University of Basel
Department of Physics

Funding
Swiss National Science Foundation
Probing the Origin of Flavor with Colliders and Gravitational Waves
State Secretariat for Education, Research and Innovation
CHEF: Swiss High Energy Physics for the FCC

Minimal Flavor Protection

Admir Greljo

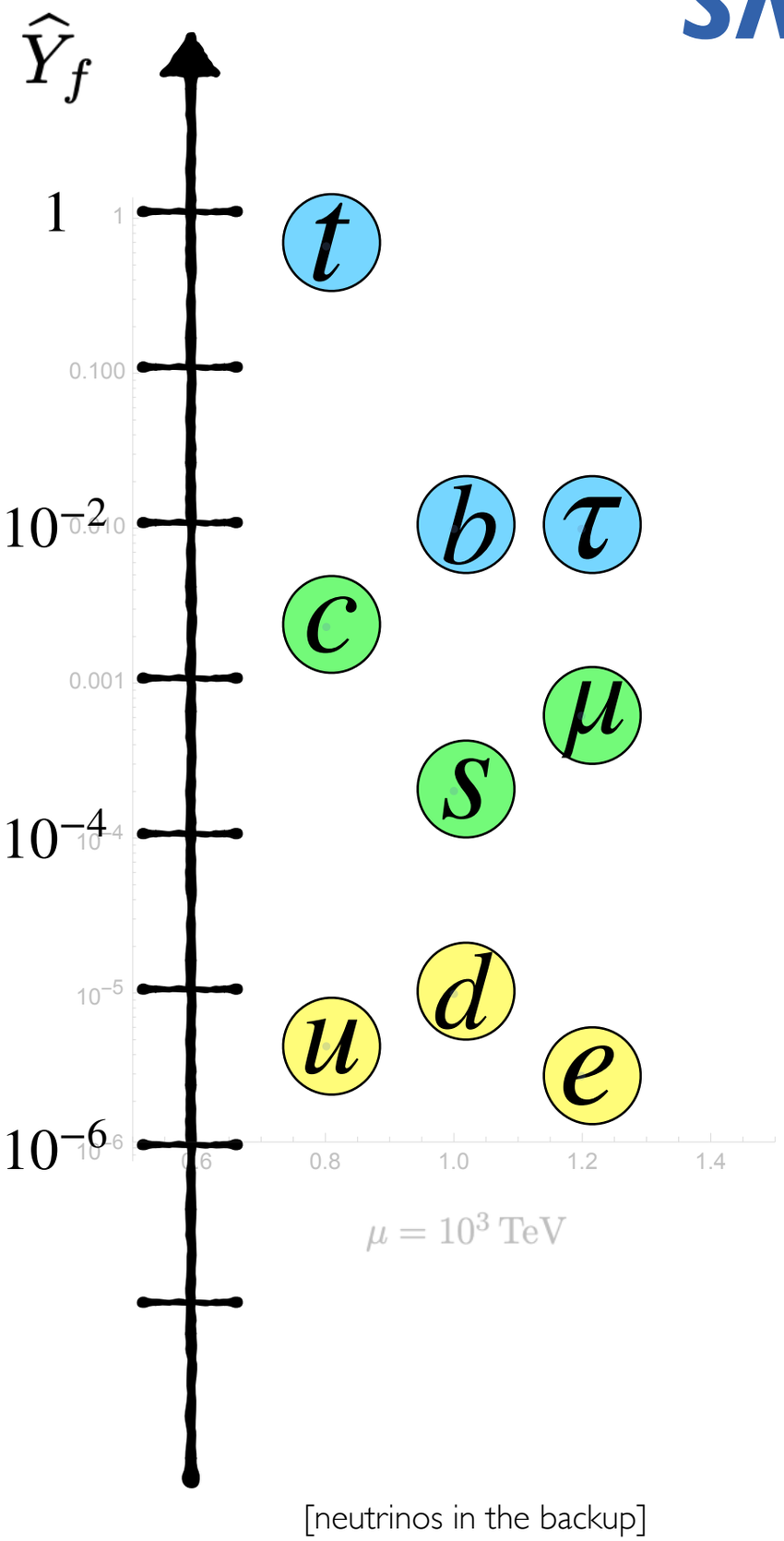
24.10.2026, CEPC2026

Problems

- SM & BSM flavor puzzle

SM flavor puzzle

Recent review: Altmannshofer, AG, 2412.04549



[neutrinos in the backup]

?

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

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

$U(3)^5$ & SVD: $Y_f = L_f \widehat{Y}_f R_f^\dagger \quad V_{\rm CKM} = L_u^\dagger L_d$

Flavor indices $i, j = 1,2,3$ enter the theory in the same way:

Why hierarchies? $\Longrightarrow$ UV dynamics **B**eyond **SM**

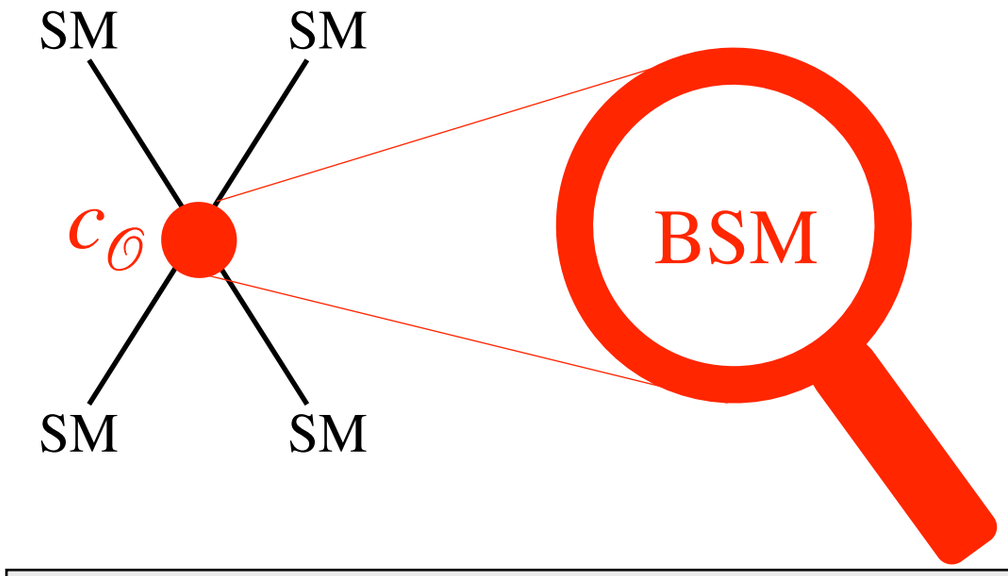
Implications

Y_f^{ij} hierarchies $\Longrightarrow$ ***Approximate symmetries of increasing quality***

- $\mathscr{L}_{SM}$ without Yukawa: $U(3)_q \times U(3)_u \times U(3)_d \times U(3)_\ell \times U(3)_e$
- Only large breaking $y_t \sim 1 \rightarrow U(2)_q \times U(2)_u \times U(1)_t \times U(3)^3$
- Next breaking $y_{b,\tau} \sim 10^{-2} \rightarrow U(2)^5 \times U(1)_{t+b} \times U(1)_\tau$
- …
- Residual exact symmetry $\rightarrow U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$

Symmetries $\Longrightarrow$ ***Selection rules*** → Understand SM flavor violation

→ Search for physics **B**eyond the **SM**



A hunt for new interactions $c_{\mathcal{O}}$

SMEFT*

$$\mathscr{L} - \mathscr{L}_{\rm SM} = \sum_{\mathcal{O}>4}^{\infty} \frac{c_{\mathcal{O}}}{\Lambda_{\mathcal{O}}^{[\mathcal{O}]-4}} \mathcal{O}$$

*Proxy for IR effects of UV physics

** not a replacement for model building

$\Delta B = 0$

$\dim[\mathcal{O}] = 6$	$\# c_{\mathcal{O}}$
1 family	**59**
3 families	**2499**

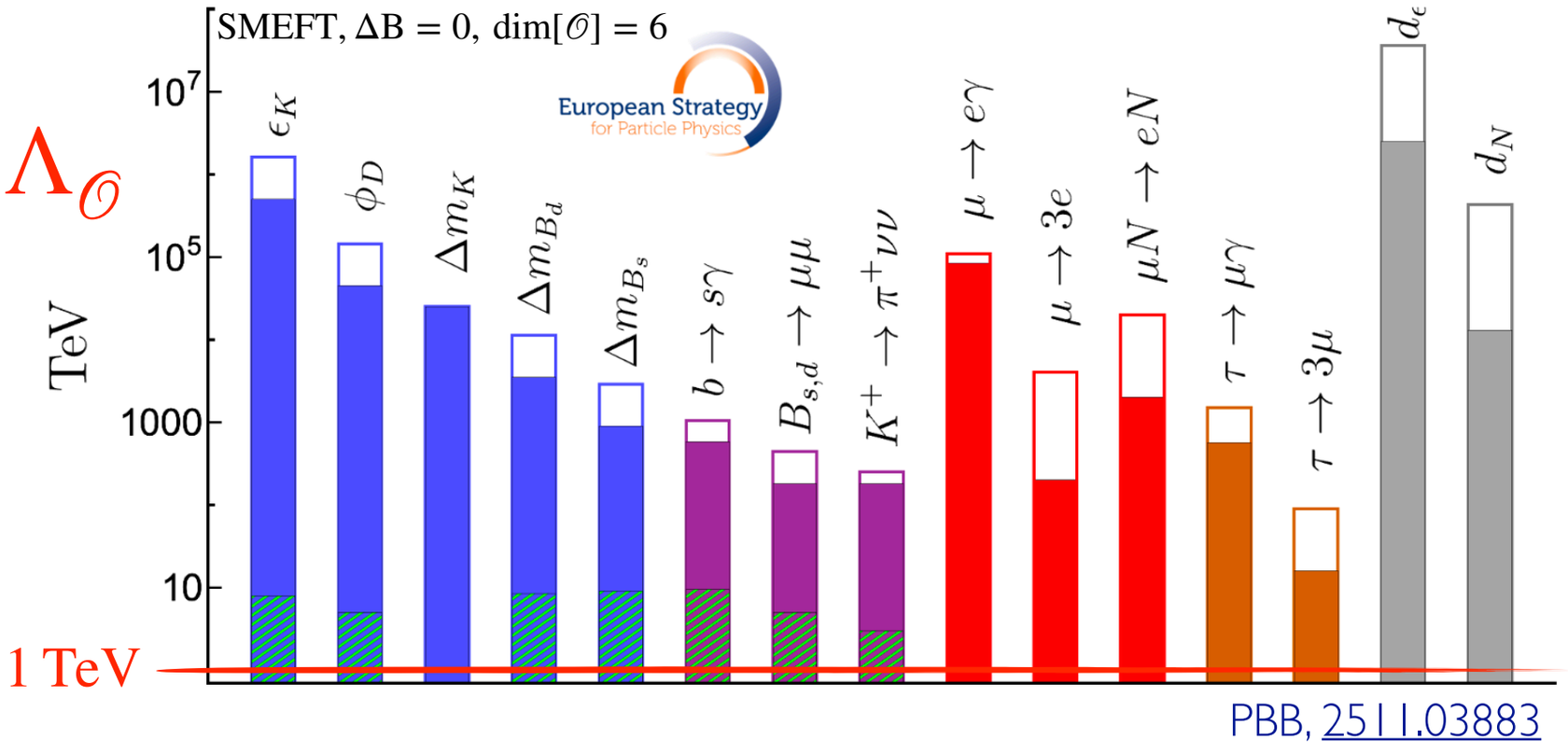
A wealth of information about flavor

++new sources of violation of approximate f.s.

