# Exploring the Flavor Symmetry Landscape

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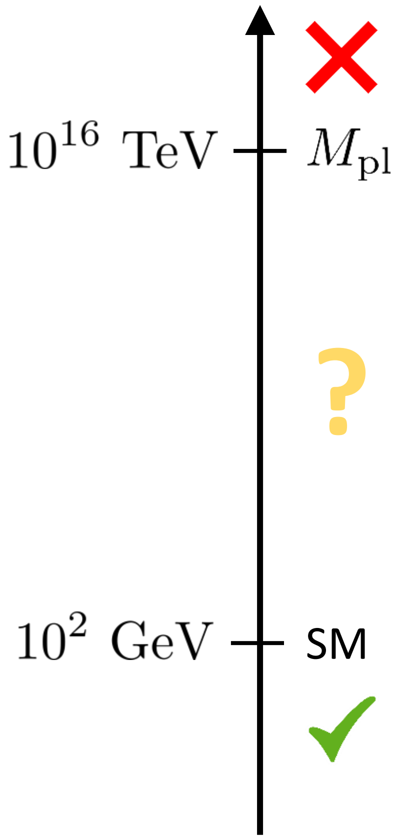
Based on **2402.09503**, AG, Riccardo Rattazzi, Lorenzo Ricci, Luca Vecchi

# New physics searches




Several things still missing from the SM: **gravity**, **dark matter**, **baryogenesis**, ….
Also no explanation for the SM structure and parameters
(e.g. flavor hierarchy, weak scale… )

**The SM is an EFT**

$$\mathcal{L} = \mathcal{L}^{d\leq 4} + \frac{1}{\Lambda}\mathcal{L}^{d=5} + \frac{1}{\Lambda^2}\mathcal{L}^{d=6} + \ldots$$

Standard Model

Possible deviations due to new **heavy** states

The **big question**: what is $\Lambda$?

$\Lambda$ = **High scale**

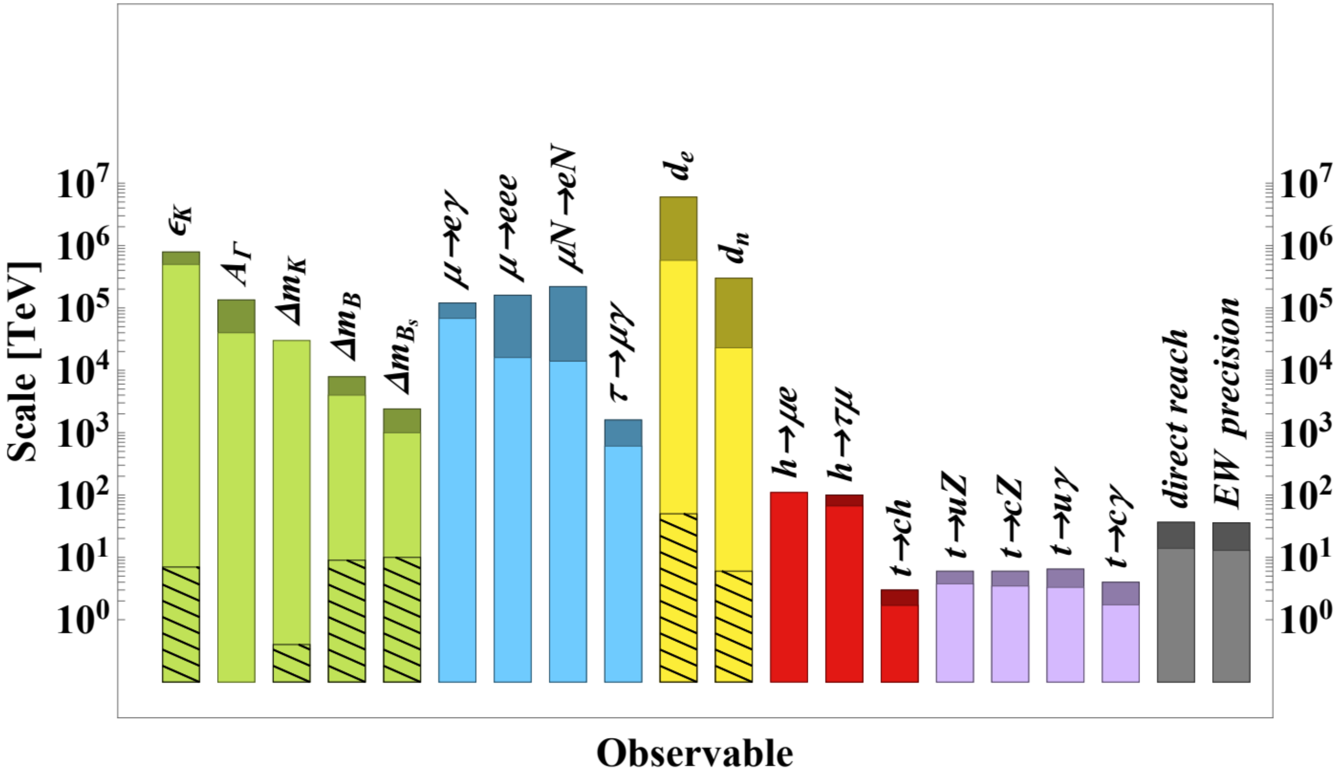
- All the SM "accidents" are natural
- But the weak scale becomes unnatural

$\Lambda$ = **TeV scale**

- Weak scale can be natural
- Needs a "clever" flavor structure to be consistent with precision tests

# Indirect probes

Precision measurements can indirectly probe scales much higher than the energies of colliders




However, $\Lambda$ is **NOT** the scale at which we will find new particles

The connection between $\Lambda$ and the mass can only be done through a concrete model of the UV physics

# Our workflow

UV Hypotheses ⟹ Observables consequences ⟹ Available parameter space

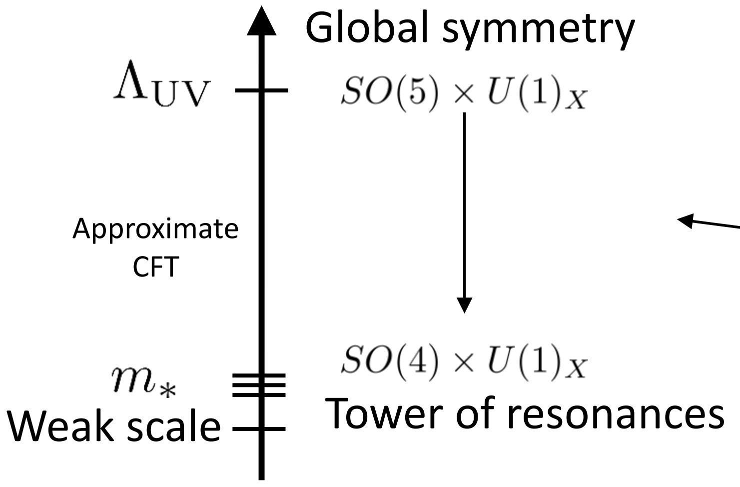
**What are the hypotheses that allow for physics at TeV?**

