Exploring the Flavor Symmetry Landscape

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Beyond the Flavor Anomalies 2025

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

Indirect vs Direct

SMEFT analyses give **indirect bounds** on a “**new physics scale**” Λ

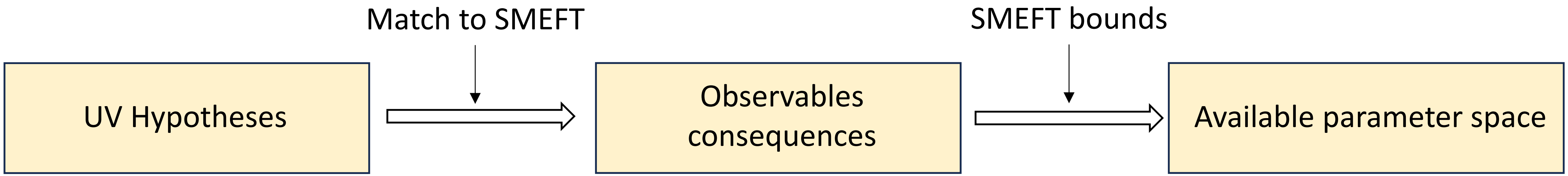
What is the relation between this Λ and the mass at which we could find new particles?

How can we compare SMEFT bounds and direct searches into the same parameter space?

How do the various indirect searches and measurement influence each other?

The only way to answer all these questions is through a **concrete model** of the UV physics

Our workflow



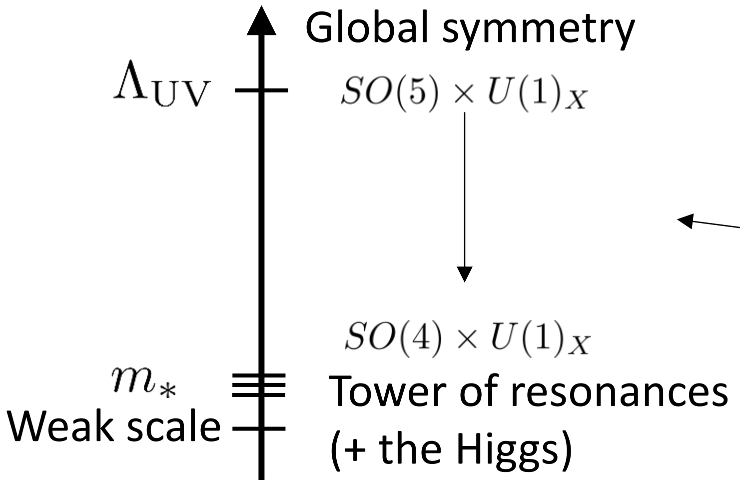
What are the hypotheses that allow for physics at TeV?

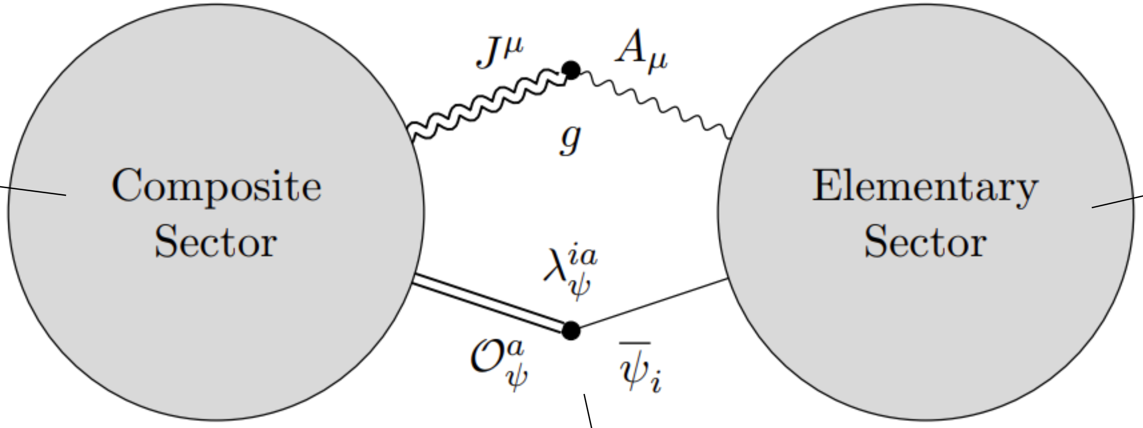
Many BSM models studied in the recent decades

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

Given the current (and near future) indirect bounds,
what could be DIRECTLY discovered by LHC / FCChh?