BSM flavor puzzle

Flavor & CP violation

$$\mathscr{L} \supset \frac{c_{\mathcal{O}}}{\Lambda^2_{\mathcal{O}}}\mathcal{O} \qquad c_{\mathcal{O}} \sim 1 \text{ (anarchy)}$$

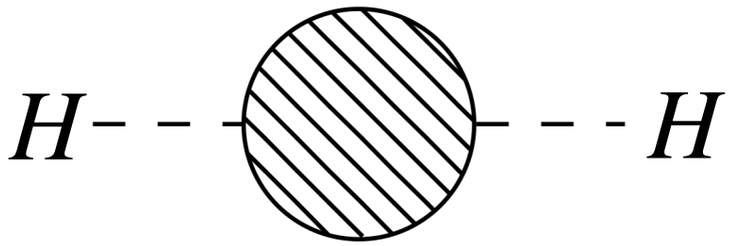


PBB, 2511.03883

$\Lambda_{\rm UV} \gg$ TeV

Higgs hierarchy problem

$y_t \sim 1$



$$\delta m_H^2 \propto y_t^2\, \Lambda^2_{\rm UV}$$

No tuned cancelations $\Longrightarrow$

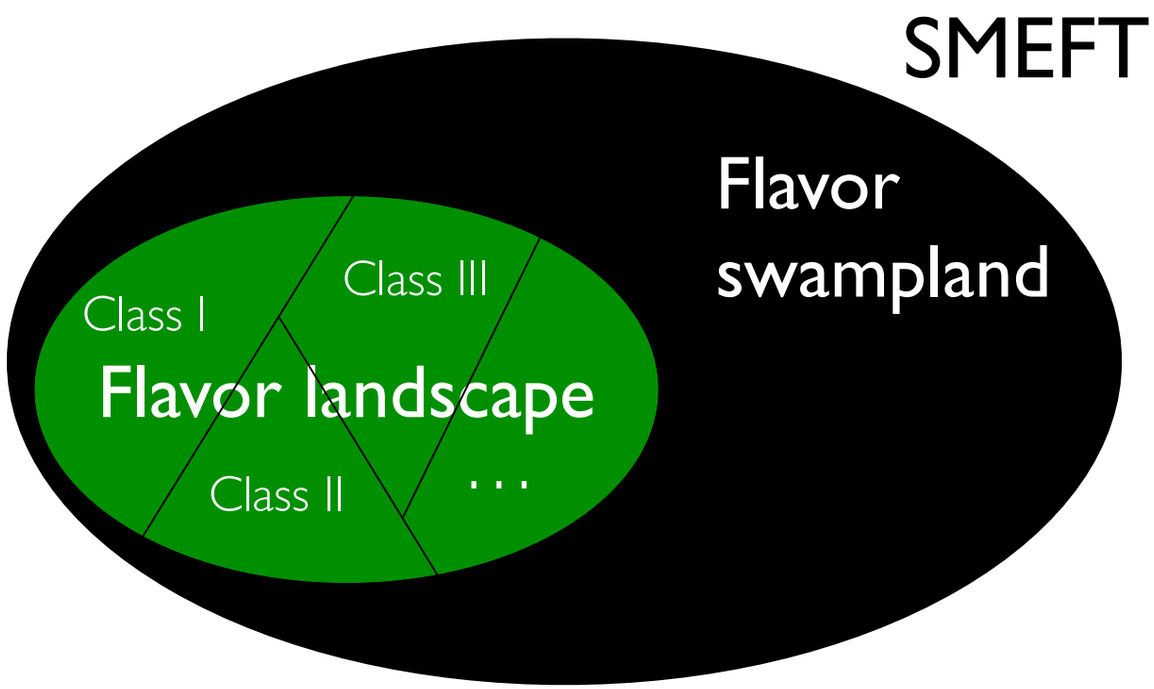
$\Lambda_{\rm UV} \lesssim$ TeV

?
tension

IR perspective

- Flavored EFTs

Organizing frameworks:
- Flavored EFTs



SMEFT + ***Flavor Symmetry-Spurion Structure*** $\quad G \xrightarrow{\{S_i\}} H$

☑ Organizes $c_{\mathcal{O}}$ couplings (and Y_f) in a controlled manner:
power counting in the spurion expansion $c_{\mathcal{O}} \sim \prod_i S_i^{n_i}$

☑ No fine-tuned cancellations, stable under RGE

Classes of UV models $\Longrightarrow$ Different symmetry–spurion frameworks $\Longrightarrow$ Different selection rules

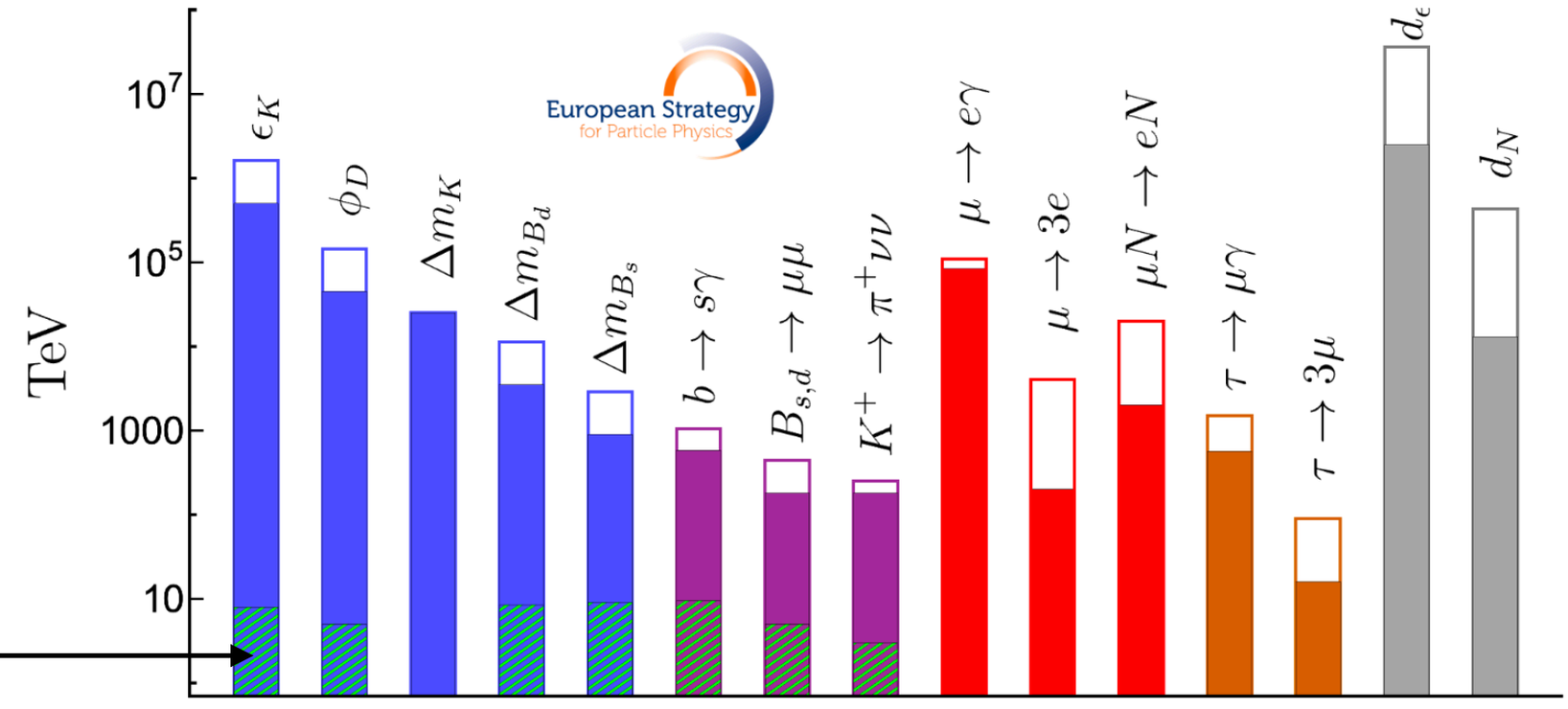
Minimal Flavor Violation

— Maximal Flavor Protection

D'Ambrosio, Giudice, Isidori, Strumia; hep-ph/0207036

Symmetry: $U(3)^5$

Spurions: $Y_u \sim (\mathbf{3}_q, \overline{\mathbf{3}}_u), \quad Y_d \sim (\mathbf{3}_q, \overline{\mathbf{3}}_d), \quad Y_e \sim (\mathbf{3}_\ell, \overline{\mathbf{3}}_e)$



European Strategy for Particle Physics

BSM flavor puzzle ✓

MFV →

$\Lambda_{\mathcal{O}} \lesssim 10\,\text{TeV}$

$c_{\mathcal{O}}$ built from positive powers of Y_f respecting $U(3)^5$ covariance $\Longrightarrow$ mimic the selection rules of the SM

$\text{eg.}\ [Y_u Y_u^\dagger]_{ij}^2 (\bar{q}_i \gamma^\mu q_j)^2$

$\sim \lambda^{10}$

(Cabbibo $\lambda \approx 0.2$)

Minimal Flavor Violation

— Maximal Flavor Protection

Shortcomings



SM flavor puzzle

Y_f^{ij} simply taken as is, nothing about their origin.



Flavor-sterile TeV scale dynamics

not an appropriate interpretation framework for the era of precision!

- ***MFV*** guarantees sufficient flavor protection,
  but it is ***not strictly necessary*** and is ***overly restrictive***.
- Excludes a broad class of interesting flavor phenomena
  that could still be compatible with TeV-scale dynamics.

Minimal Flavor Protection

Q: How much protecting symmetry is necessary?

AG, Palavric, Stefanek, 2512.04159

Minimal Flavor Protection

AG, Palavric, Stefanek, 2512.04159

What is the *smallest continuous subgroup $G_{\rm MFP} \subset U(3)^5$, such that:

1. $\mathcal{O}(1)$ breaking of $U(3)^5 \to G_{\rm MFP}$ in the SMEFT

2. Minimal set of small spurions $\{S_i\}$: $G_{\rm MFP} \to U(1)_B$ reproduces SM Y_f hierarchies

3. Structural protection against FCNC:

$$\mathscr{L} \supset \frac{c_{\mathcal{O}}}{\Lambda^2_{\mathcal{O}}}\mathcal{O} \quad \text{power counting:} \quad c_{\mathcal{O}} \sim \prod_i S_i^{n_i}$$

require $\Lambda_{\mathcal{O}} \lesssim 10\,\text{TeV}\ \ \forall \mathcal{O}$ in the Warsaw basis.