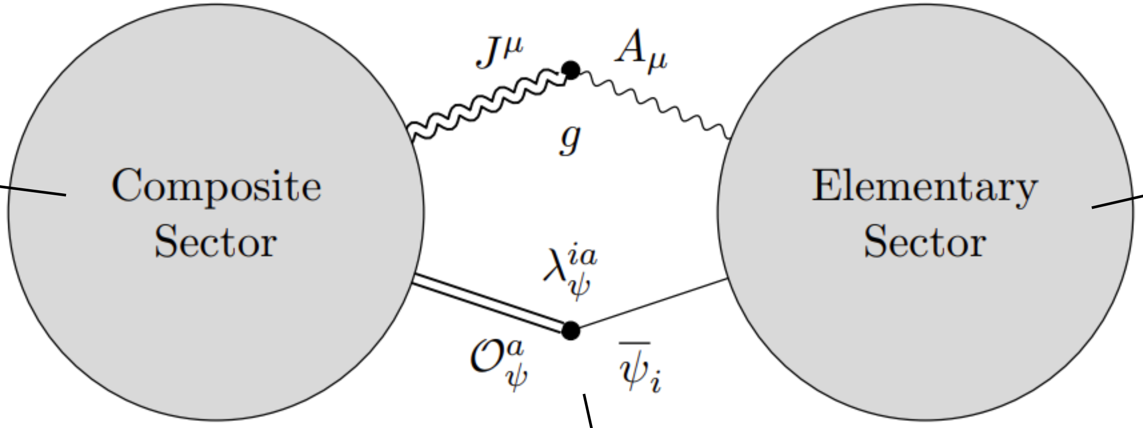
This can only be answered with a concrete model
Many BSM flavor models studied these last decades

Our choice: **Composite Higgs + Partial Compositeness**

Given the current (and near future) indirect bound, **what can be discovered by LHC / FCC**?

# Composite Higgs Review




All SM particles, except H

$U(3)^5$ global symmetry

**Two parameters**

**Mass**: $m_*$

**Coupling**: $g_{\mathrm{SM}} < g_* < 4\pi$

SO(5) → SO(4) spontaneously broken

Higgs is the lightest resonance, possibly a **Nambu-Goldstone boson**

The two sectors talk through:

1) Gauging
2) Fermion mixings

Contain **Yukawas** + **flavor and CP violation**

# Partial compositeness

The **Yukawas** come from the interactions between composite and elementary sector

**Two possibilities**

**Bilinear** (Technicolor-like)

$$\mathcal{L} \supset c\,\mathcal{O}_H^2 + y^{ij}\,\bar{\psi}_L^i \psi_R^j \mathcal{O}_H$$

Marginal

Irrelevant

Disfavored by CFT theorems

All Yukawa couplings become RG suppressed

**Linear mixing** (Partial compositeness)

$$\mathcal{L} \supset \lambda^{ij}\,\bar{\psi}^i \mathcal{O}_\psi$$

No bounds on anomalous dimension of *O*

$$\dim[\mathcal{O}_\psi] = 5/2 + \gamma_\psi$$

$$\lambda(m_*) \approx \lambda(\Lambda_{\rm UV}) \left(\frac{m_*}{\Lambda_{\rm UV}}\right)^{\gamma_\psi}$$

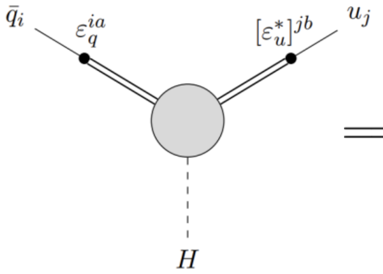
Can generate both small and large yukawas dynamically

# SILH Lagrangian

Putting together these hypotheses, one obtains a general effective Lagrangian

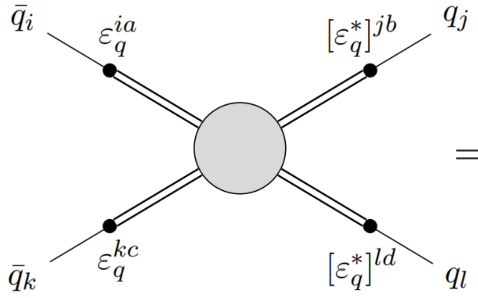
$$\mathcal{L}_{\rm EFT} = \mathcal{L}_{\rm SM'} + \frac{m_*^4}{g_*^2}\widehat{\mathcal{L}}_{\rm EFT}\left(\frac{g_* H}{m_*}, \frac{D_\mu}{m_*}, \frac{\lambda_\psi^{ia}\overline{\psi}^i}{m_*^{3/2}}, \frac{g_*^2}{16\pi^2}, \frac{g^2}{16\pi^2}, \frac{[\lambda_\psi^*]^{ia}\lambda_\psi^{ib}}{16\pi^2}\right),$$

Possible loop factors




$$\Longrightarrow\ Y_u^{ij} = g_*\varepsilon_q^{ia}c_{ab}[\varepsilon_u^*]^{jb}$$

Unknown O(1) factors




$$\Longrightarrow\ \frac{g_*^2}{m_*^2}c_{abcd}\varepsilon_q^{ia}[\varepsilon_q^*]^{jb}\varepsilon_q^{kc}[\varepsilon_q^*]^{ld}\bar{q}^i\gamma_\mu q^j\bar{q}^k\gamma^\mu q^l$$

$$\varepsilon_\psi \equiv \lambda_\psi/g_*$$

Fermion compositeness

# Bosonic Constraints

Before discussing flavor, main constraints from the bosonic sector

**Higgs couplings**

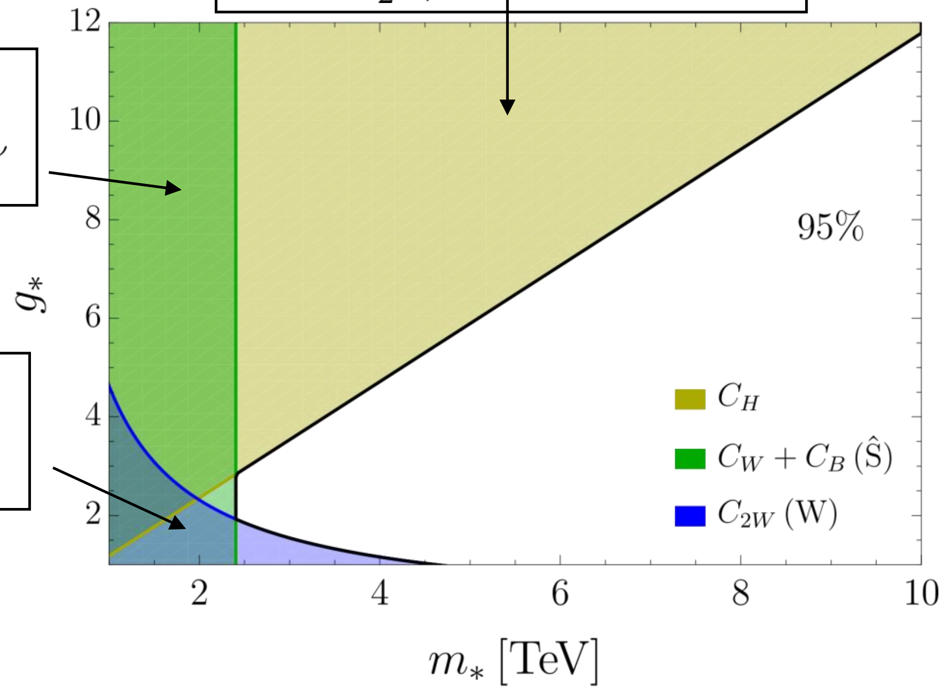
$$\mathcal{O}_H = \frac{1}{2}\partial_\mu(H^\dagger H)\partial^\nu(H^\dagger H)$$