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

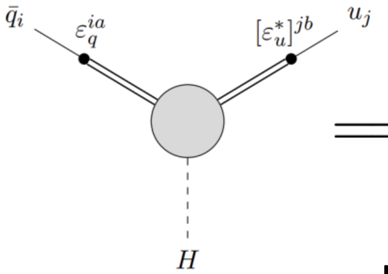
SILH Lagrangian

Giudice, Grojean, Pomarol, Rattazzi

Putting together these hypotheses, one obtains a general effective Lagrangian

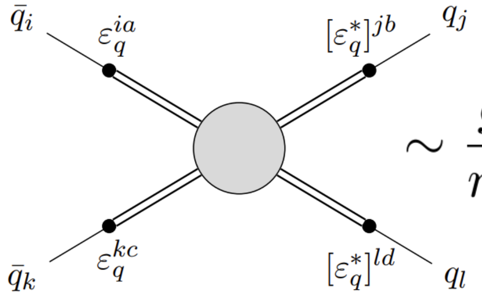
$$\mathcal{L}_{\rm EFT} = \mathcal{L}_{\rm SM'} + \frac{m_*^4}{g_*^2}\widehat{\mathcal{L}}_{\rm EFT}\left(\frac{g_* H}{m_*}, \frac{D_\mu}{m_*}, \frac{\lambda_\psi^{ia}\overline{\psi}^i}{m_*^{3/2}}, \frac{g_*^2}{16\pi^2}, \frac{g^2}{16\pi^2}, \frac{[\lambda_\psi^*]^{ia}\lambda_\psi^{ib}}{16\pi^2}\right),$$

Possible loop factors



$$\Longrightarrow \; Y_u^{ij} \sim g_* \varepsilon_q^i \varepsilon_u^j$$

Up to O(1) factors



$$\sim \frac{g_*^2}{m_*^2}\varepsilon_q^i\varepsilon_q^j\varepsilon_q^k\varepsilon_q^l(\overline{q}^i\gamma_\mu q^j)(\overline{q}^k\gamma^\mu q^l)$$

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

Fermion compositeness

Bosonic Constraints

Before discussing flavor, main constraints from the bosonic sector

Higgs couplings

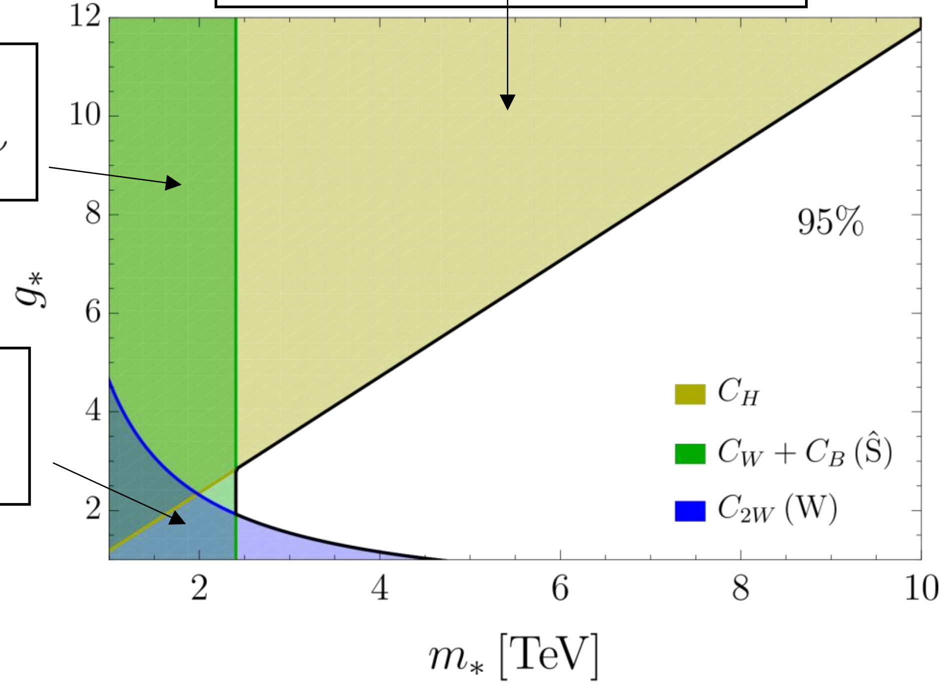
$\mathcal{O}_H = \frac{1}{2}\partial_\mu(H^\dagger H)\partial^\nu(H^\dagger H)$