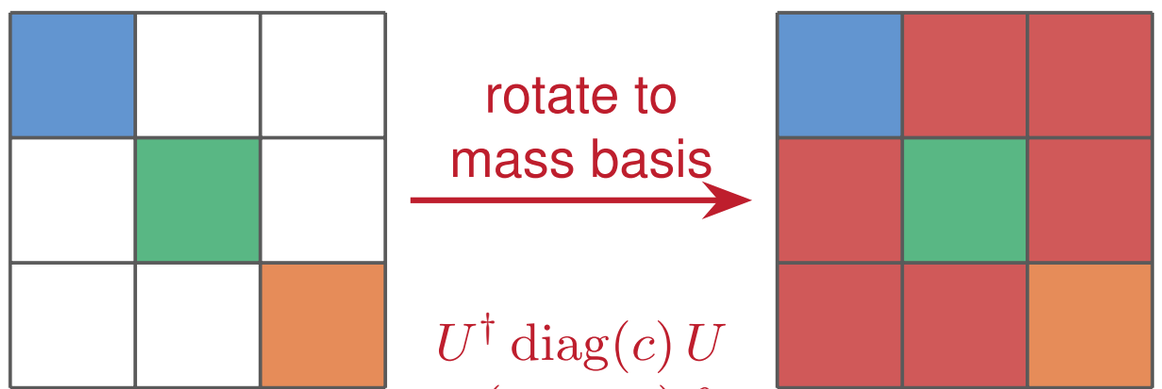
*smallest dimension of the Lie algebra

chain of thought...

Consider $J^\mu = C_{ij}\,(\bar{f}_i\,\gamma^\mu f_j)$

$U(1)_X\colon\ x_{f_1} \neq x_{f_2} \neq x_{f_3}$

Flavor non-universality → **Flavor violation**



$C = \mathrm{diag}(c_1, c_2, c_3)$ $\qquad$ $U^\dagger\,\mathrm{diag}(c)\,U$ $\Rightarrow (c_i - c_j)\,\theta_{ij}$ $\qquad$ $C_{ij} \neq 0,\ i \neq j$

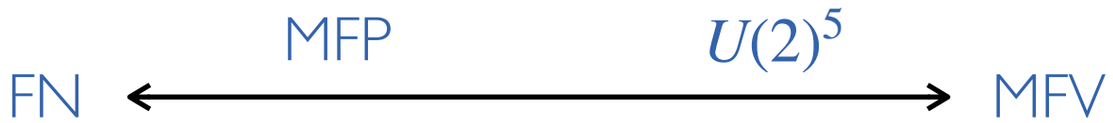
- A small group $\Longrightarrow$ Flavor non-universality
  $\Longrightarrow$ Rotations from **Interaction-To-Mass** basis must be small

- For a larger group:
  $c_1 = c_2 = c_3 \to U(3) \Longrightarrow$ No FV
  $c_1 = c_2 \neq c_3 \to U(2) \Longrightarrow$ suppressed $1\text{–}2$ FV $\sim (c_3 - c_2)\,\theta_{13}\theta_{23}$

chain of thought...

Step 1: establish minimal algebra

$$SU(2)_q \times U(1)_X$$



Personally, the most surprising discovery…
Would have expected a larger group:

Step 2: establish fermion irreps under $SU(2)_q \times U(1)_X$

LH quarks

$$\mathbf{3}_{x_q} \to \mathbf{2}_{x_q} \oplus \mathbf{1}_{x_{q_3}} \,,$$

Other $f = u,\, d,\, \ell,\, e$

$$\mathbf{3}_{x_f} \to \mathbf{1}_{x_{f_1}} \oplus \mathbf{1}_{x_{f_2}} \oplus \mathbf{1}_{x_{f_3}}$$

AG, Palavric, Stefanek, 2512.04159
see also:
AG, Valenti, 2605.15267
Biondini, AG, Ponce Diaz, Valenti, 2601.07921

Step 3: establish minimal spurion sector with flavor protection

Spurions: $\boldsymbol{z} \sim \mathbf{1}_{X_z}, \quad \boldsymbol{V} \sim \mathbf{2}_{X_V}, \quad \boldsymbol{W} \sim \mathbf{2}_{X_W}, \quad \boldsymbol{U} \sim \mathbf{2}_{X_U}$

[details in the backup]

MFP lepton Yukawa

= Flavor-protecting FN

$$Y_e = \begin{pmatrix} z^3 & 0 & 0 \\ 0 & z^2 & 0 \\ 0 & 0 & z \end{pmatrix}$$

SM fields	ℓ_i	e_i
$U(1)_X$ charge	X_i	$X_i - (4-i)X_z$

- Condition that gives exact cLF conservation:

$$(X_i - X_j) \bmod X_z \neq 0 \quad \forall\, i \neq j$$

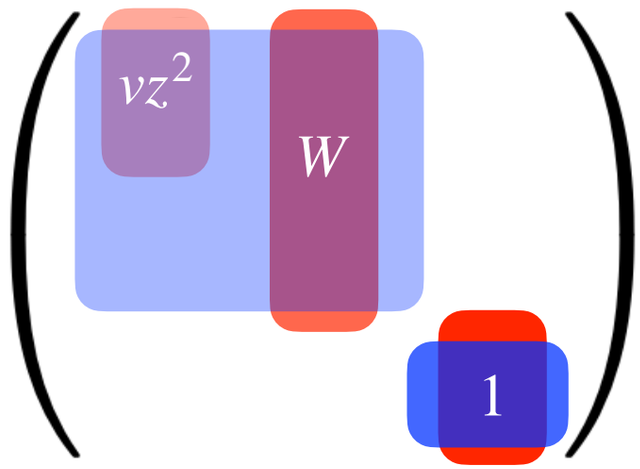
*can be relaxed to saturate cLFV bounds

MFP quark Yukawas

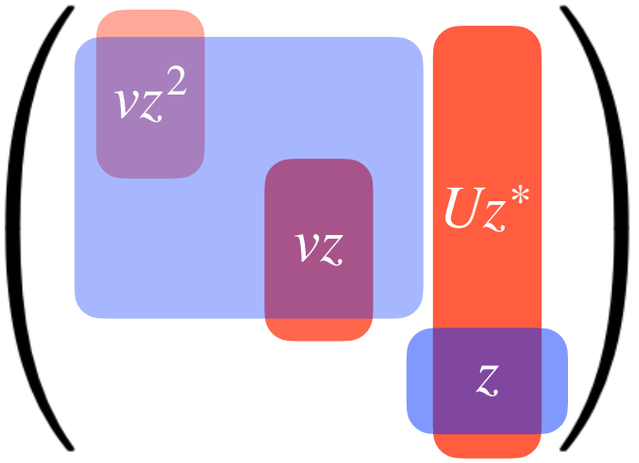
= hybrid

$U(1)_X$ FN-like hierarchy — right-handed

$SU(2)_q$ U(2)-like hierarchy — left-handed



$U(1)_X$ FN-like hierarchy — right-handed



*1-2 down-alignment

$$Y_u = \begin{pmatrix} \boldsymbol{V}z^2 & \boldsymbol{W} & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad Y_d = \begin{pmatrix} \boldsymbol{V}z^2 & \widetilde{\boldsymbol{V}}z^* & \boldsymbol{U}z^* \\ 0 & 0 & \boldsymbol{z} \end{pmatrix}$$

Without loss of generality: $\boldsymbol{z} = z$, $\boldsymbol{V} = v\begin{pmatrix}1\\0\end{pmatrix}$, $\widetilde{\boldsymbol{V}} = i\sigma_2\boldsymbol{V}^*$, $\boldsymbol{W} = w\begin{pmatrix}\sin\alpha\\\cos\alpha\end{pmatrix}$, $\boldsymbol{U} = u\begin{pmatrix}\sin\beta\, e^{i\phi}\\\cos\beta\end{pmatrix}$

SM fields	$d_1,\, u_1$	d_2	u_2	d_3	$q_3,\, u_3$
$U(1)_X$ charge	$-X_V - 2X_z$	$X_V + X_z$	$-X_W$	$X_z - X_U$	$2X_z - X_U$

MFP

✓ **SM flavor puzzle**

Excellent $\mathcal{O}(1)$ fit for
$v, w, u, z \sim \mathcal{O}(10^{-2})$

✓ **BSM flavor puzzle**

Impose conditions on $U(1)_X$ charges to suppress FCNC from:
spurions insertions + basis rotations

Masses

$$y_u \sim v z^2\,, \qquad y_c \sim w\,, \qquad y_t \sim 1\,,$$
$$y_d \sim v z^2\,, \qquad y_s \sim v z\,, \qquad y_b \sim z\,,$$
$$y_e \sim z^3\,, \qquad y_\mu \sim z^2\,, \qquad y_\tau \sim z\,.$$

CKM

$$\alpha \approx -\lambda\,,\ \tan\phi \approx \frac{\eta}{1-\rho}\,,\ \beta \approx -\lambda\,\frac{1-\rho}{\cos\phi}\,,\ \frac{y_q^d\, u}{y_3^d} \approx A\lambda^2$$

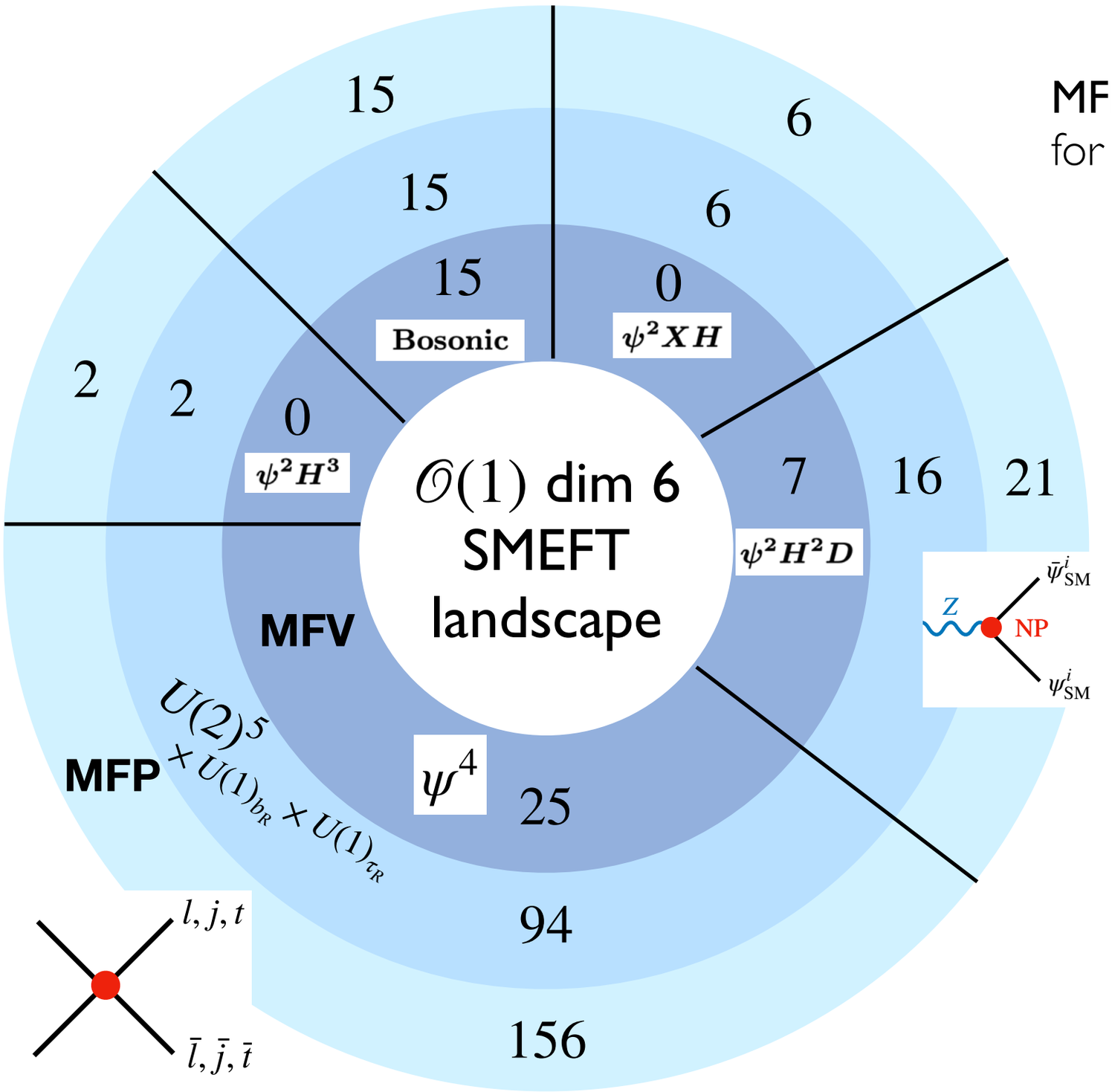
Rotation angles are small

	θ_{12}	θ_{13}	θ_{23}
u_L	λ	0	0
u_R	$\lambda\,\frac{m_u}{m_c} \approx 5\times 10^{-4}$	0	0
d_L	$V_{td}\,V_{ts}^*$	V_{td}	V_{ts}
d_R	$\frac{m_d}{m_s}\,V_{td}\,V_{ts}^*$	$\frac{m_d}{m_b}\,V_{td}$	$\frac{m_s}{m_b}\,V_{ts}$
$e_L,\ e_R$	0	0	0

