Exploring the Flavor Symmetry Landscape

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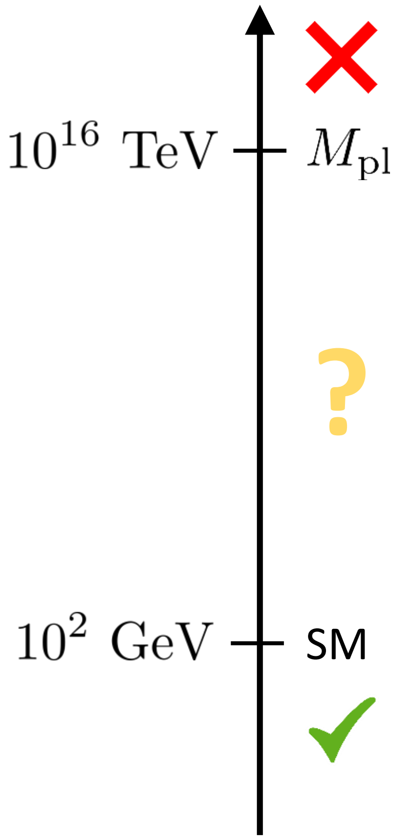
TPPC 2024 THEORY RETREAT
19/12/2024
Based on **2402.09503**, AG, Riccardo Rattazzi, Lorenzo Ricci, Luca Vecchi

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

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

Standard Model

Possible deviations due to new **heavy** states

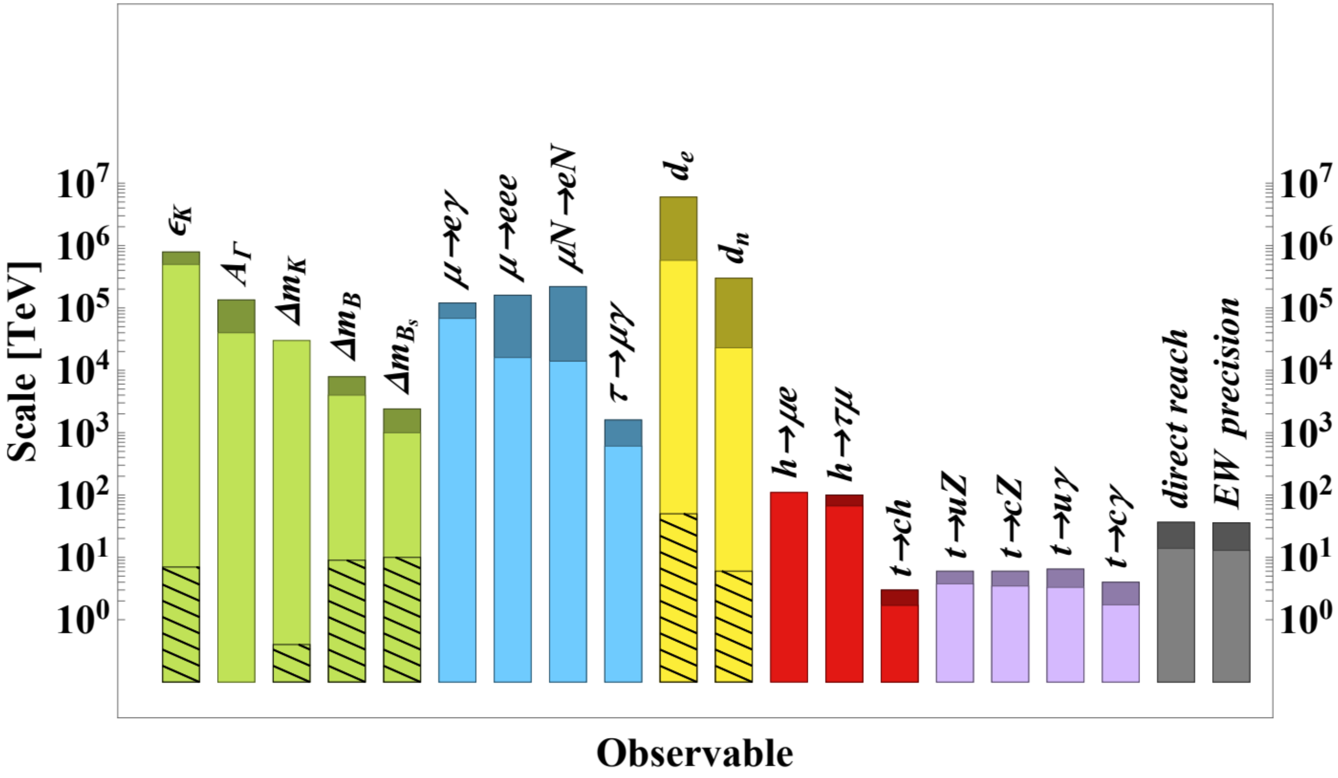
The **big question**: what is Λ?