**S parameter**

$$\mathcal{O}_W = i\frac{g}{2}\left(H^\dagger \overleftrightarrow{D}^a_\mu H\right) D_\nu W^{a\,\mu\nu}$$

**Drell-Yan (W parameter)**

$$\mathcal{O}_{2W} = \frac{g^2}{2}(D^\mu W^a_{\mu\nu})(D_\rho W^{a\rho\nu})$$




Less relevant

**T parameter**

$$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)\left(H^\dagger \overleftrightarrow{D}^\mu H\right)$$

Suppressed by custodial

$$H \to \gamma\gamma$$

$$\mathcal{O}_\gamma = H^\dagger H B_{\mu\nu} B^{\mu\nu}$$

Suppressed by NGB symmetry

# Flavor Anarchy

Anarchic partial compositeness: structureless O(1) flavor and CP violating coefficients

Can explain flavor hierarchies dynamically, but suffers from strong bounds…

**Leptons**

Electron EDM

$$m_* \gtrsim 2200 \frac{g_*}{4\pi}\,\mathrm{TeV}$$

$\mu \to e\,\gamma$

$$m_* \gtrsim 250 \frac{g_*}{4\pi}\,\mathrm{TeV}$$

**Quarks**

$\Delta F = 2$ & $b \to s\,\gamma$

$$m_* \gtrsim 20 - 30\,\mathrm{TeV}$$

D meson CP asymm

$$m_* \gtrsim 120 \frac{g_*}{4\pi}\,\mathrm{TeV}$$

Neutron EDM

$$m_* \gtrsim 40 - 60 \frac{g_*}{4\pi}\,\mathrm{TeV}$$

Even forgetting leptons, this leads to a large Higgs mass tuning $\frac{g_*^2 v^2}{m_*^2} \sim 10^{-3}$

**Are there better scenarios?**

# Maximal Flavor Symmetry

Another possibility is assuming the maximal flavor symmetry structure in the strong sector that reproduces the Standard Model (focus on the quark sector)

$$\mathcal{L}_{\text{mix}} = \lambda^{ia}_{q_u} \overline{q}^i_L \mathcal{O}^a_{q_u} + \lambda^{ia}_{q_d} \overline{q}^i_L \mathcal{O}^a_{q_d} + \lambda^{ia}_{u} \overline{u}^i_R \mathcal{O}^a_{u} + \lambda^{ia}_{d} \overline{d}^i_R \mathcal{O}^a_{d},$$

For some models we need two different partners for the left quarks

Two sets of mixings: **Universal** = real and proportional to Identity, **Non-universal** = contain flavor- and CP- breaking

$$\mathcal{G}_{\text{strong}} \times \mathcal{G}_{\text{elem}} \times CP \to \mathcal{G}_{\text{F}} \times CP \to U(1)_B$$

Maximal Flavor Symmetry → Minimal Flavor Violation

# Right-Universality MFV

$$\mathcal{L}_{\rm mix} = \underbrace{\lambda^{ia}_{q_u}\bar{q}^i_L\mathcal{O}^a_{q_u} + \lambda^{ia}_{q_d}\bar{q}^i_L\mathcal{O}^a_{q_d}}_{\propto Y_\psi} + \underbrace{\lambda^{ia}_{u}\bar{u}^i_R\mathcal{O}^a_{u} + \lambda^{ia}_{d}\bar{d}^i_R\mathcal{O}^a_{d}}_{\propto \mathbf{1}},$$

$$\mathcal{G}_{\rm strong} = U(3)_U \times U(3)_D \quad \longrightarrow \quad \mathcal{G}_F \equiv U(3)_q \times U(3)_{U+u} \times U(3)_{D+d}$$

$$\text{RU}: \begin{cases} \lambda_{q_u} \sim \frac{1}{\varepsilon_u}\begin{pmatrix} y_u & 0 & 0 \\ 0 & y_c & 0 \\ 0 & 0 & y_t \end{pmatrix}, & \lambda_{q_d} \sim \frac{1}{\varepsilon_d} V_{\rm CKM}\begin{pmatrix} y_d & 0 & 0 \\ 0 & y_s & 0 \\ 0 & 0 & y_b \end{pmatrix}, \\ \lambda_u \sim g_*\begin{pmatrix} \varepsilon_u & 0 & 0 \\ 0 & \varepsilon_u & 0 \\ 0 & 0 & \varepsilon_u \end{pmatrix}, & \lambda_d \sim g_*\begin{pmatrix} \varepsilon_d & 0 & 0 \\ 0 & \varepsilon_d & 0 \\ 0 & 0 & \varepsilon_d \end{pmatrix}. \end{cases}$$

With $\frac{y_t}{g_*} \lesssim \varepsilon_u \lesssim 1 \qquad \frac{y_b}{g_*} \lesssim \varepsilon_d \lesssim 1$

$\epsilon \sim 1 \implies$ The "elementary" quarks are actually composite

# Left-Universality MFV

Alternatively, we could have Left-Universality

$$\boxed{\mathcal{L}_{\text{mix}} = \lambda_q^{ia} \overline{q}_L^i \mathcal{O}_q^a + \lambda_u^{ia} \overline{u}_R^i \mathcal{O}_u^a + \lambda_d^{ia} \overline{d}_R^i \mathcal{O}_d^a \,,}$$

$$\mathcal{G}_{\text{strong}} = U(3)_Q \longrightarrow \mathcal{G}_F = U(3)_{Q+q} \times U(3)_u \times U(3)_d$$