MFP signatures

- Maximal Flavor Non-Universality
- Flavor Charged Currents

Maximal Flavor Universality Violation



FUV in non-resonant high-p_T tails
(dijet, $t\bar{t}$, dilepton, …)

MFP: The maximal set of operators relevant for FUV consistent with FCNC

robust under the $U(1)_X$ charge choices:
— it originates mostly from $SU(2)_q \times U(1)^{13}$

Universality violation at Z/W pole

— Lower symmetry: Richer Flavor Universality Violation

Flavor Charged Currents

$$\mathscr{L} \supset \frac{c_{\mathcal{O}}}{\Lambda^2_{\mathcal{O}}}\mathcal{O}$$

power counting:

$$c_{\mathcal{O}} \sim \prod_i S_i^{n_i}$$

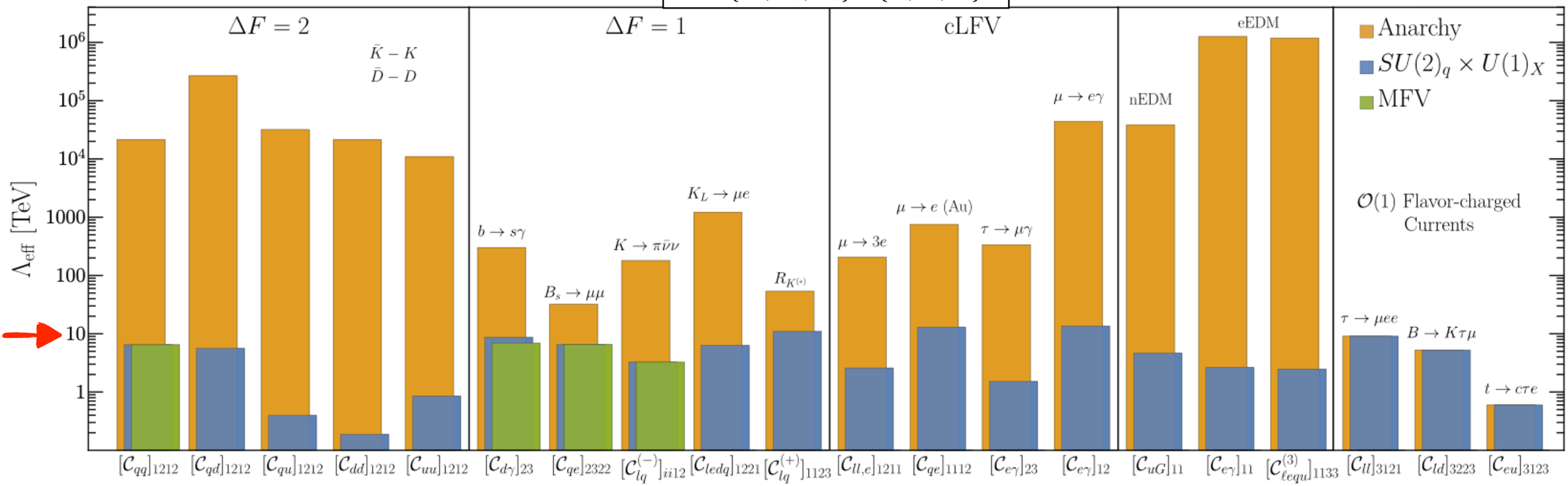
+ rotation

… constructed operator bases
order by order in spurion expansion

*a proof-of-principle charge assigment

$$\{X_V, X_W, X_U, X_z\} = \{1, -2, -3, 7\},$$
$$\{X_1, X_2, X_3\} = \{-2, -3, -1\}.$$

AG, Palavric, Stefanek, 2512.04159



✓ **BSM flavor puzzle**

Minimal **F**lavor **P**rotection
is still $\Lambda_{\mathcal{O}} \lesssim 10\,\text{TeV}$

Flavor-Charged Currents

Allowed at $O(1)$: $[\mathcal{C}_{ll}]_{3121}$ $[\mathcal{C}_{ld}]_{3223}$ $[\mathcal{C}_{eu}]_{3123}$

— Lower symmetry: Richer Flavor Violation

Towards models

- TeV-scale flavor models

Flavor EFT Landscape

— three frameworks

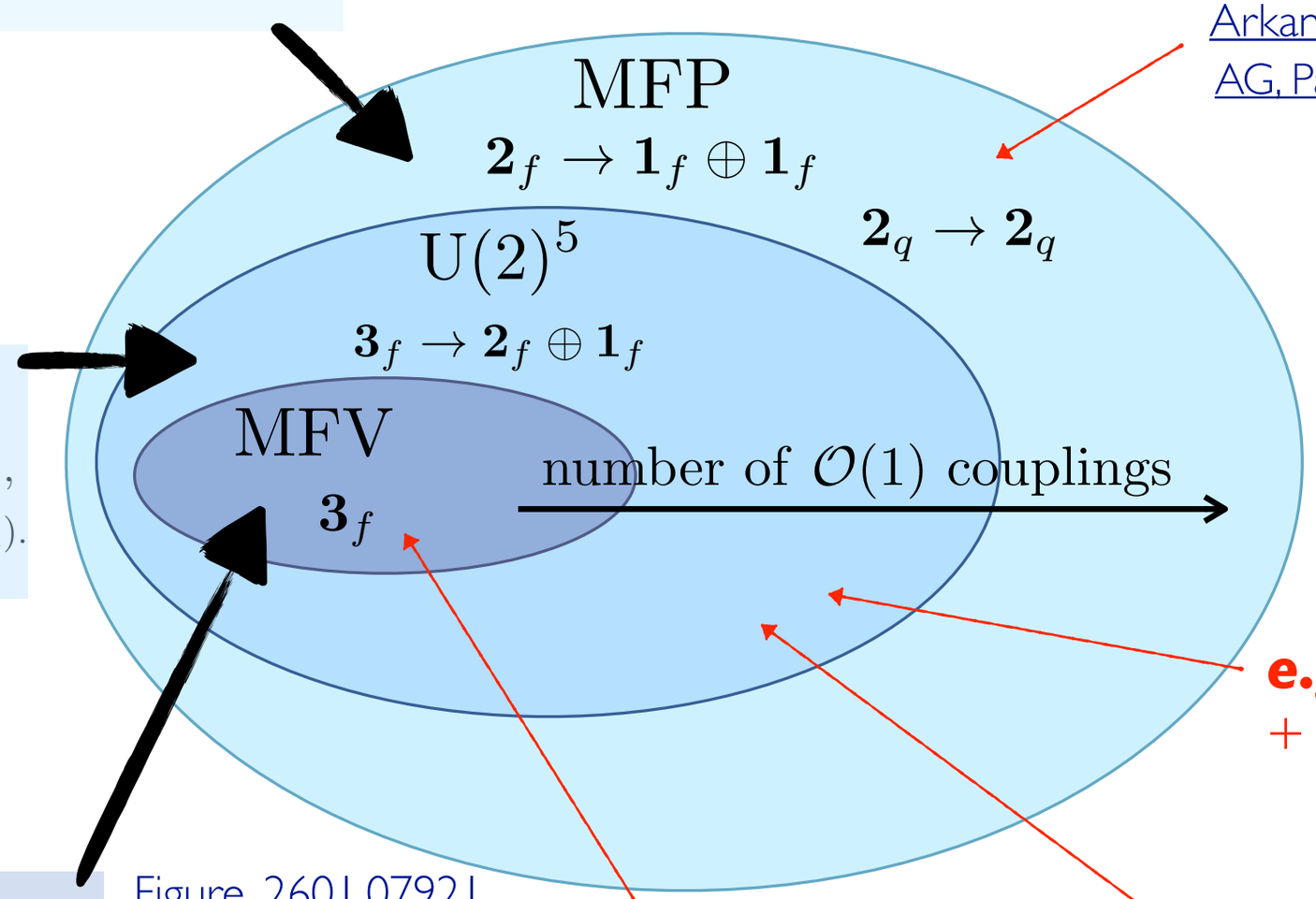
2512.04159

$$SU(2)_q \times (U(1)_X \subset U(1)^{14})$$

$$V \sim \mathbf{2}_{X_V}, \quad W \sim \mathbf{2}_{X_W}, \quad U \sim \mathbf{2}_{X_U}, \quad z \sim \mathbf{1}_{X_z}$$

UV models examples—

e.g. TeV chains of VLF
Arkani-Hamed et al, 2602.17754
AG, Palavric, Stefanek, 2512.04159



Figure, 2601.07921

1105.2296

$$U(2)^5$$

$$V_q \sim \mathbf{2}_q, \quad \Delta_u \sim (\mathbf{2}_q, \overline{\mathbf{2}}_u),$$
$$\Delta_d \sim (\mathbf{2}_q, \overline{\mathbf{2}}_d), \quad \Delta_e \sim (\mathbf{2}_\ell, \overline{\mathbf{2}}_e).$$

hep-ph/0207036

$$U(3)^5$$

$$Y_u \sim (\mathbf{3}_q, \overline{\mathbf{3}}_u), \quad Y_d \sim (\mathbf{3}_q, \overline{\mathbf{3}}_d),$$
$$Y_e \sim (\mathbf{3}_\ell, \overline{\mathbf{3}}_e)$$

e.g. Flavor Deconstruction + Composite Higgs
Davighi, Isidori, 2512.19650

e.g. gauge mediation SUSY with high-scale FN
Λ_F imprints washed out

e.g. SUSY GUT with
$\mathrm{SU}(5)_{\mathrm{GUT}} \times \mathrm{SU}(2)_{\mathbf{10}}$
gravity mediation
Antusch et al, 2311.09288