Λ = **High scale**
- All the SM "accidents" are natural
- But the weak scale becomes unnatural

Λ = **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, Λ is **NOT** the scale at which we will find new particles

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

Our workflow

UV Hypotheses → Observables consequences → Available parameter space

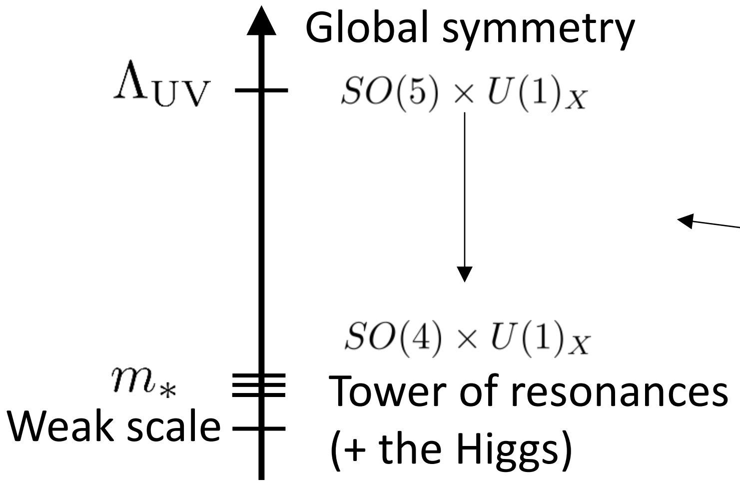
What are the hypotheses that allow for physics at TeV?

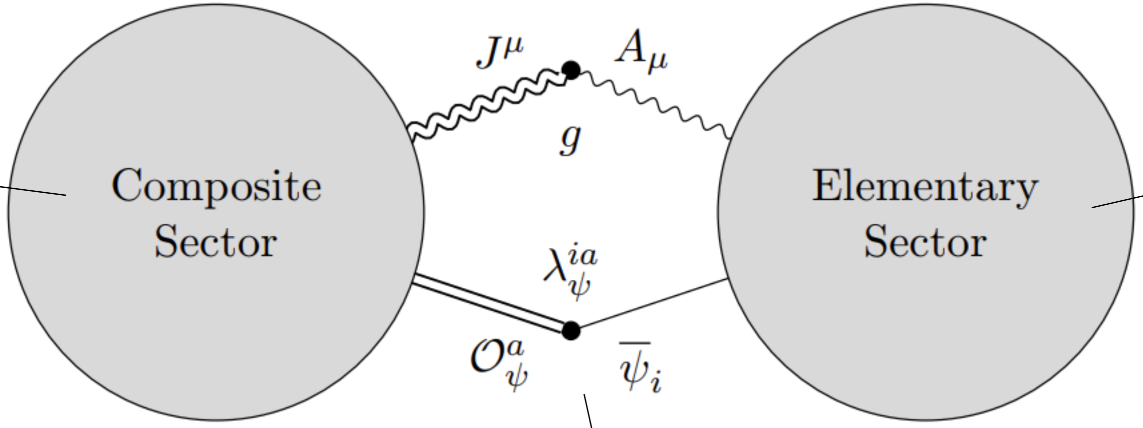
This can only be answered with a concrete model
Many BSM flavor models studied these last decades

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: $g_{\rm SM} < g_* < 4\pi$

The two sectors talk through:

1) Gauging
2) Fermion mixings

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*

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

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

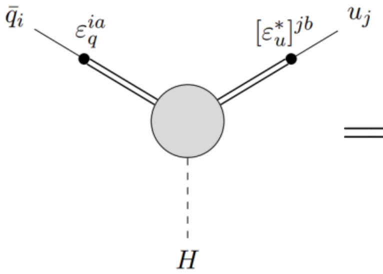
Can generate both small and large yukawas dynamically

SILH Lagrangian

Putting together these hypotheses, one obtains a general effective Lagrangian

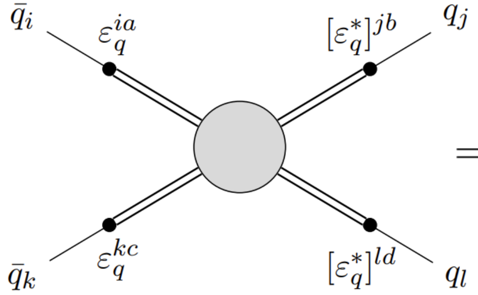
$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}'} + \frac{m_*^4}{g_*^2}\widehat{\mathcal{L}}_{\mathrm{EFT}}\left(\frac{g_* H}{m_*}, \frac{D_\mu}{m_*}, \frac{\lambda_\psi^{ia}\overline{\psi}^i}{m_*^{3/2}}, \frac{g_*^2}{16\pi^2}, \frac{g^2}{16\pi^2}, \frac{[\lambda_\psi^*]^{ia}\lambda_\psi^{ib}}{16\pi^2}\right),$$

Possible loop factors



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

Unknown O(1) factors



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

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

Fermion compositeness

Bosonic Constraints

Before discussing flavor, main constraints from the bosonic sector

Higgs couplings

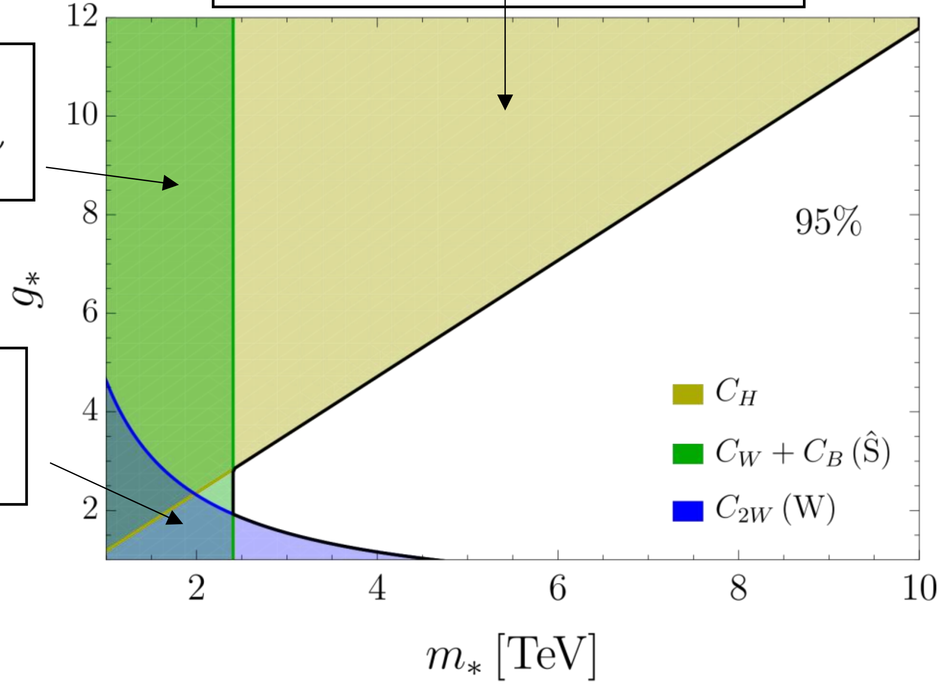
$\mathcal{O}_H = \frac{1}{2}\partial_\mu(H^\dagger H)\partial^\nu(H^\dagger H)$

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

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

$\mu \to e\gamma$

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

Quarks

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

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

D meson CP asymm

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

Neutron EDM

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

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)