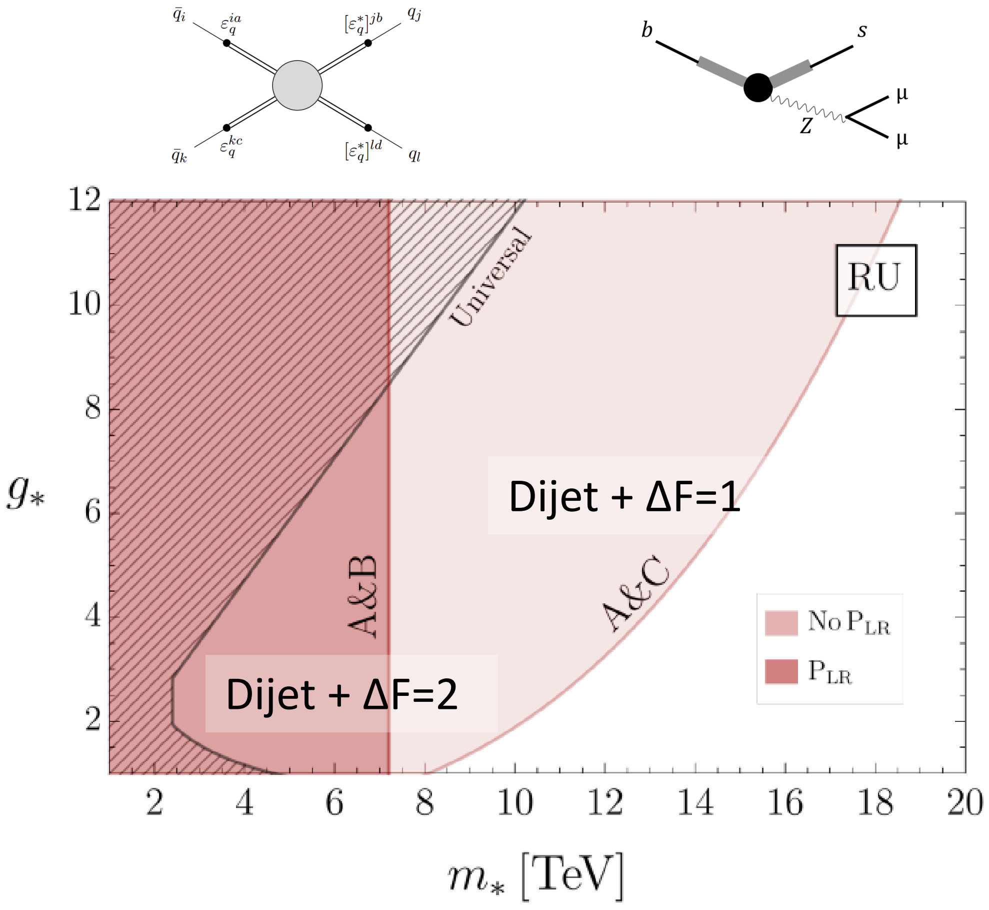
$$\text{LU}: \begin{cases} \lambda_q \sim \begin{pmatrix} \varepsilon_q & 0 & 0 \\ 0 & \varepsilon_q & 0 \\ 0 & 0 & \varepsilon_q \end{pmatrix} g_*, \\ \lambda_u \sim \frac{1}{\varepsilon_q} \begin{pmatrix} y_u & 0 & 0 \\ 0 & y_c & 0 \\ 0 & 0 & y_t \end{pmatrix}, \\ \lambda_d \sim \frac{1}{\varepsilon_q} \begin{pmatrix} y_d & 0 & 0 \\ 0 & y_s & 0 \\ 0 & 0 & y_b \end{pmatrix} V_{\text{CKM}}^\dagger \end{cases}$$

In this case there is a single ε parameter

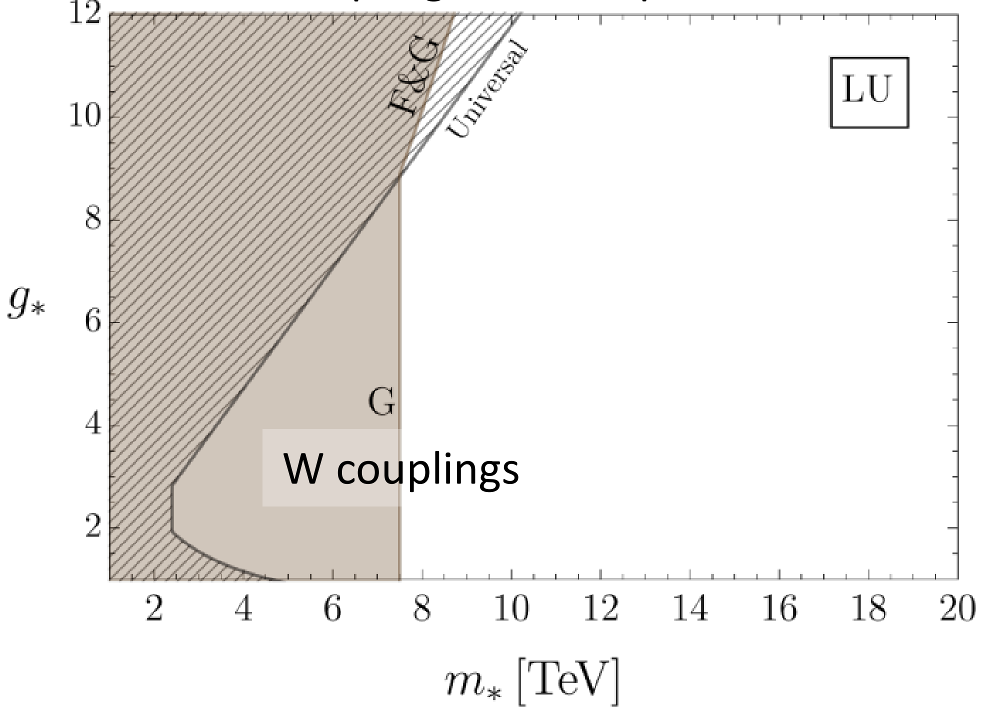
$$\boxed{\frac{y_t}{g_*} \lesssim \varepsilon_q \lesssim 1.}$$

Still MFV, but a completely different phenomenology than the right-handed counterpart

# MFV Recap




W couplings + b → s γ



# The flavor problem

**Anarchy**

Flavor explanation

Large tuning

Add more hypotheses

Add flavor symmetries

**Structured Models**

No flavor explanation

Smaller tuning

**How close to the TeV can Composite Higgs models be?**

**What’s in the middle between these two possibilities?**

- Smaller global symmetry group
- Adding LR global symmetry
- Dipoles at one loop

# Partial-up Right Universality

$$\boxed{\mathcal{L}_{\text{mix}} = \lambda^{ia}_{q_u}\bar{q}^i_L\mathcal{O}^a_{q_u} + \lambda^{ia}_{q_d}\bar{q}^i_L\mathcal{O}^a_{q_d} + \lambda^{ia}_{u}\bar{u}^i_R\mathcal{O}^a_{u} + \lambda^{ia}_{d}\bar{d}^i_R\mathcal{O}^a_{d},}$$

$$\mathcal{G}_{\text{strong}} = U(2)_U \times U(1)_U \times U(3)_D \longrightarrow \mathcal{G}_F = U(3)_q \times U(2)_{U+u} \times U(1)_{U+u} \times U(3)_{D+d}$$

$\sim V_{\text{CKM}}$

$$\text{puRU}: \begin{cases} \lambda_{q_u} \sim \frac{1}{\varepsilon_u}\begin{pmatrix} y_u & 0 \\ 0 & y_c \\ a y_c & b y_c \end{pmatrix} \oplus \frac{1}{\varepsilon_{u3}}\begin{pmatrix} 0 \\ 0 \\ y_t \end{pmatrix}, \quad \lambda_{q_d} \sim U_d \frac{1}{\varepsilon_d}\begin{pmatrix} y_d & 0 & 0 \\ 0 & y_s & 0 \\ 0 & 0 & y_b \end{pmatrix}, \\ \lambda_u \sim g_*\begin{pmatrix} \varepsilon_u & 0 \\ 0 & \varepsilon_u \\ 0 & 0 \end{pmatrix} \oplus g_*\begin{pmatrix} 0 \\ 0 \\ \varepsilon_{u3} \end{pmatrix}, \quad \lambda_d \sim g_*\begin{pmatrix} \varepsilon_d & 0 & 0 \\ 0 & \varepsilon_d & 0 \\ 0 & 0 & \varepsilon_d \end{pmatrix}. \end{cases}$$

$$Y_u \sim \lambda_{q_u}\lambda_u^\dagger/g_*,\ Y_d \sim \lambda_{q_d}\lambda_d^\dagger/g_*$$