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	$\mu \to e\gamma$
$m_* \gtrsim 2200 \frac{g_*}{4\pi}$ TeV	$m_* \gtrsim 250 \frac{g_*}{4\pi}$ TeV

Quarks

$\Delta F = 2$ & $b \to s\gamma$	D meson CP asymm	Neutron EDM
$m_* \gtrsim 20 - 30$ TeV	$m_* \gtrsim 120 \frac{g_*}{4\pi}$ TeV	$m_* \gtrsim 40 - 60 \frac{g_*}{4\pi}$ 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

See also Barbieri et al., Isidori et al., Redi-Weiler

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

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

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

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

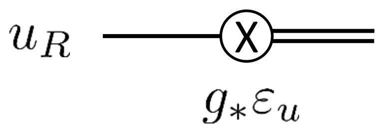
Maximal Flavor Symmetry → Minimal Flavor Violation

Flavor symmetries however make the explanation of the flavor hierarchies more complicated

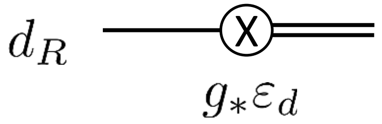
Right-Universality = MFV

Assumption: the strong sector has a global flavor symmetry

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

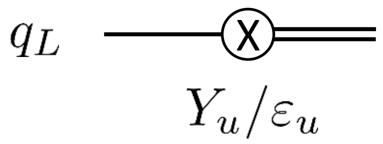


$O_U \sim 3 \in U(3)_U$

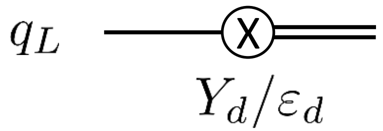


$O_D \sim 3 \in U(3)_D$

Flavor Universal mixings

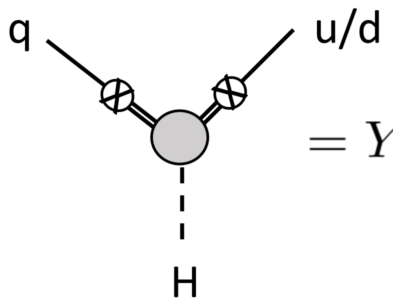


$O_{QU} \sim 3 \in U(3)_U$



$O_{QD} \sim 3 \in U(3)_D$

Flavor Violating mixings

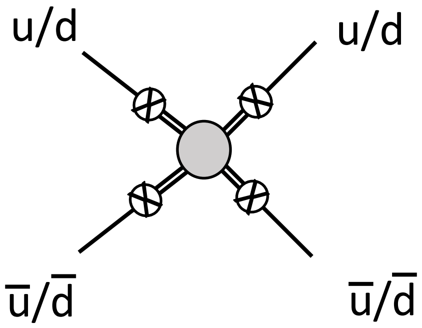


$= Y_{u/d}$ SM Yukawa

Right-Universality = MFV

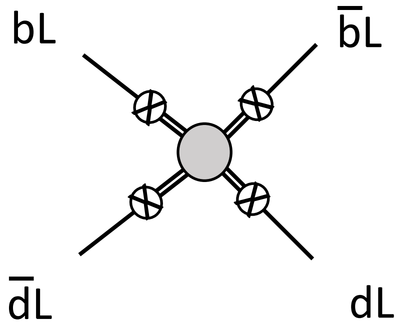
The strongest bounds come from **4-fermion interactions**