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

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

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

Maximal Flavor Symmetry → Minimal Flavor Violation

Right-Universality MFV

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

$\propto Y_\psi$ $\qquad$ $\propto \mathbf{1}$

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

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

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

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

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

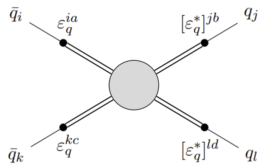
$$\text{LU}: \begin{cases} \lambda_q \sim \begin{pmatrix} \varepsilon_q & 0 & 0 \\ 0 & \varepsilon_q & 0 \\ 0 & 0 & \varepsilon_q \end{pmatrix} g_*, \\ \lambda_u \sim \frac{1}{\varepsilon_q} \begin{pmatrix} y_u & 0 & 0 \\ 0 & y_c & 0 \\ 0 & 0 & y_t \end{pmatrix}, \\ \lambda_d \sim \frac{1}{\varepsilon_q}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

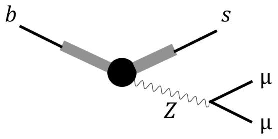
In this case there is a single ε parameter

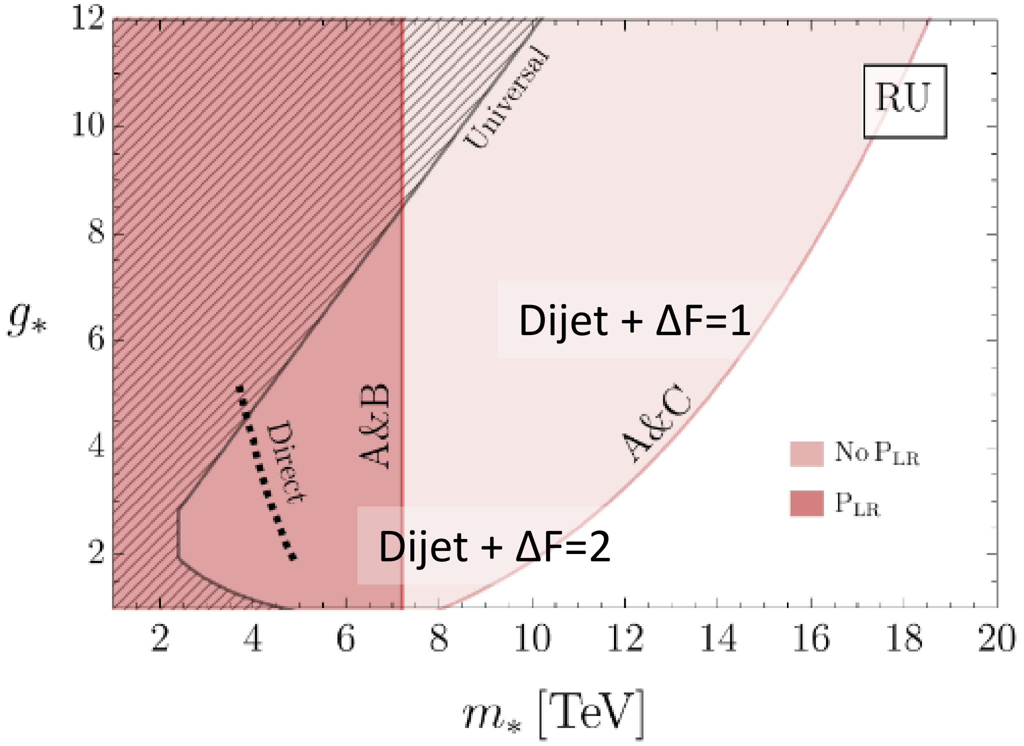
$$\frac{y_t}{g_*} \lesssim \varepsilon_q \lesssim 1.$$