1st,2nd generations are separated from the 3rd in the up-sector

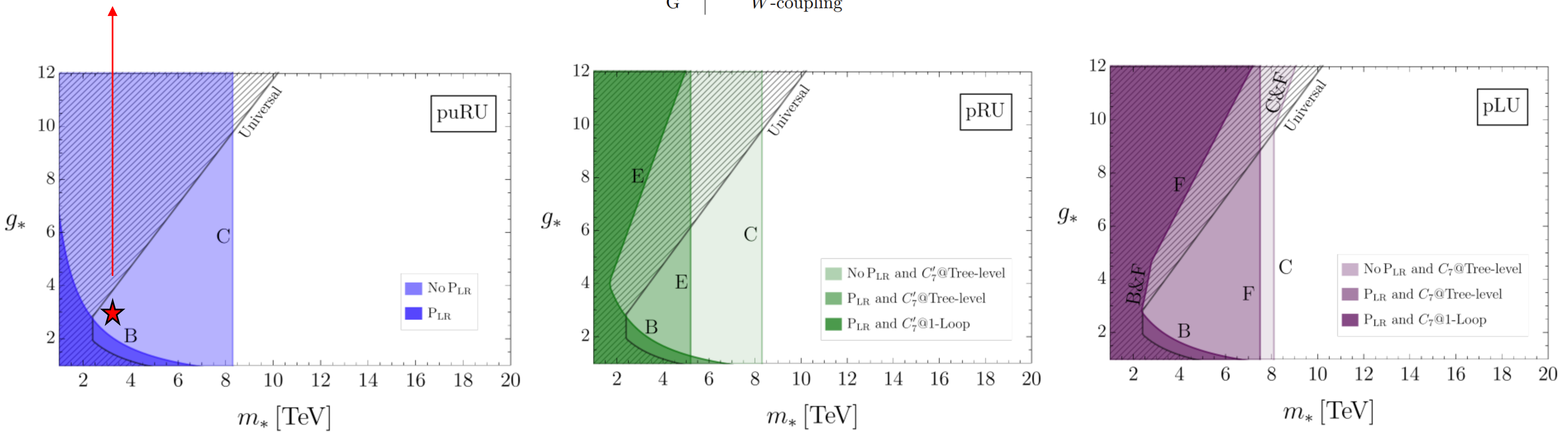
…but two real and two new complex parameters appear

$$\boxed{\frac{y_c}{g_*} \lesssim \varepsilon_u \lesssim 1, \quad \frac{y_t}{g_*} \lesssim \varepsilon_{u3} \lesssim 1, \quad \frac{y_b}{g_*} \lesssim \varepsilon_d \lesssim 1, \quad |a| \sim 1, \quad |b| \sim 1}$$

# Partial Universality

| Label | Observable |
|---|---|
| A | $pp \to jj$ |
| B | $\Delta F = 2\,(B_d)$ |
| C | $B_s \to \mu^+\mu^-$ |
| D | nEDM |
| E | $B^0 \to K^{*0}e^+e^-\ (C_7')$ |
| F | $B \to X_s\gamma\ (C_7)$ |
| G | $W$-coupling |

Sweet spot
5-10% tuning



# The future

| Label | Observable |
|---|---|
| A | $pp \to jj$ |
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| C | $B_s \to \mu^+\mu^-$ |
| D | nEDM |
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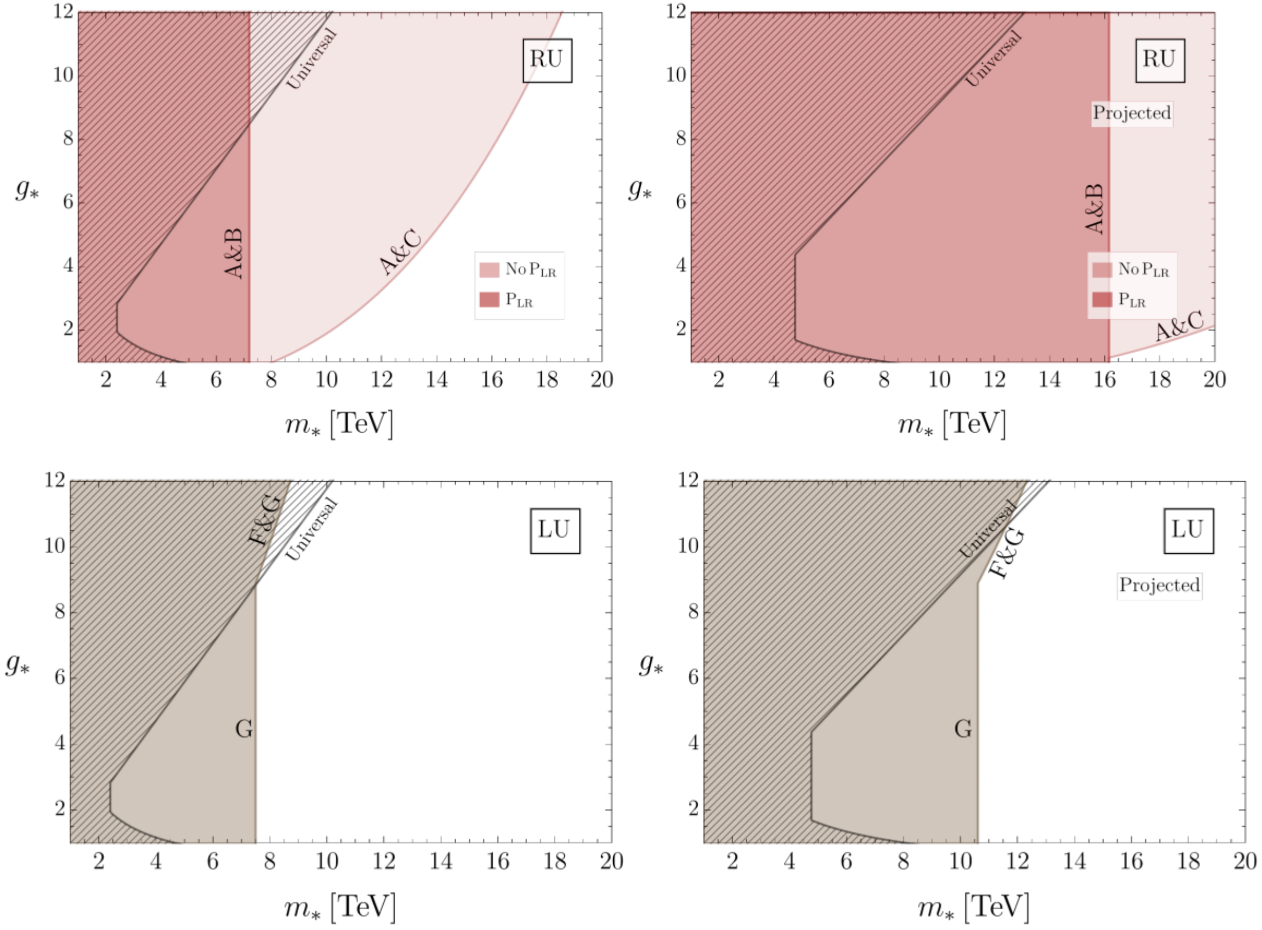
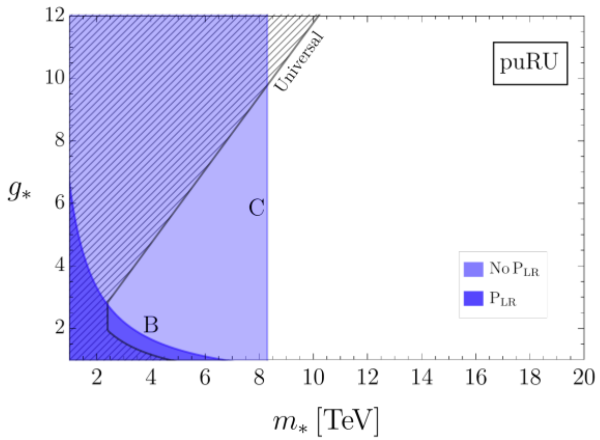
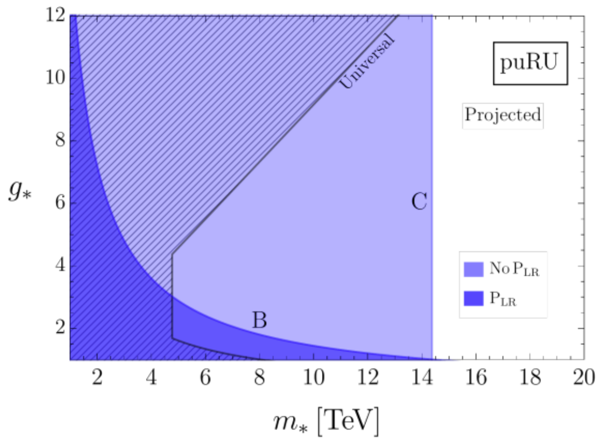
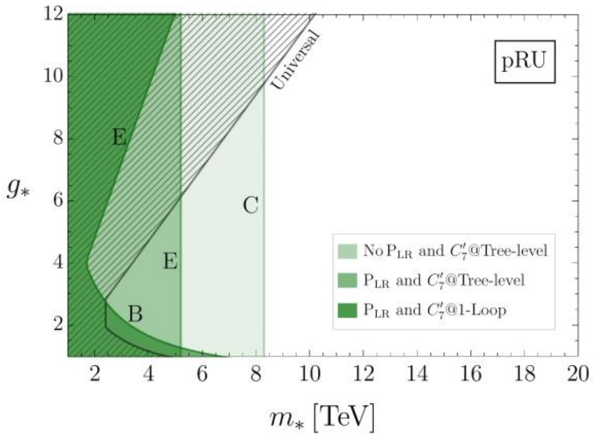
| F | $B \to X_s\gamma\ (C_7)$ |
| G | $W$-coupling |