Dijet production



$$m_* \gtrsim (3-8) g_* \varepsilon^2_{u/d} \text{ TeV}$$

ΔF = 2 (Bd)

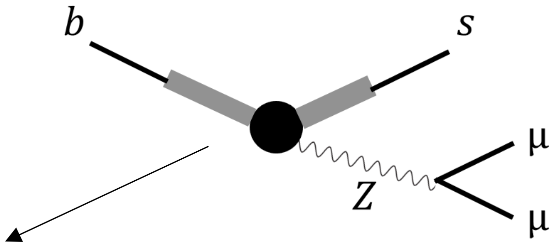


$$m_* \gtrsim \frac{7}{g_* \varepsilon^2_u} \text{ TeV}$$

$$m_* \gtrsim 8 \text{ TeV}$$

Right-Universality = MFV

Another important bound from b → sμμ transitions



$$m_* \gtrsim \frac{8}{\varepsilon_u}\ \text{TeV}$$

Modified Z coupling from

$$(H^\dagger i D_\mu H)(\bar{q}\gamma^\mu q)$$

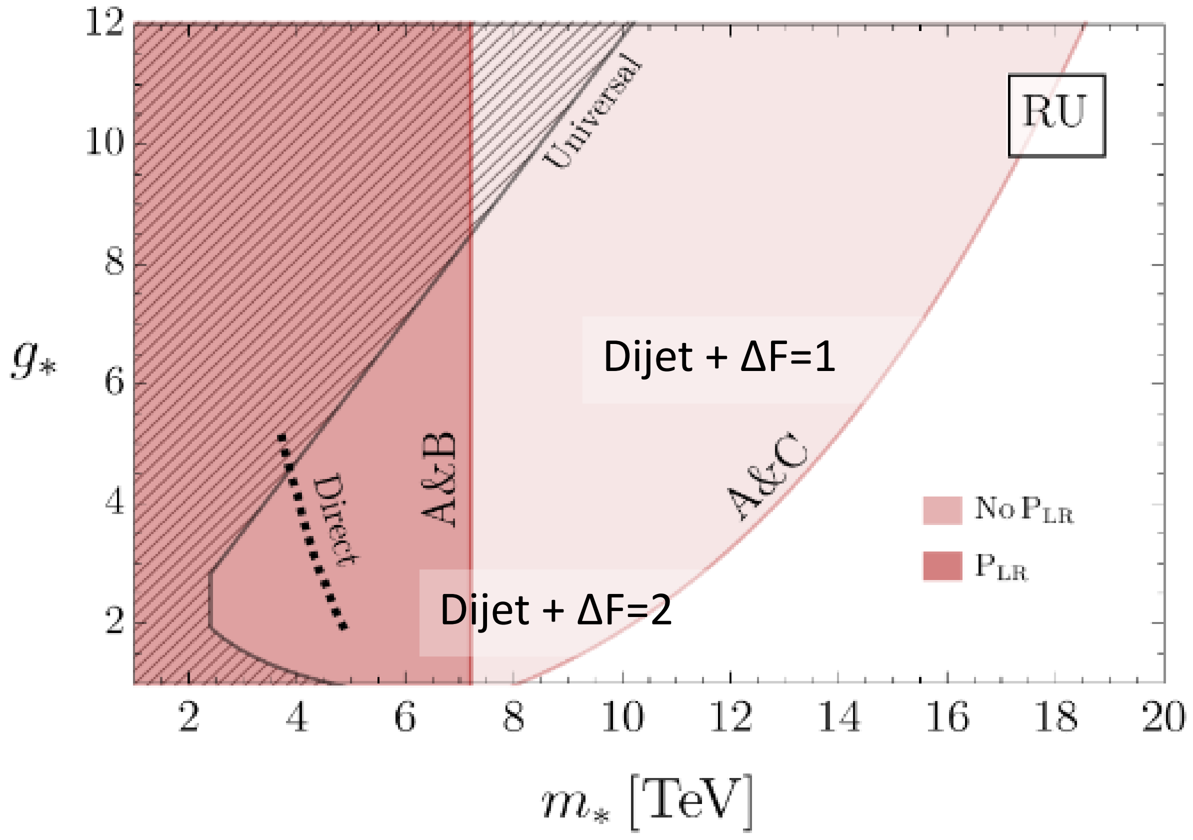
Agashe, Contino, Da Rold, Pomarol

But this bound depends on the **representation** of the **composite fermions** under O(4)