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

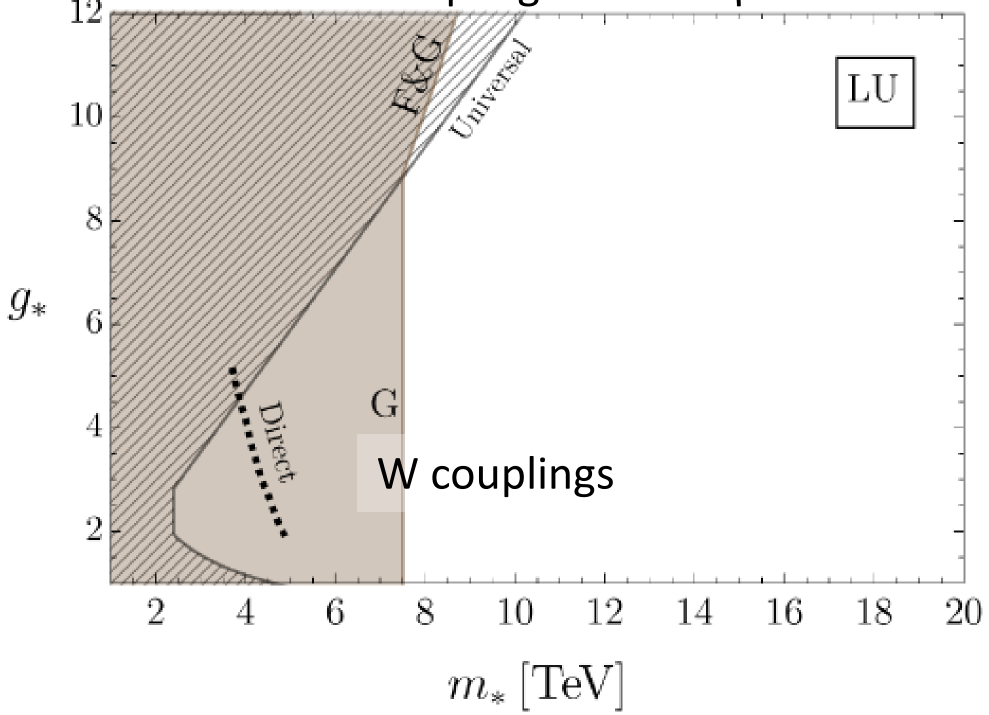
MFV Recap







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

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

$$\mathcal{G}_{\text{strong}} = U(2)_U \times U(1)_U \times U(3)_D$$

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

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

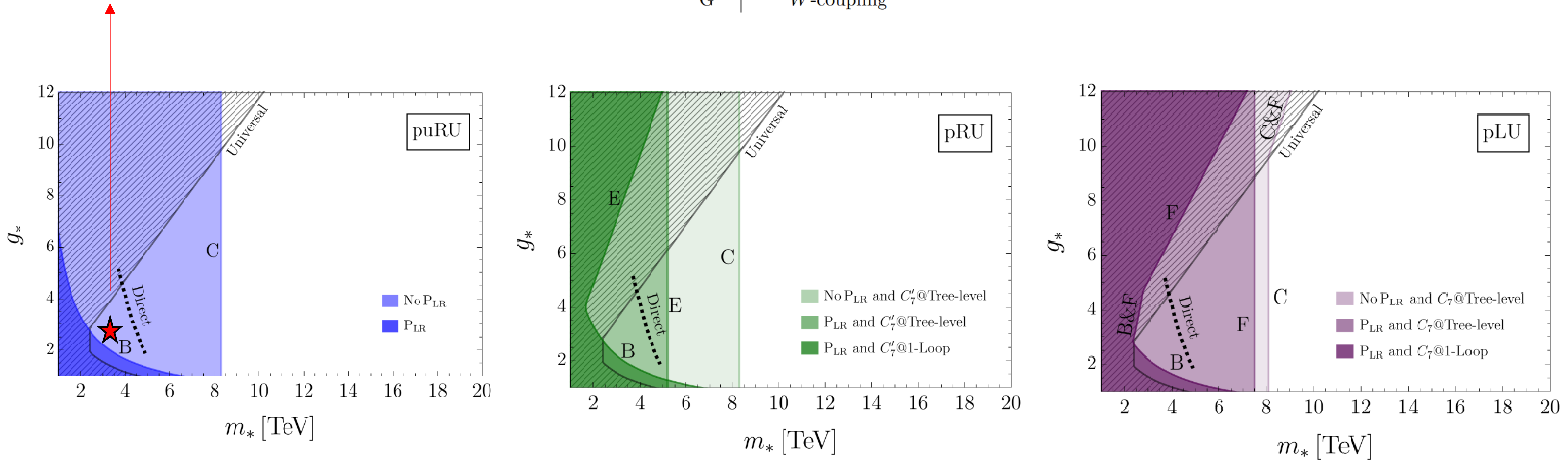
1st,2nd generations are separated from the 3rd in the up-sector