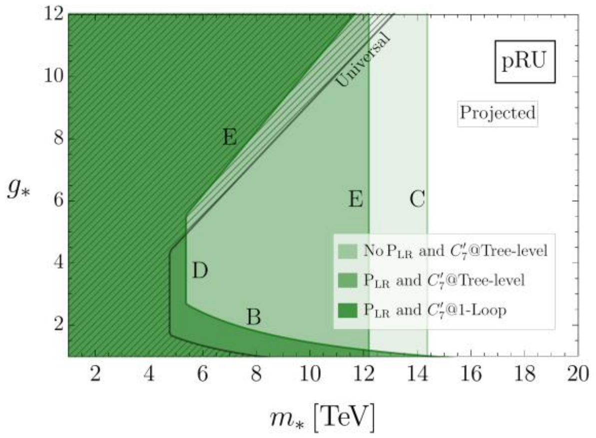


# The future

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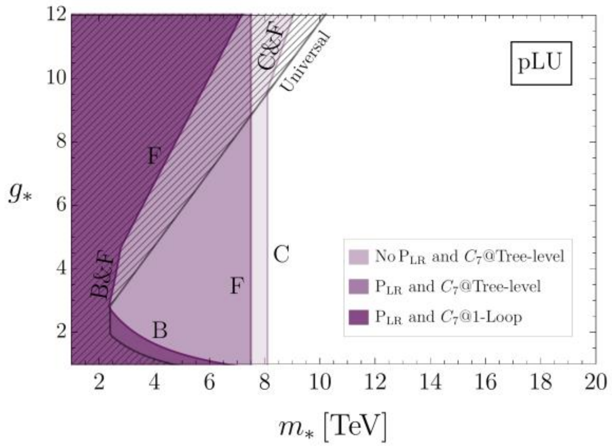
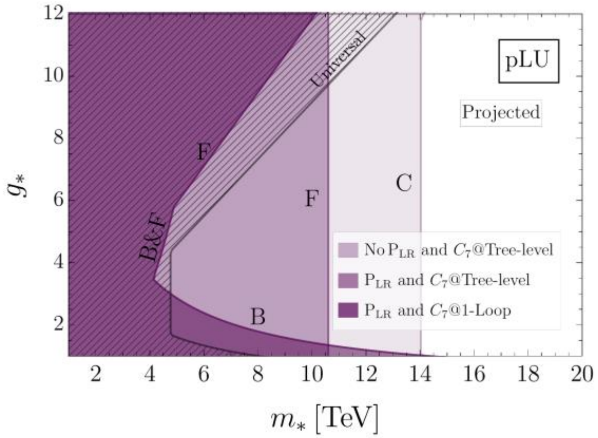


# Summary

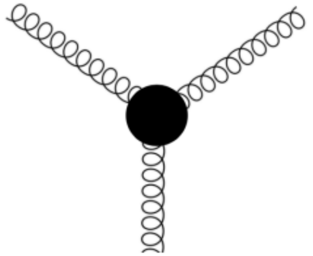
- **Flavor** is one of the biggest hurdles for models that address the **hierarchy problem**
- **Concrete UV hypotheses** are necessary to have a complete picture of the phenomenology. Hypotheses translate to **selection rules** and **correlations between observables**
- **TeV scale new physics** is still possible, especially in the **puRU** scenario, and will be tested/excluded in the next decade(s)
- Other models seem to live farther from the TeV and the next decades of experiment will tell us their fate
- In particular **MFV is NOT the best choice** in the case of a Strongly interacting Higgs
- In general, **flavor observables** are the ones that gives the **stronger indirect tests** on possible new physics models

# BACKUP

# CP violation

There is another flavor-independent bound, seemingly missed by the literature

If the strong sector dynamics violates CP we generate a neutron EDM from



$$\mathcal{L}_{\rm EFT} \supset c_* \frac{g_s^3(m_*)}{g_*^2 m_*^2} \frac{1}{3!} f^{abc} G^a_{\mu\rho} G^{b\rho}{}_{\nu} G^c_{\alpha\beta} \epsilon^{\mu\nu\alpha\beta}$$

$$\frac{d_n}{e} \approx c(1\ \mathrm{GeV}) \frac{g_s^3(m_*)}{g_*^2 m_*^2} \frac{\Lambda_{\rm QCD}}{4\pi} \quad \Longrightarrow \quad m_* \gtrsim 110/g_*\ \mathrm{TeV}$$

This bound is independent on the BSM flavor structure.

