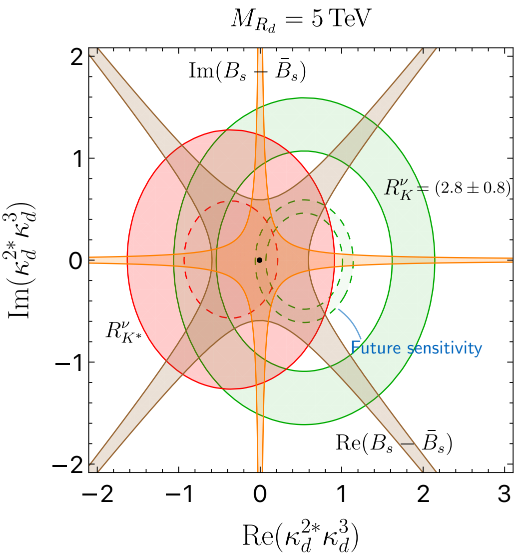
- Belle II 2023: $R_K^\nu = 2.8 \pm 0.8$

$$R^\nu_{K^{(*)}} = \frac{\text{BR}(B \to K^{(*)}\nu\nu)}{\text{BR}(B \to K^{(*)}\nu\nu)^{\text{SM}}}$$

- Consistency with meson mixing:

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

- Collider limits: $\gtrsim 1.5$ TeV



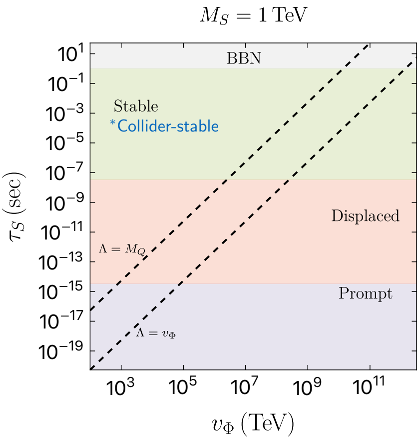
Long-lived particles—phenomenology of S

S as the lightest new particle:

- No renormalizable couplings to SM particles
- Decays suppressed by the UV scale

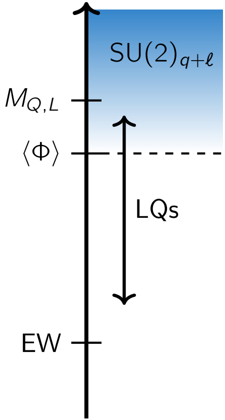
$$\frac{\Gamma_S}{M_S} \sim \frac{1}{16\pi^2} \frac{v_{\mathrm{EW}}^2}{\Lambda^2}$$

- Interesting collider phenomenology for light S: **long-lived exotic hadrons**
- Collider signature dependent on UV scale



Summary

- A single $\mathrm{U}(2)_{q+e(\ell)}$ can explain the entire flavor structure of the SM ($-$ neutrinos)
- The simplicity of symmetry and breaking allows for simple(?) UV realizations of the mechanism
- There is interesting low-energy flavor phenomenology associated with its realization ($\mu \to e$ conversion in particular)
- Interesting variant in SU(5), where $\mathbf{10}^\alpha$ is charged under U(2) and $\bar{\mathbf{5}}$ is a singlet



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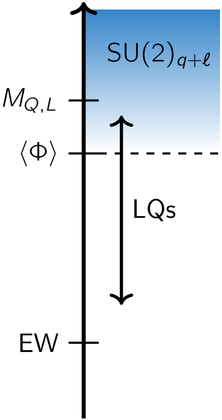

Thank You!