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

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

5-10% tuning



The future

Label	Observable
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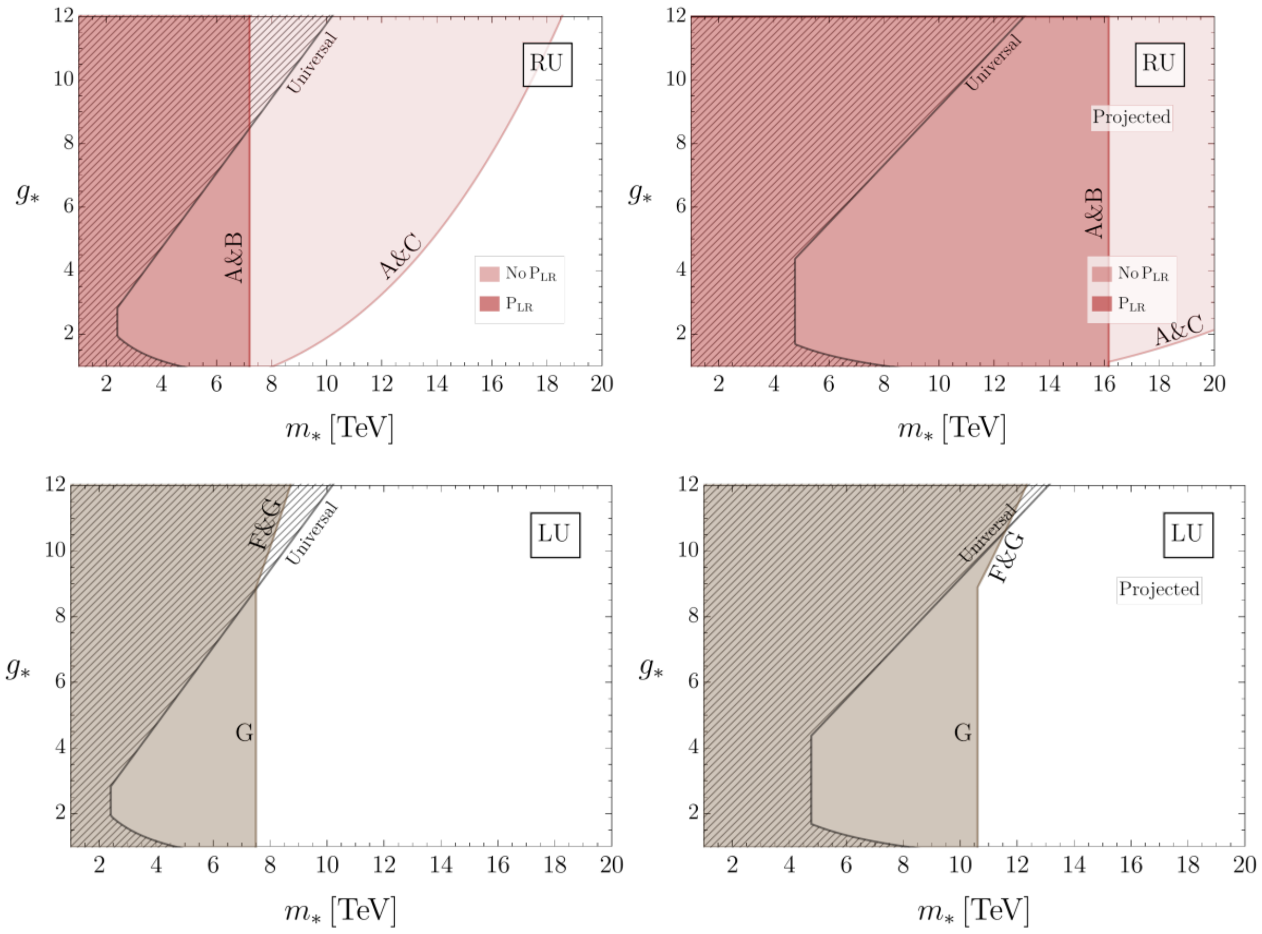