VLF chains @ Tera Z

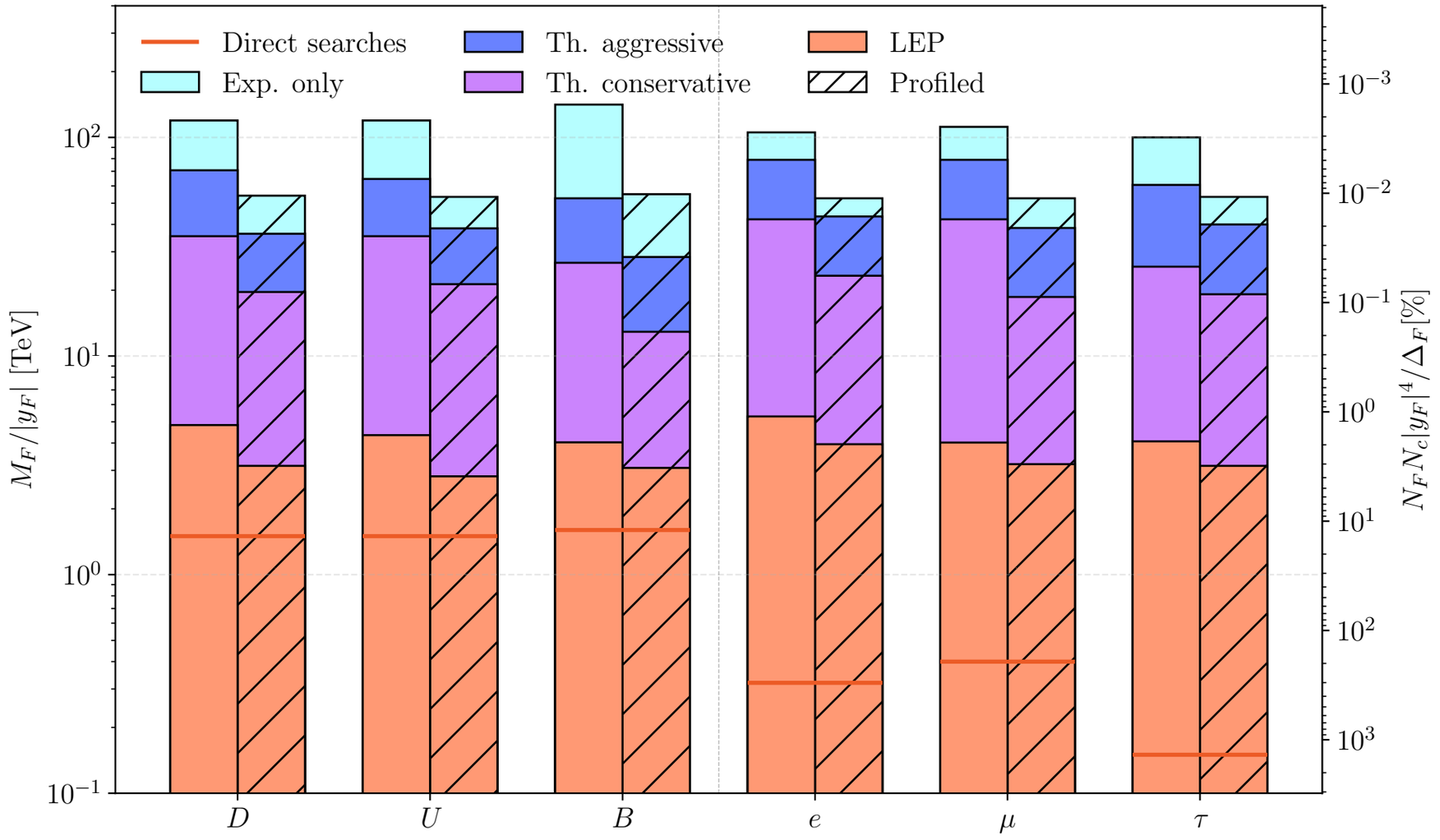
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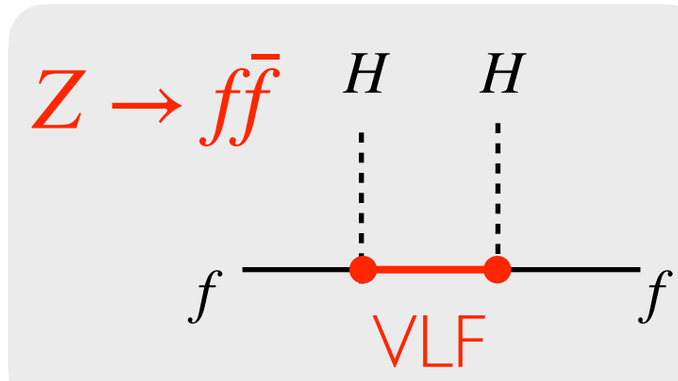
Arkani-Hamed et al, 2602.17754

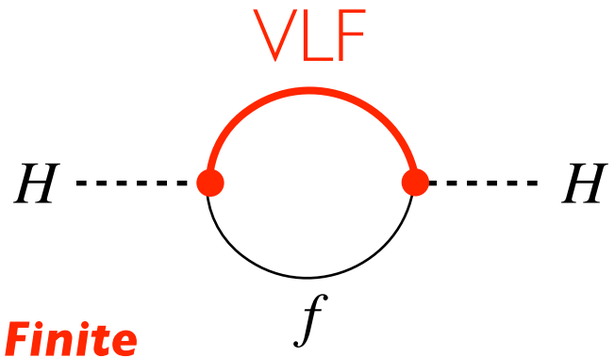
AG, Palavric, Stefanek, 2512.04159

Where to look for TeV-scale chains producing flavor hierarchies?



AG, Ponce Díaz, Schöneweiß, wip.





Finite naturalness

Now $1 \to 10^{-3}$ FCC-ee

Summary

- Flavored EFT Landscape

Take home

— experimentalist's take home

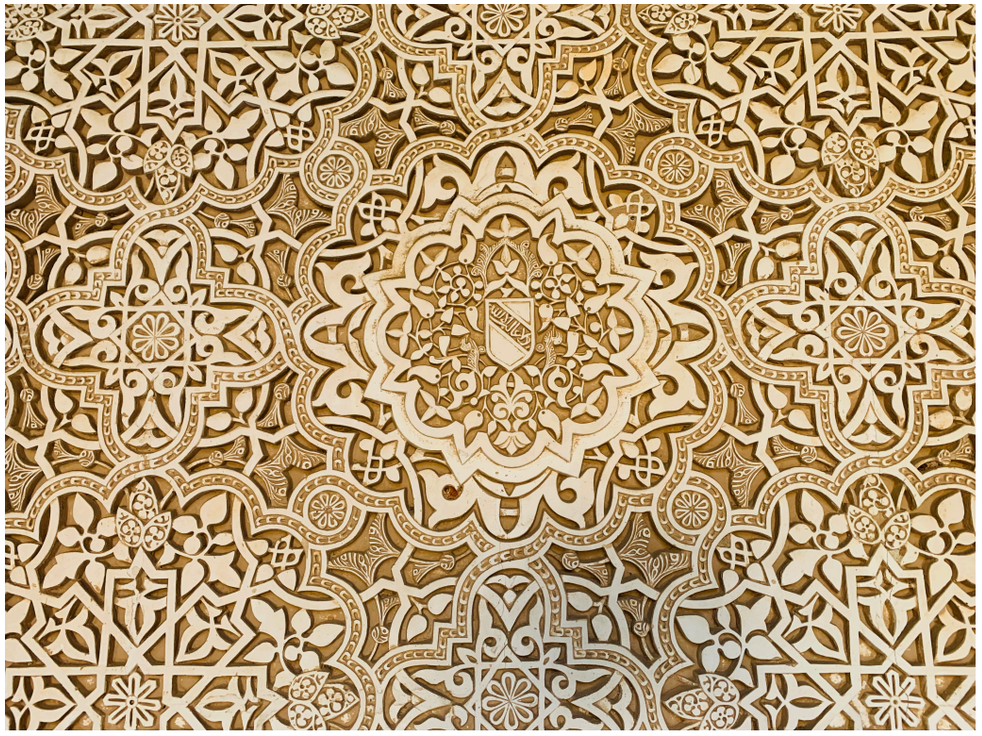
MFP: interpretation framework across scales!

— *Maximal Universality Violation*
— *Flavor-Charged Currents*

— theorist's take home:

MFP opens new model building directions

— *A model of flavor at the TeV scale?*



Alhambra of **Granada**

Thank you!

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Backup

AG, Palavric, Stefanek, 2512.04159

chain of thought...

Step 1: establish minimal algebra

$$SU(2)_q$$

Q: Can a single $U(1)_q$ work?

$$(c_1 - c_2)^2 \lambda^2 (\bar{q}_1 \gamma^\mu q_2)^2$$

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

K & D mixing (Cabbibo $\lambda \approx 0.2$*)*

$\Longrightarrow SU(2)_q$ is unavoidable

$$q \equiv (q_1, q_2)^T \oplus q_3$$

$\mathbf{1} \oplus \mathbf{1} \oplus \mathbf{1}$, $\mathbf{2} \oplus \mathbf{1}$, ✓ or $\mathbf{3}$. ✗

$$\sum_{a,b=1}^{3} (\bar{q}_a \gamma_\mu q_b)(\bar{q}_a \gamma^\mu q_b)$$

K- or D-meson mixing

Q: What is actually needed?

binary tetrahedral group

$$2T/Z_2 \simeq A_4, \qquad 2T \subset SU(2), \qquad |2T| = 24$$

AG, Palavric, Stefanek, 2512.04159

chain of thought...

Step 1: establish minimal algebra

$$SU(2)_q \times U(1)_X$$

Q: Can a single $U(1)_q$ work?

$$(c_1 - c_2)^2 \lambda^2 (\bar{q}_1 \gamma^\mu q_2)^2$$

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K & D mixing (Cabbibo $\lambda \approx 0.2$)

$\Longrightarrow SU(2)_q$ is unavoidable

$$q \equiv (q_1, q_2)^T \oplus q_3$$

$\mathbf{1} \oplus \mathbf{1} \oplus \mathbf{1}$, $\mathbf{2} \oplus \mathbf{1}$, or $\mathbf{3}$.

Q: Can a single $SU(2)_q$ work?

Other fields must be singlets of $SU(2)_q$

Otherwise, unsuppressed flavor transfers

$\Longrightarrow$ extra $U(1)_X$ symmetry needed

$$\sum_{A=1}^{3} (\bar{q}\gamma_\mu t^A q)(\bar{\ell}\gamma^\mu t^A \ell) \longrightarrow (\bar{q}_1\gamma_\mu q_2)(\bar{\ell}_2\gamma^\mu \ell_1)$$

$$\boxed{K_L \to \mu e}$$

$$\sum_{A=1}^{3} (t^A)_{ij}(t^A)_{kl} = \frac{1}{2}\delta_{il}\delta_{jk} - \frac{1}{4}\delta_{ij}\delta_{kl}$$

AG, Palavric, Stefanek, 2512.04159

chain of thought...