Accidental **LR symmetry** can be used to protect **EITHER** Zdd OR Zuu vertices

Historically used for the Zbb bound, now bsμμ is stronger

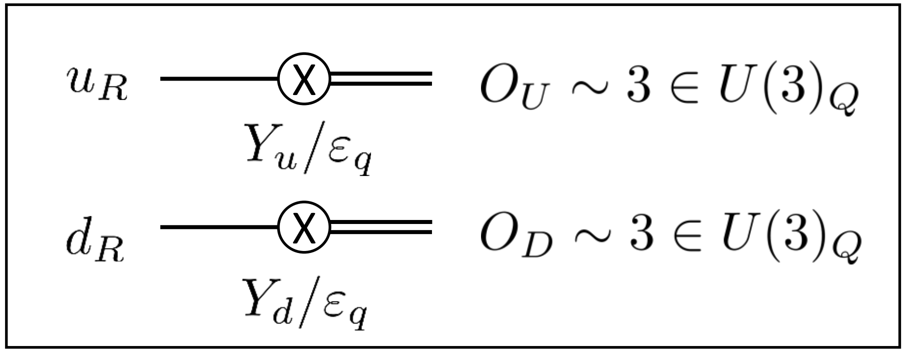
Right-Universality = MFV



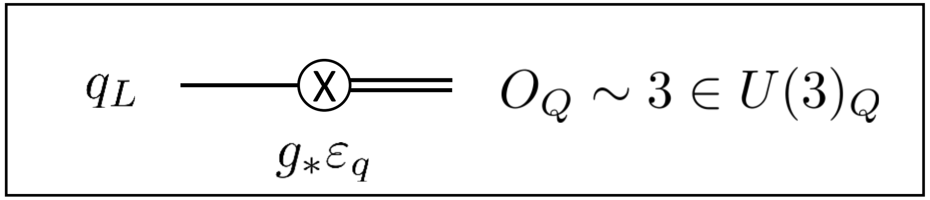
Left-Universality = a different MFV

Assumption: the strong sector has a global flavor symmetry

$$\mathcal{G}_{\text{strong}} = U(3)_Q$$



Flavor Violating mixings



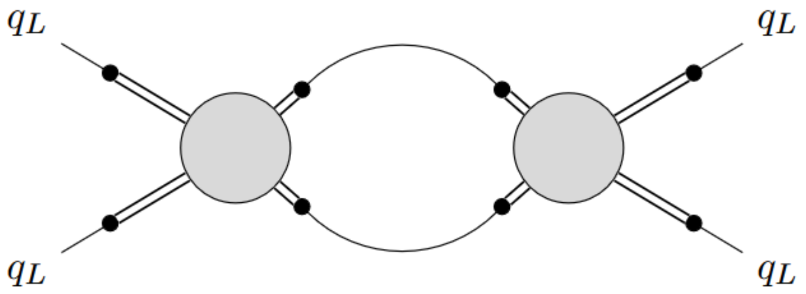
Flavor Universal mixing

With left-handed universality, **only one set of left partners** are needed to minimally reproduce the SM