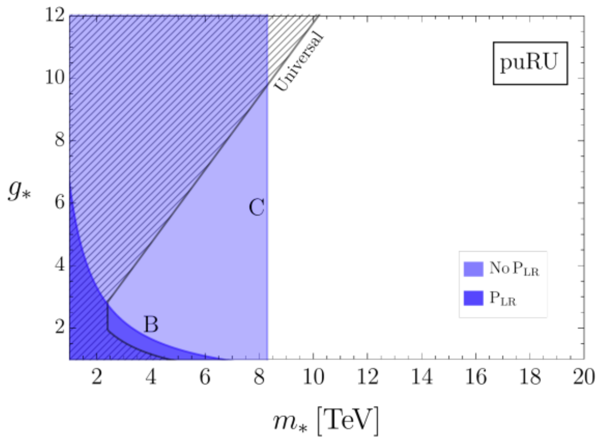
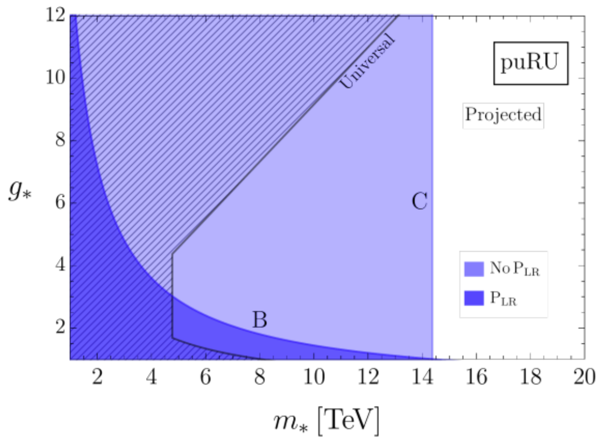
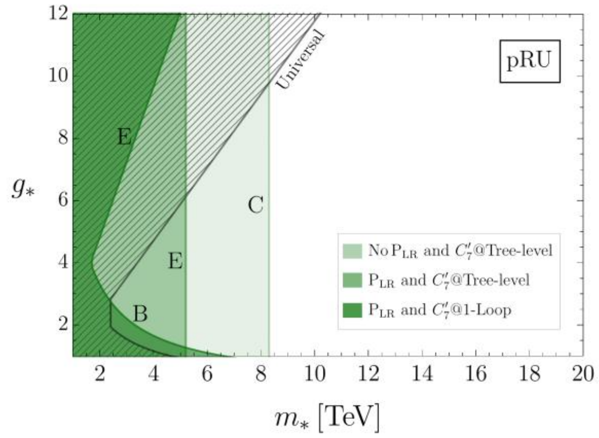
E	$B^0 \to K^{*0} e^+ e^-$ (C_7')
F	$B \to X_s \gamma$ (C_7)
G	W-coupling