**Physics at TeV requires that the composite dynamics is CP invariant**

# Maximal Flavor Symmetry

The extreme symmetric scenario is when all flavor breaking is contained in the SM Yukawas

Usually referred as **Minimal Flavor Violation**

$$\mathcal{L}_{\text{mix}} = \lambda_{q_u}^{ia}\overline{q}_L^i \mathcal{O}_{q_u}^a + \lambda_{q_d}^{ia}\overline{q}_L^i \mathcal{O}_{q_d}^a + \lambda_u^{ia}\overline{u}_R^i \mathcal{O}_u^a + \lambda_d^{ia}\overline{d}_R^i \mathcal{O}_d^a,$$

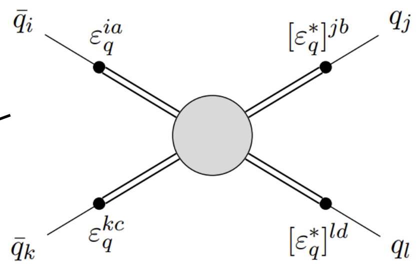
A total of 5 different possibilities

| Name | $\mathcal{G}_{\text{strong}}$ | Universal $\lambda_\psi$ | $\mathcal{G}_F$ | Non-universal $\lambda_\psi$ |
|---|---|---|---|---|
| Right Univ. | $U(3)_U \times U(3)_D$ | $\lambda_u \propto \mathbf{1}, \lambda_d \propto \mathbf{1}$ | $U(3)_q \times U(3)_{U+u} \times U(3)_{D+d}$ | $\lambda_{q_u} \propto Y_u, \lambda_{q_d} \propto Y_d$ |
| Left Univ. $(Q_u Q_d)$ | $U(3)_U \times U(3)_D$ | $\lambda_{q_u} \propto \mathbf{1}, \lambda_{q_d} \propto \mathbf{1}$ | $U(3)_{q+U+D} \times U(3)_u \times U(3)_d$ | $\lambda_u \propto Y_u^\dagger, \lambda_d \propto Y_d^\dagger$ |
| Mixed Univ. $(Q_u D)$ | $U(3)_U \times U(3)_D$ | $\lambda_{q_u} \propto \mathbf{1}, \lambda_d \propto \mathbf{1}$ | $U(3)_{q+U} \times U(3)_u \times U(3)_{D+d}$ | $\lambda_u \propto Y_u^\dagger, \lambda_{q_d} \propto Y_d$ |
| Mixed Univ. $(Q_d U)$ | $U(3)_U \times U(3)_D$ | $\lambda_u \propto \mathbf{1}, \lambda_{q_d} \propto \mathbf{1}$ | $U(3)_{q+D} \times U(3)_{U+u} \times U(3)_d$ | $\lambda_{q_u} \propto Y_u, \lambda_d \propto Y_d^\dagger$ |
| Left Univ. $(Q)$ | $U(3)_{U+D}$ | $\lambda_{q_u} \propto \mathbf{1}, \lambda_{q_d} \propto \mathbf{1}$ | $U(3)_{q+U+D} \times U(3)_u \times U(3)_d$ | $\lambda_u \propto Y_u^\dagger, \lambda_d \propto Y_d^\dagger$ |

We focused on these two

# Right-Universality MFV

Most important constraints come from 4-fermion operators




**Compositeness (dijets)**

$$(\bar{f}_R\gamma^\mu f_R)^2\,, \quad f = u, d$$

$$m_* \gtrsim (3.0 \div 3.6) g_* \varepsilon_d^2 \,\text{TeV}$$

$$m_* \gtrsim (4.8 \div 7.8) g_* \varepsilon_u^2 \,\text{TeV}$$

**ΔF =2 (Bd)**

$$(\bar{b}_L\gamma^\mu d_L)^2$$

$$m_* \gtrsim \frac{6.6}{g_* \varepsilon_u^2}\,\text{TeV}$$

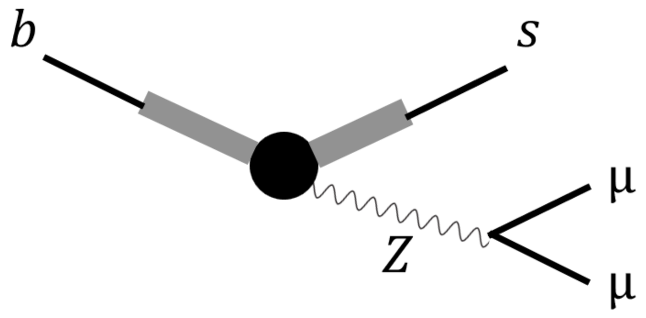
Small $\varepsilon_u$

Large $\varepsilon_u$

$$m_* \gtrsim 5.6 \div 7.2\,\text{TeV}$$

# Right-Universality MFV

Also Z coupling corrections




ΔF =1 ($B_s \to \mu\mu$)

$$\left(H^\dagger i \overleftrightarrow{D}_\mu H\right) \bar{\psi}^i \gamma^\mu \psi^j$$

$$m_* \gtrsim \frac{6.5 \div 8.3}{\varepsilon_u} \text{TeV}$$

But they can be suppressed by “PLR protection”

Accidental symmetry that happens in some embedding of SO(5)→O(4)

$$[\mathcal{O}_{qD}^{(1)}]^{ij} \equiv \bar{q}_L^i \gamma^\mu q_L^j \, \partial^\nu B_{\nu\mu} \Longrightarrow m_* \gtrsim \frac{1.2 \div 3.5}{g_* \varepsilon_u} \text{TeV}$$

# Left-Universality MFV

In this model there are **no flavor-violating 4 fermion operators** at tree-level

Dijet

$$(\bar{f}_L \gamma^\mu f_L)^2\,, \quad f = u, d$$

$$m_* \gtrsim (5.2 \div 8.7)\, g_* \varepsilon_q^2 \,\text{TeV}$$

New bound: W coupling modification (CKM univarity test)

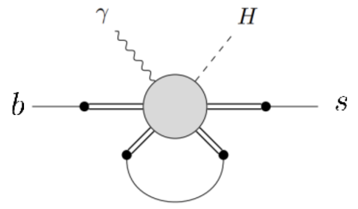
$$\frac{g}{\sqrt{2}}(1+\delta g_W)\bar{u} V_{\text{CKM}} \gamma^\mu P_L d W_\mu^+$$

$$m_* \gtrsim 9.3\, g_* \varepsilon_q \,\text{TeV}$$

b → s γ
at 1-loop

$$[\mathcal{O}_{dB}]^{ij} = (\bar{q}_L^i \sigma^{\mu\nu} d_R^j) H B_{\mu\nu}$$

$$m_* \gtrsim \frac{0.45 \div 0.68}{\varepsilon_q} \,\text{TeV}$$




$$m_* \gtrsim 7.5 \,\text{TeV}$$

# Partial-up Right Universality

Main constraints

Dijets

$$m_* \gtrsim (4.8 \div 7.8)\, g_* \varepsilon_u^2 \,\mathrm{TeV}$$
$$m_* \gtrsim (3.0 \div 3.6)\, g_* \varepsilon_d^2 \,\mathrm{TeV}$$

$\Delta F = 2$ (Bd)

$$m_* \gtrsim \frac{6.6}{g_* \varepsilon_{u3}^2} \,\mathrm{TeV}$$

$\Delta F = 1$ ($B \to \mu\mu$) (if no PLR)

$$m_* \gtrsim \frac{6.5 \div 8.3}{\varepsilon_{u3}} \,\mathrm{TeV}$$

Tension is reduced!