Left-Universality = a different MFV

Even though this model is still "MFV", the phenomenology is completely different

Most Flavor violation effects start at 1-loop. For example

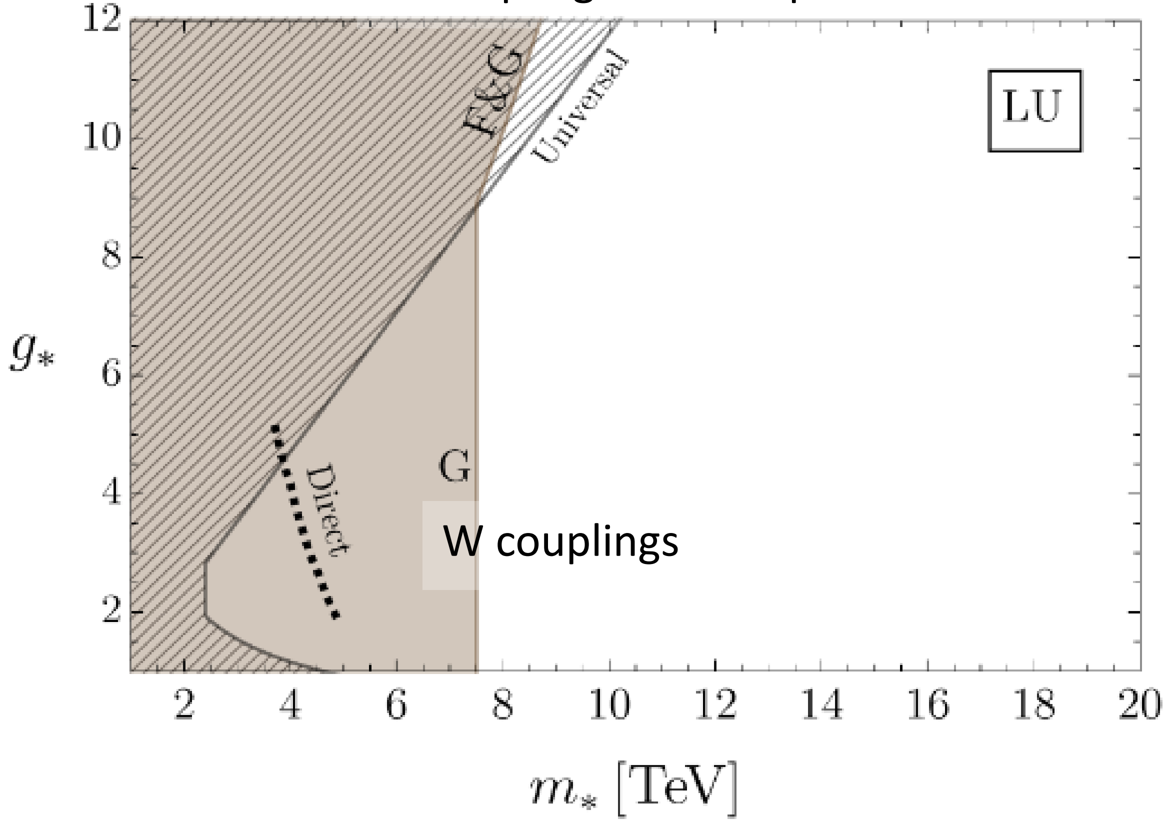


$$\sim \frac{1}{16\pi^2 m_*^2}(Y_u^\dagger Y_u)^2$$

The **MFV structure is still there**, but the different UV hypothesis gives additional selection rules leading to a **loop suppression**

Left-Universality = a different MFV

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?