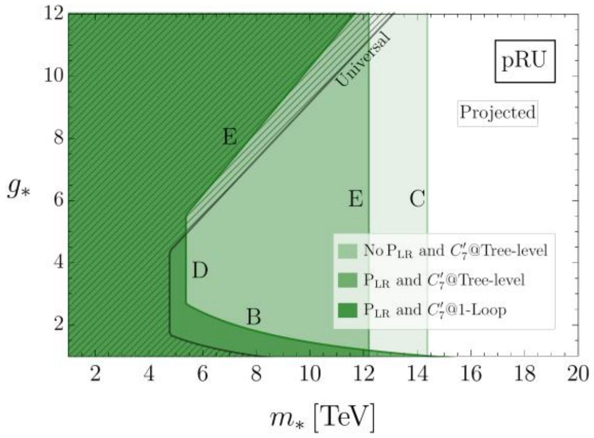


The future









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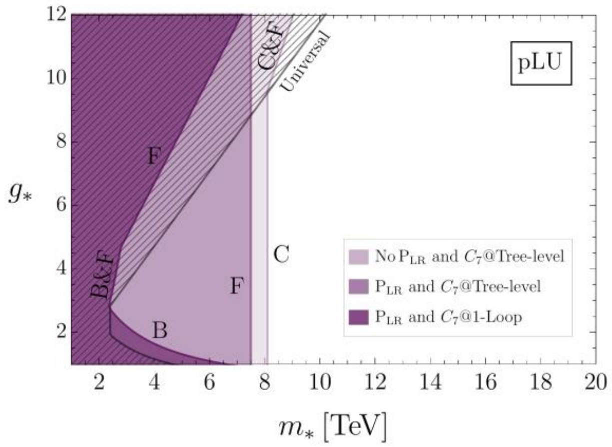
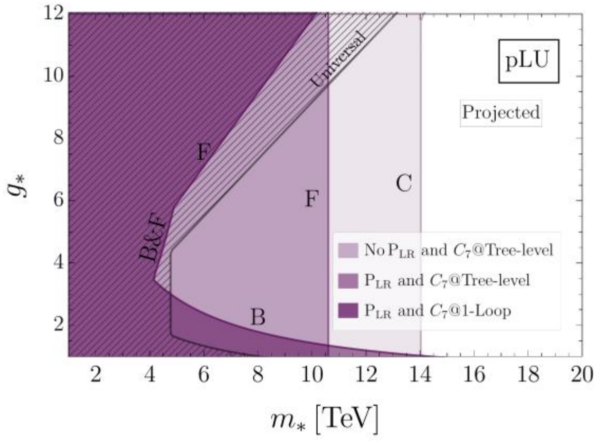




Summary

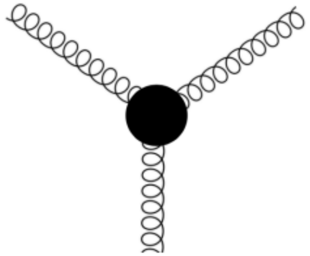
- **Flavor** is one of the biggest hurdles for models that address the **hierarchy problem**
- **Concrete UV hypotheses** are necessary to have a complete picture of the phenomenology. Hypotheses translate to **selection rules** and **correlations between observables**
- **TeV scale new physics** is 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



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

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

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**

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

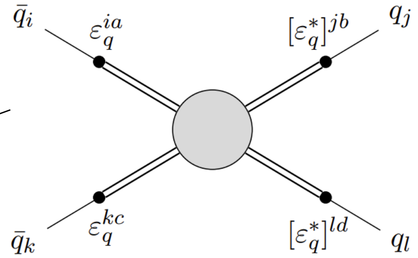
A total of 5 different possibilities

Name	$\mathcal{G}_{\rm strong}$	Universal λ_ψ	$\mathcal{G}_F$	Non-universal λ_ψ
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)

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

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

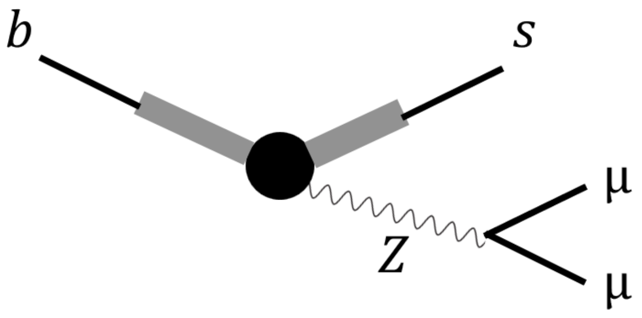
Small ε_u

Large ε_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)

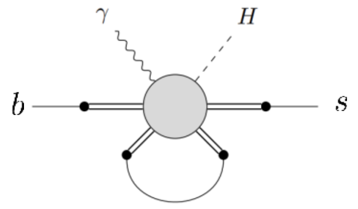
$$\frac{g}{\sqrt{2}}(1 + \delta g_W)\bar{u} V_{\text{CKM}} \gamma^\mu P_L d W_\mu^+$$

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

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

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

ΔF =2 (Bd)

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

ΔF =1 (B → μμ) (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

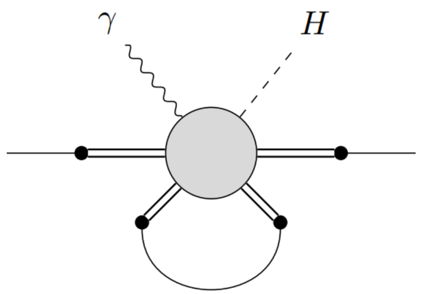
For example, for the up dipole

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

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

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

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

$\tilde{O}_d$: $O(\lambda)$ matrix

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

With

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

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 $\frac{g_*^2}{16\pi^2}$