With PLR

$$m_* \gtrsim 2.4 \;\; \mathrm{TeV}$$

Without PLR

$$m_* \gtrsim \frac{6.5 \div 8.3}{\varepsilon_{u3}} \,\mathrm{TeV} > 6.5 \div 8.3 \,\mathrm{TeV}$$

# Partial-up Right Universality

Luckily the structure is such neutron EDMs are not generated at tree-level

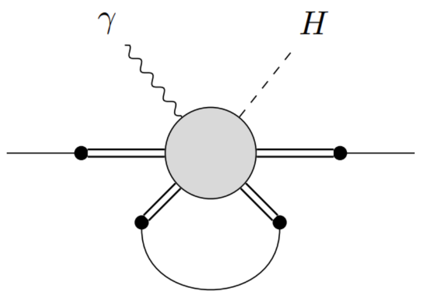
For example, for the up dipole

$$[\mathcal{O}_{u\gamma}]^{ij} = (\bar{q}_L^i \sigma^{\mu\nu} u_R^j)\widetilde{H} F_{\mu\nu}$$

$$\boxed{\mathcal{C}_{u\gamma} \propto \lambda_{q_u}^{(2)}[\lambda_u^{(2)}]^\dagger + r_\gamma \lambda_{q_u}^{(1)}[\lambda_u^{(1)}]^\dagger = \begin{pmatrix} y_u & 0 & 0 \\ 0 & y_c & 0 \\ a y_c & b y_c & r_\gamma y_t \end{pmatrix}}$$

All the phases can be rotated to the down-sector

$$u_R^1 \to u_R^1\, e^{-i\arg[a]}\,, \qquad u_R^2 \to u_R^2\, e^{-i\arg[b]}$$
$$q_L^1 \to q_L^1\, e^{-i\arg[a]}\,, \qquad q_L^2 \to q_L^2\, e^{-i\arg[b]}$$




The only physical imaginary parts involve both up and down structures → EDMs arise at **loop level**

# Partial Right Universality

Extending the U(2) also to the down-sector

$$\text{pRU}: \begin{cases} \lambda_{q_u} \sim \frac{1}{\varepsilon_u}\begin{pmatrix} y_u & 0 \\ 0 & y_c \\ a y_c & b y_c \end{pmatrix} \oplus \frac{1}{\varepsilon_{u_3}}\begin{pmatrix} 0 \\ 0 \\ y_t \end{pmatrix}, & \lambda_{q_d} \sim \widetilde{U}_d \frac{1}{\varepsilon_d}\begin{pmatrix} y_d & 0 \\ 0 & y_s \\ a' y_s & b' y_s \end{pmatrix} \oplus \widetilde{U}_d \frac{1}{\varepsilon_{d_3}}\begin{pmatrix} 0 \\ 0 \\ y_b \end{pmatrix} \\ \lambda_u \sim g_* \begin{pmatrix} \varepsilon_u & 0 \\ 0 & \varepsilon_u \\ 0 & 0 \end{pmatrix} \oplus g_* \begin{pmatrix} 0 \\ 0 \\ \varepsilon_{u_3} \end{pmatrix}, & \lambda_d \sim g_* \begin{pmatrix} \varepsilon_d & 0 \\ 0 & \varepsilon_d \\ 0 & 0 \end{pmatrix} \oplus g_* \begin{pmatrix} 0 \\ 0 \\ \varepsilon_{d_3} \end{pmatrix}. \end{cases}$$

New parameters

$$\frac{y_s}{g_*} \lesssim \varepsilon_d \lesssim 1, \quad \frac{y_b}{g_*} \lesssim \varepsilon_{d_3} \lesssim 1$$

$$Y_u \sim \lambda_{q_u}\lambda_u^\dagger/g_*, \; Y_d \sim \lambda_{q_d}\lambda_d^\dagger/g_*$$

a, b, a’, b’ still O(1)

# Partial Left-Universality

Or similarly for the Left-Universality model

$$\text{pLU}: \begin{cases} \lambda_q \sim \begin{pmatrix} \varepsilon_q & 0 \\ 0 & \varepsilon_q \\ 0 & 0 \end{pmatrix} g_* \oplus \begin{pmatrix} 0 \\ 0 \\ \varepsilon_{q3} \end{pmatrix} g_* \\ \lambda_u \sim \frac{1}{\varepsilon_q} \begin{pmatrix} y_u & 0 \\ 0 & y_c \\ a^* y_c & b^* y_c \end{pmatrix} \oplus \frac{1}{\varepsilon_{q3}} \begin{pmatrix} 0 \\ 0 \\ y_t \end{pmatrix} \\ \lambda_d \sim \frac{1}{\varepsilon_q} \begin{pmatrix} y_d & 0 \\ 0 & y_s \\ a'^* y_s & b'^* y_s \end{pmatrix} \tilde{O}_d \oplus \frac{1}{\varepsilon_{q3}} \begin{pmatrix} 0 \\ 0 \\ y_b \end{pmatrix} \end{cases}$$

O(λ) matrix

$$Y_u = \lambda_q \lambda_u^\dagger / g_*, \; Y_d = \lambda_q \lambda_d^\dagger / g_*$$

With

$$\boxed{\frac{y_c}{g_*} \lesssim \varepsilon_q \lesssim 1\,, \qquad \frac{y_t}{g_*} \lesssim \varepsilon_{q3} \lesssim 1}$$

a, b, b’ are O(1), but a’ must be O(λ) to reproduce the CKM, but no constraint on their phases

# Partial Right/Left Universality

For both models nEDMs appear at loop level and give lower bound for the various ε

But new observables become important

b → s γ
at tree-level

$$[\mathcal{O}_{dB}]^{ij} = (\bar{q}_L^i \sigma^{\mu\nu} d_R^j) H B_{\mu\nu}$$

pRU: $m_* \gtrsim (4.5 \div 5.2)\,\mathrm{TeV}$

pLU: $m_* \gtrsim (4.9 \div 7.5)\,\mathrm{TeV}$

But in all known holographic models, such operators arise at loop level

→ There could be a further suppression factor $\dfrac{g_*^2}{16\pi^2}$