Step 2: establish fermion irreps under $SU(2)_q \times U(1)_X$

LH quarks

$$\mathbf{3}_{x_q} \to \mathbf{2}_{x_q} \oplus \mathbf{1}_{x_{q_3}} \,,$$

Other $f = u, d, \ell, e$

$$\mathbf{3}_{x_f} \to \mathbf{1}_{x_{f_1}} \oplus \mathbf{1}_{x_{f_2}} \oplus \mathbf{1}_{x_{f_3}}$$

$SU(2)_q$ embedding is unique!

$$\implies \quad q = (q_1, q_2)^T \sim \mathbf{2}, \quad u, d, \ell, e \sim \mathbf{1} \oplus \mathbf{1} \oplus \mathbf{1},$$

$U(1)_X$ is not:

$x_{f_1} \neq x_{f_2} \neq x_{f_3}$ + other conditions

AG, Palavric, Stefanek, 2512.04159

chain of thought...

Step 2: establish fermion irreps under $SU(2)_q \times U(1)_X$

LH quarks

$$\mathbf{3}_{x_q} \to \mathbf{2}_{x_q} \oplus \mathbf{1}_{x_{q_3}} ,$$

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$$\mathbf{3}_{x_f} \to \mathbf{1}_{x_{f_1}} \oplus \mathbf{1}_{x_{f_2}} \oplus \mathbf{1}_{x_{f_3}}$$

$SU(2)_q$ embedding is unique!

$$\implies \quad q = (q_1, q_2)^T \sim \mathbf{2}, \quad u, d, \ell, e \sim \mathbf{1} \oplus \mathbf{1} \oplus \mathbf{1},$$

$U(1)_X$ is not:

$$x_{f_1} \neq x_{f_2} \neq x_{f_3} + \text{other conditions}$$

Step 3: establish minimal spurion sector with flavor protection

- Higher-spin irreps produce large FCNCs $\implies$ spurions are doublets or singlets AG, Valenti, 2605.15267
- At least three doublets are needed for the CKM phase: $J = \mathfrak{I}[(V^\dagger W)(W^\dagger U)(U^\dagger V)]$
- Plus a singlet for the lepton mass hierarchies: $(y_e, y_\mu, y_\tau) \sim (z^3, z^2, z)$

Spurions: $\quad z \sim \mathbf{1}_{X_z}, \quad V \sim \mathbf{2}_{X_V}, \quad W \sim \mathbf{2}_{X_W}, \quad U \sim \mathbf{2}_{X_U}$

Maximal Flavor Universality Violation

Operator class	$U(1)^{15}$		$U(1)^{14}$		$SU(2)_q \times U(1)^{13}$		$SU(2)_q \times U(1)_X$	
CP	even	odd	even	odd	even	odd	even	odd
Bosonic	9	6	9	6	9	6	9	6
$\psi^2 H^3$	–	–	1	1	1	1	1	1
$\psi^2 X H$	–	–	3	3	3	3	3	3
$\psi^2 H^2 D$	21	–	21	–	19	–	20	1
$(\bar{L}L)(\bar{L}L)$	45	–	45	–	31	–	32	1
$(\bar{R}R)(\bar{R}R)$	60	–	60	–	60	–	61	1
$(\bar{L}L)(\bar{R}R)$	72	–	72	–	57	–	58	1
$(\bar{L}R)(\bar{R}L)$	–	–	–	–	–	–	1	1
$(\bar{L}R)(\bar{L}R)$	–	–	–	–	–	–	–	–
Total	**207**	**6**	**211**	**10**	**180**	**10**	**185**	**15**

The FUV is robust under the $U(1)_X$ charge choices:
— it originates mostly from $SU(2)_q \times U(1)^{13}$

MFP: an ultimate interpretation framework for FUV

TeV-scale Fermion Chains

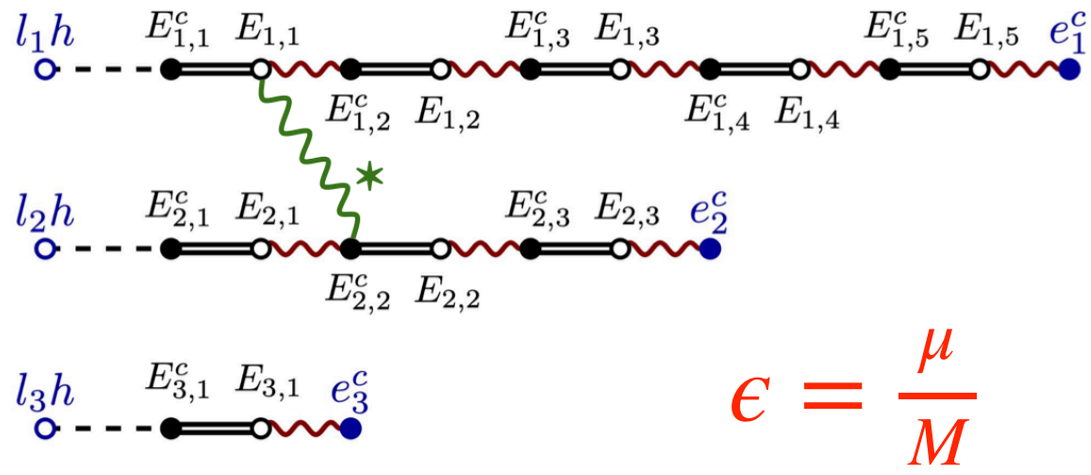
A model of Flavor Hierarchies entirely at the TeV scale

Arkani-Hamed, Figueiredo, Hall, Manzari; 2602.17754

$$
\begin{bmatrix} E_{1,1} \\ E_{1,2} \\ \vdots \\ E_{1,5} \\ l_1 h \\ \hline E_{2,1} \\ \vdots \\ l_2 h \\ \hline E_{3,1} \\ l_3 h \end{bmatrix}^T
\begin{bmatrix} M & \mu & 0 & \cdots & 0 \\ 0 & M & \mu & 0 & \vdots \\ \vdots & \ddots & \ddots & \ddots & 0 \\ & \cdots & 0 & M & \mu \\ \hat{\lambda}_1 & 0 & \cdots & 0 & 0 \end{bmatrix}
\begin{bmatrix} M & \mu & 0 & 0 \\ 0 & M & \mu & 0 \\ 0 & 0 & M & \mu \\ \hat{\lambda}_2 & 0 & 0 & 0 \end{bmatrix}
\begin{bmatrix} M & \mu \\ \hat{\lambda}_3 & 0 \end{bmatrix}
$$

1^{st} chain, 2^{nd} chain, 3^{rd} chain

$$
\begin{bmatrix} 0 & * & 0 & 0 & 0 & 0 \\ & & & & & \\ & & \mathbf{0} & & & \mathbf{0} \\ & & & & & \\ & & & & & \\ & & \mathbf{0} & & & \mathbf{0} \end{bmatrix}
\begin{bmatrix} E^c_{1,1} \\ E^c_{1,2} \\ \vdots \\ E^c_{1,5} \\ e^c_1 \\ \hline E^c_{2,1} \\ \vdots \\ e^c_2 \\ \hline E^c_{3,1} \\ e^c_3 \end{bmatrix}
$$



$$\epsilon = \frac{\mu}{M}$$

Achieves

- Hierarchies $y_{ij} \sim \left(\frac{\mu}{M}\right)^{n_{ij}}$
- Flavor protection when integrating out the proposed chains

Two key questions

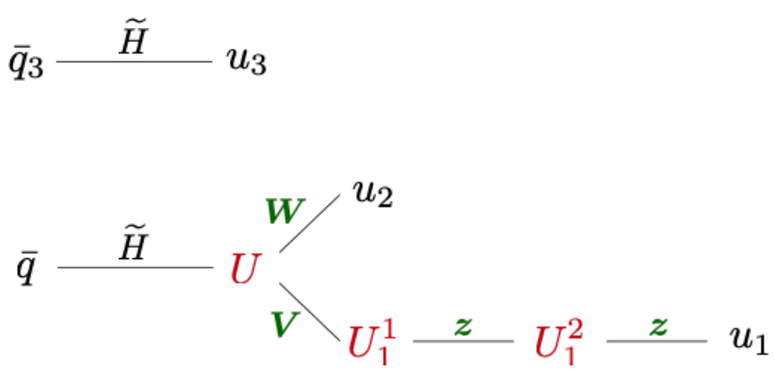
1. What controls "zeros"?
2. Flavor-protection if extra TeV-scale dynamics?

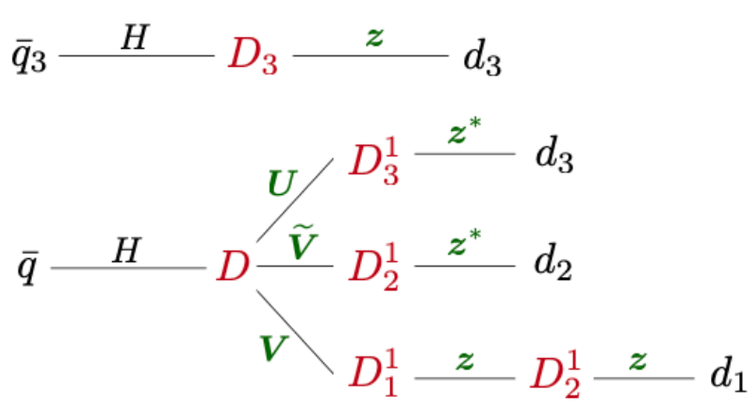
→ **MFP**

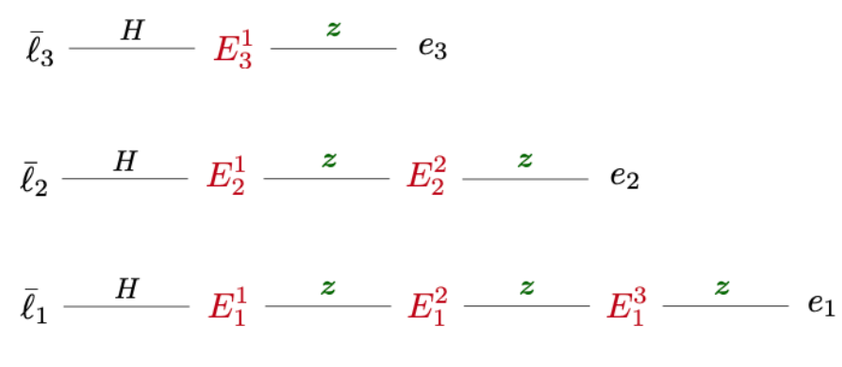
TeV-scale Fermion Chains

The MFP realisation:

AG, Palavric, Stefanek; 2512.04159







A proto-model of flavor at the TeV scale

$SU(2)_q \times U(1)_X$ softly broken by mass mixings

$\mu = M \cdot x$, with spurions $x = V, W, U, z$

The MFP guarantees flavor protection, even in the presence of extra dynamics!

Comment 1

MFP: UV-dependence?

- The assumption is SMEFT, with all $c_{\mathcal{O}} \sim 1$ but for the flavor suppression.

- Extra power counting in specific setups?

- Specific dynamics imply additional selection rules: e.g. loops in MSSM

- Example of specific dynamics:
  - Partial Compositeness (Glioti, Rattazzi, Ricci, Vecchi; 2402.09503).

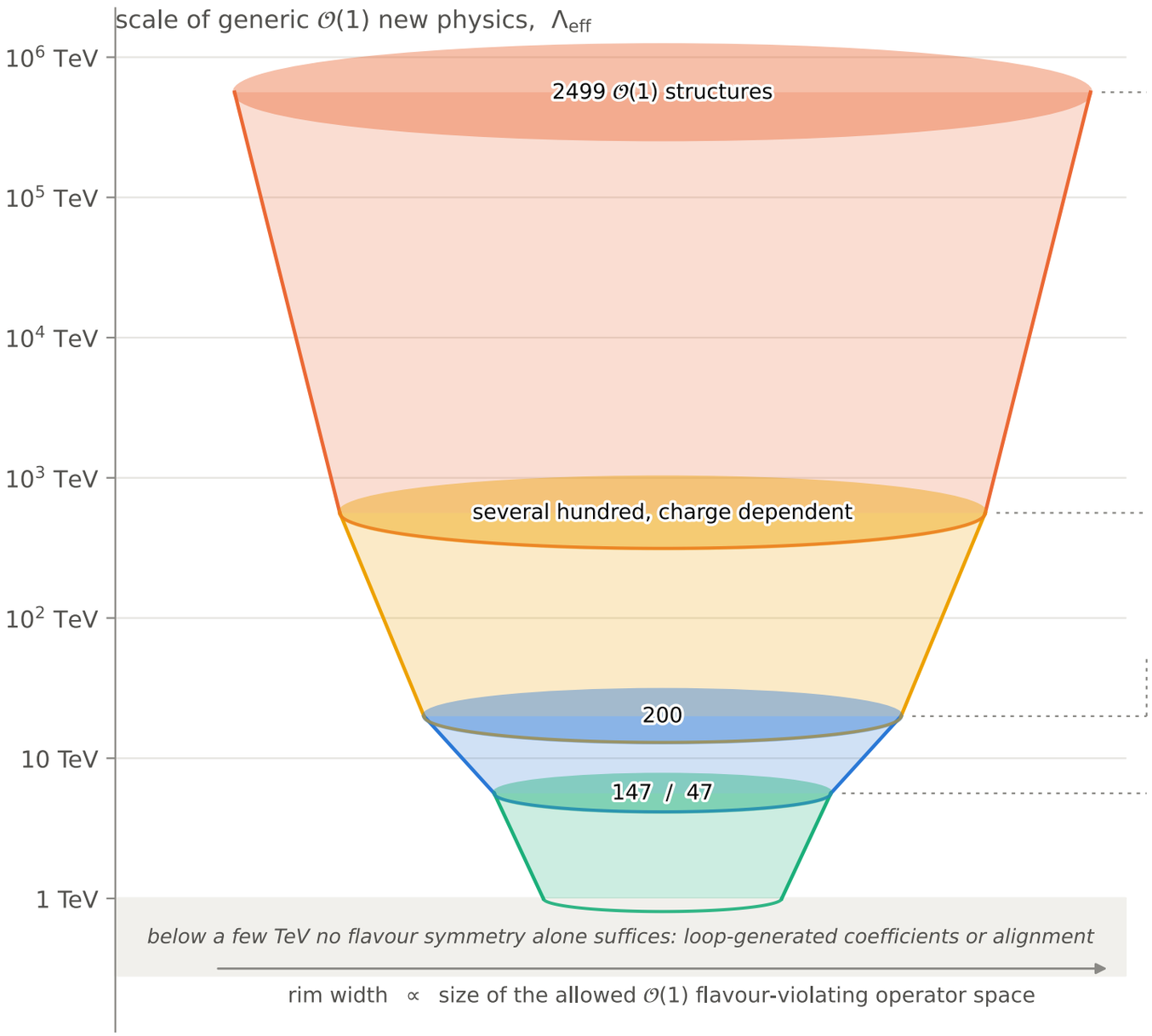
- MFP is a conservative boundary?

- MFP for specific UV dynamics is a subgroup?

MFP Ladder

How much flavour symmetry must new physics respect?

The minimal protecting symmetry is a function of the scale: each rim marks the scale down to which that symmetry, with generic order-one coefficients, is enough.



Anarchy

ε_K, $\mu \to e\gamma$ push generic physics to $10^{5\text{-}6}$ TeV

$U(1)_{\text{FN}}$ (optimised charges)

K and D mixing through the Cabibbo rotation: $10^{2\text{-}3}$ TeV

MFP: $SU(2)_q \times U(1)_X$

ε_K (LR octet), $\mu \to e$ conversion, $\mu \to e\gamma$: 15–20 TeV

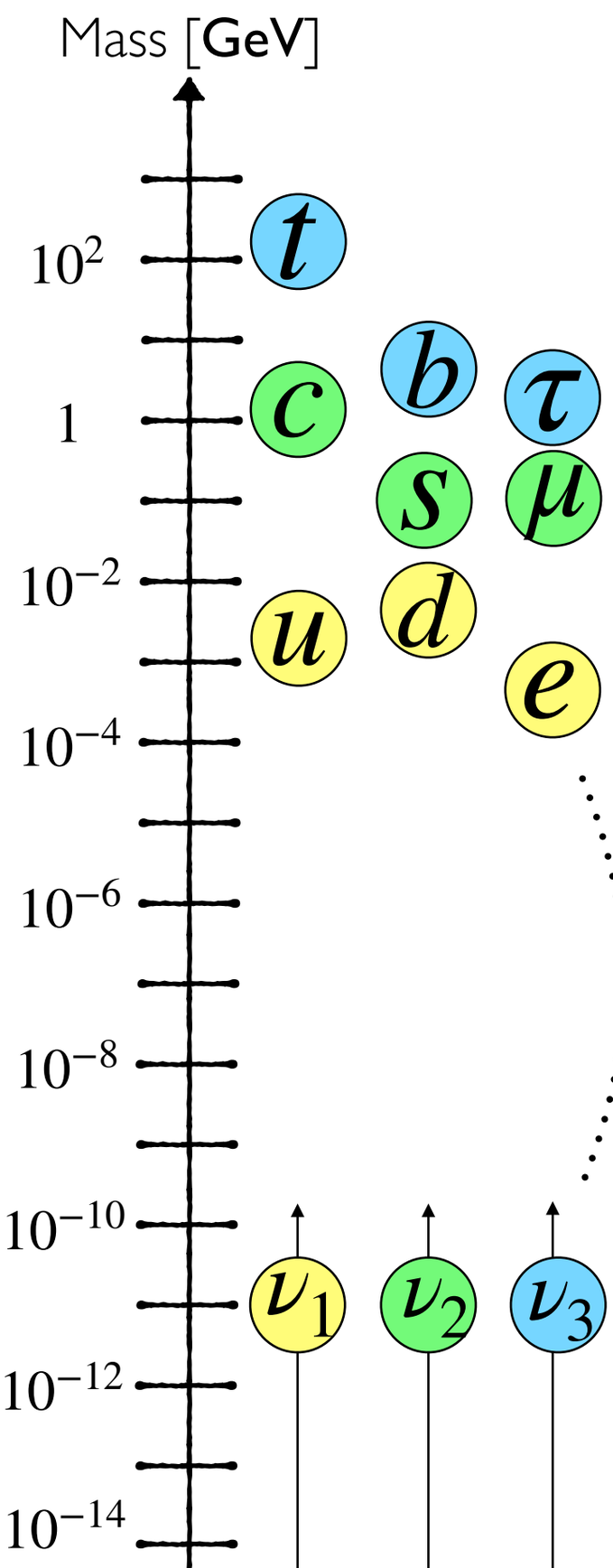
$U(2)^5$ ($\times U(1)_{b_R} \times U(1)_{\tau_R}$), MFV

$(V_{td}V_{ts})^2$ in ε_K, $b \to s\gamma$, $B_s \to \mu\mu$: 5–8 TeV

tiers are ordered by the size of the operator space, not by group inclusion

SM flavor puzzle

A recent review: 2412.04549



?

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

$$-\mathcal{L}_{\text{SMEFT}} \supset \frac{1}{\Lambda_\nu} \ell_i Y_\nu^{ij} \ell_j H H \qquad \Delta L = 2$$

$$Y_\nu \sim \mathbf{6}_\ell$$

Very different?!

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

CPV? stay tuned

Comment 2

Neutrinos in MFP

AG, Palavric, Stefanek, 2512.04159

- Selection rules on the Weinberg operator: $\frac{c_{ij}}{\Lambda}\ell_i\ell_j H H$
- c_{ij} never populated by z when: $(X_i + X_j) \bmod X_z \neq 0 \quad \forall\, i,j$
- c_{ij} populated at $\mathcal{O}(s^2)$ when:

$$|X_i + X_j| = \left|[\boldsymbol{a}^\dagger \boldsymbol{b}] \text{ or } [\boldsymbol{a}^\dagger \widetilde{\boldsymbol{b}}]\right| \quad \forall\, i,j\,,$$
$$\boldsymbol{a}^\dagger \boldsymbol{b} \text{ or } \boldsymbol{a}^\dagger \widetilde{\boldsymbol{b}},\ \text{with } \boldsymbol{a},\boldsymbol{b} \in \{\boldsymbol{V},\boldsymbol{W},\boldsymbol{U}\} \text{ and } \boldsymbol{a} \neq \boldsymbol{b}$$

Benchmark charges:
$c_{ij} \sim s^2$, only $c_{22} \sim s^3$ ✓

- Since ***all*** $s = v, w, u, z \sim 10^{-2}$, neutrino ***anarchy*** is predicted!
- Large PMNS! Also, $\Lambda \sim O(10^{11})\,\mathbf{GeV}$ from m_ν.
- $U(2)^5$ inevitably introduces a hierarchy in c_{ij} to be "undone" in a model.

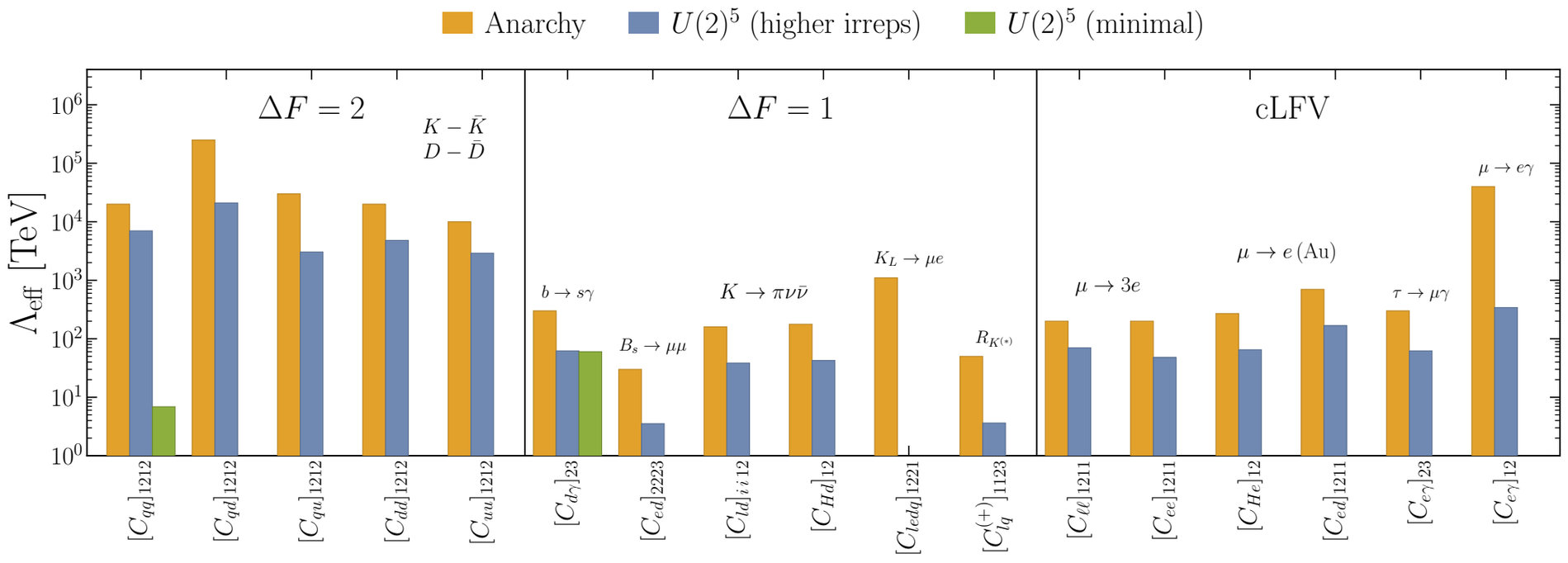
AG, Isidori, 2406.01696

CPV?

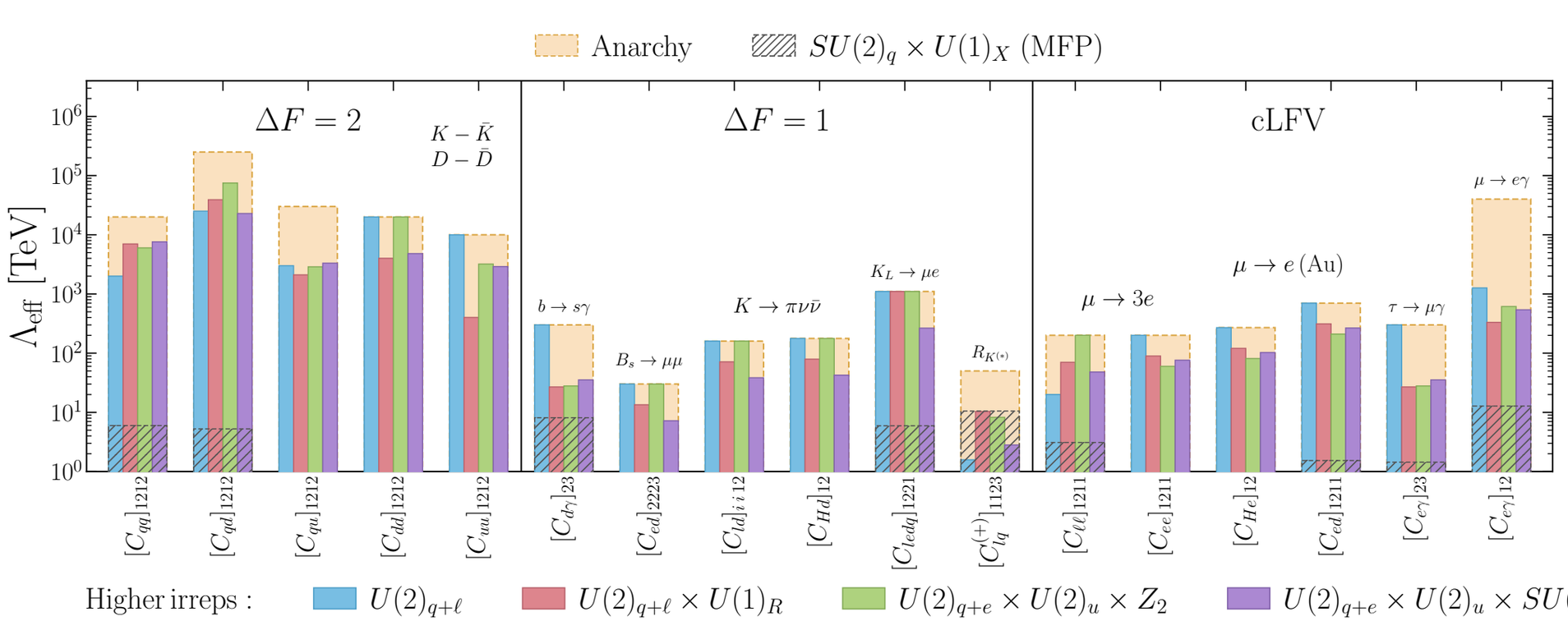
$$\{X_V, X_W, X_U, X_z\} = \{1, -2, -3, 7\}\,,$$
$$\{X_1, X_2, X_3\} = \{-2, -3, -1\}\,.$$

- CP is assumed to be broken by $\boldsymbol{U}$ spurion only
  ($U(3)^5$ also needs CP)
  $\Longrightarrow$ An assumption only important for EDMs:

Operator	Order	Invariants
$[Q_{e(B,W)}]_{11}$	$\mathcal{O}(\boldsymbol{UV^2Wz^2})$	$\boldsymbol{z^2(U^\dagger V)(W^\dagger V)}[Q_{e(B,W)}]_{11}$
	$\mathcal{O}(\boldsymbol{U^2VWz^2})$	$\boldsymbol{z^2}(\varepsilon^{ac}\boldsymbol{U}^\dagger_a\boldsymbol{V}^\dagger_c)(\varepsilon^{bd}\boldsymbol{U}^\dagger_b\boldsymbol{W}^\dagger_d)[Q_{e(B,W)}]_{11}$
$[Q_{u(B,W,G)}]_{11}$	$\mathcal{O}(\boldsymbol{U^2Wz})$	$\boldsymbol{z}(\varepsilon^{ab}\boldsymbol{U}^\dagger_b)(\varepsilon^{cd}\boldsymbol{U}^\dagger_c\boldsymbol{W}^\dagger_d)[Q_{u(B,W,G)}]_{a1}$
$[Q_{d(B,W,G)}]_{11}$	$\mathcal{O}(\boldsymbol{U^2Wz})$	$\boldsymbol{z}(\varepsilon^{ab}\boldsymbol{U}^\dagger_b)(\varepsilon^{cd}\boldsymbol{U}^\dagger_c\boldsymbol{W}^\dagger_d)[Q_{d(B,W,G)}]_{a1}$
$[Q^{(1,3)}_{\ell equ}]_{1133}$	$\mathcal{O}(\boldsymbol{UV^2Wz^2})$	$\boldsymbol{z^2(U^\dagger V)(W^\dagger V)}[Q^{(1,3)}_{\ell equ}]_{1133}$
	$\mathcal{O}(\boldsymbol{U^2VWz^2})$	$\boldsymbol{z^2}(\varepsilon^{ac}\boldsymbol{U}^\dagger_a\boldsymbol{V}^\dagger_c)(\varepsilon^{bd}\boldsymbol{U}^\dagger_b\boldsymbol{W}^\dagger_d)[Q^{(1,3)}_{\ell equ}]_{1133}$



(a) Bounds in the anarchic scenario, in $U(2)^5$ with higher-irrep spurions, and in traditional $U(2)^5$.



(b) Bounds in the anarchic scenario, in the higher-irreps models of section 3, and in traditional $SU(2)_q \times U(1)_X$ (MFP).

AG, Valenti, 2605.15267

MFP: Alignment

$$Y_u = \begin{pmatrix} \boldsymbol{V}\boldsymbol{z}^2 & \boldsymbol{W} & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad Y_d = \begin{pmatrix} \boldsymbol{V}\boldsymbol{z}^2 & \widetilde{\boldsymbol{V}}\boldsymbol{z}^* & \boldsymbol{U}\boldsymbol{z}^* \\ 0 & 0 & \boldsymbol{z} \end{pmatrix} \qquad Y_e = \begin{pmatrix} \boldsymbol{z}^3 & 0 & 0 \\ 0 & \boldsymbol{z}^2 & 0 \\ 0 & 0 & \boldsymbol{z} \end{pmatrix}$$

One needs to ensure that this form is sufficiently preserved since
Non-universality + Rotations = Flavor violation

1. **Alignment conditions for quark and charged lepton Yukawas**

(a) Demanding a zero in Y_d^{31} up to third order leads to the following conditions: $X_U - 4X_z - X_V \neq \{0, \pm X_z, \pm 2X_z, \pm(X_a \pm X_b)\}$ where $a \neq b$, and $a, b = \{U, V, W\}$. Note that $\boldsymbol{a}^\dagger \boldsymbol{b}$ and $\boldsymbol{a}^\dagger \widetilde{\boldsymbol{b}}$ form $SU(2)_q$ singlets.

(b) Demanding a zero in Y_d^{32} up to third order leads to the following conditions: $X_U - X_z + X_V \neq \{0, \pm X_z, \pm 2X_z, \pm(X_a \pm X_b)\}$ where $a \neq b$, and $a, b = \{U, V, W\}$.

(c) Demanding a zero in Y_d^{12} up to third order leads to the following conditions: $X_V + X_z \neq \{0, \pm X_a, \pm(X_a \pm X_z)\}$ where $a = \{U, V, W\}$ and excluding $\widetilde{\boldsymbol{V}}\boldsymbol{z}^*$.

(d) Demanding a zero in $Y_{d,u}^{21}$ up to fourth order leads to the following conditions: $X_V + 2X_z \neq \{0, \pm X_a, \pm(X_a \pm X_z), \pm(X_a \pm 2X_z), \pm(X_a \pm X_b \pm X_c)\}$ where $a, b, c = \{U, V, W\}$ and $a \neq b$.

(e) Demanding a zero in $Y_e^{12,21}$ up to fourth order leads to the following conditions: $X_2 - X_1 - 2X_z$ and $X_1 - X_2 - 3X_z \neq \{0, z, z^2, z^3, \pm(X_a \pm X_b), \pm(X_a \pm X_b \pm X_z)\}$ where $a \neq b$ and $a, b = \{U, V, W\}$.

MFP: Spurion restrictions

++ Direct spurion insertions in higher-dim operators also restrict $U(1)_X$ charges!

2. Conditions for $\Delta F = 2$ spurion insertions

(a) For $[Q_{qd}]_{1212}$ and $[Q_{qu}]_{1212}$ operators to be forbidden at quadratic level in spurions

$$|X_a \pm X_b| \neq |2X_V + 3X_z|\,, \qquad |X_a \pm X_b| \neq |X_V + 2X_z - X_W|\,, \tag{S4}$$

should hold for $\forall a, b \in \{U, V, W\}$.

(b) For $[Q_{dd}]_{1212}$ and $[Q_{uu}]_{1212}$ operators to be allowed, we need the following number of $\boldsymbol{z}$ insertions

$$N = \left|6 + \frac{4X_V}{X_z}\right|, \qquad N = \left|4 + \frac{2(X_V - X_W)}{X_z}\right|, \tag{S5}$$

such that $N > 3$ or N is not an integer.

(c) For $[Q_{qd}]_{1212}$ and $[Q_{qu}]_{1212}$ operators of the form $\boldsymbol{abz}^N$ to be allowed, we need the following number of $\boldsymbol{z}$ insertions

$$N = \pm\left|\frac{X_a \pm X_b}{X_z}\right| \pm \left|3 + \frac{2X_V}{X_z}\right|, \qquad N = \pm\left|\frac{X_a \pm X_b}{X_z}\right| \pm \left|2 + \frac{(X_V - X_W)}{X_z}\right|, \tag{S6}$$

where for both conditions $\forall a, b \in \{U, V, W\}$. Passing the bounds requires either $|N| > 2$ (1) for qd (qu) or that N does not take an integer value. Configurations producing $N = 0$ can be ignored as they are covered by condition (a).