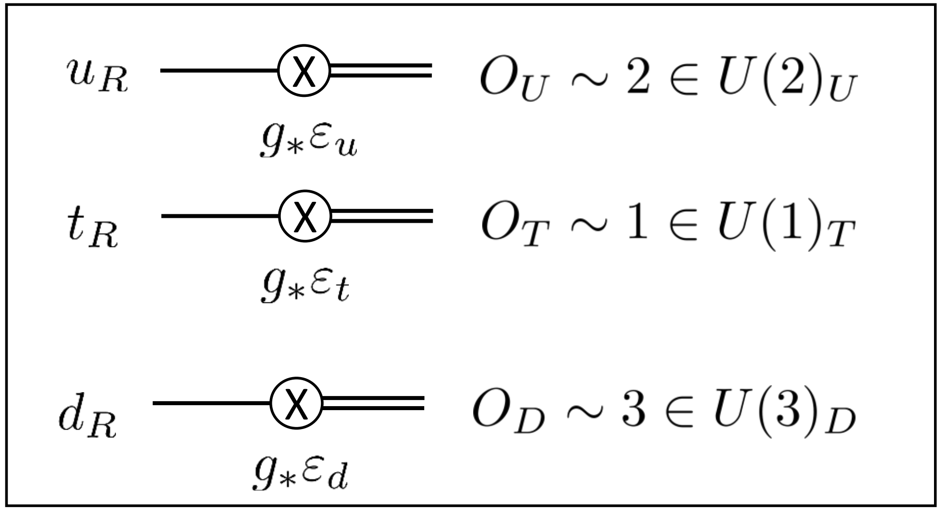
What's in the middle between these two possibilities?

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

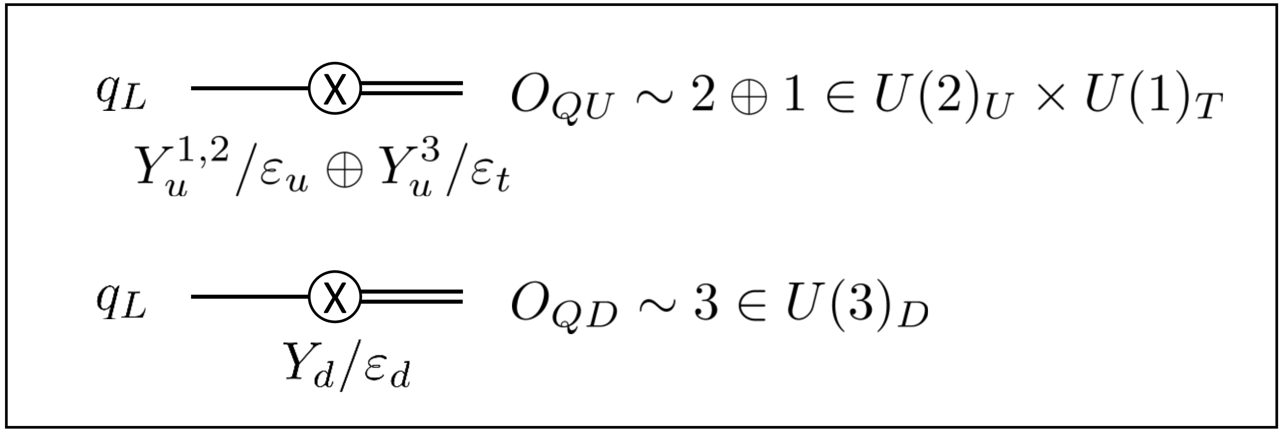
Partial-up Right Universality

Assumption: the strong sector has a global flavor symmetry

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



Flavor (Almost) Universal mixings

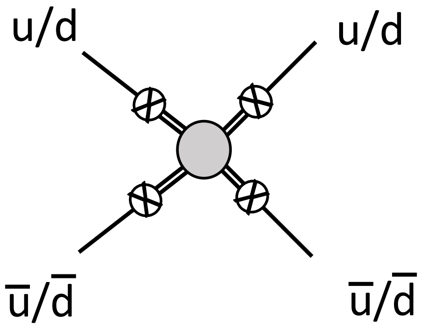


Flavor Violating mixings

Partial-up Right Universality

Same bounds as RU from 4-fermion interactions, but with different ε

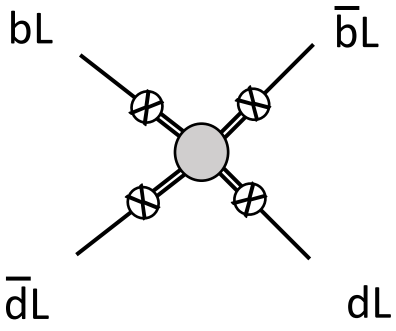
Dijet production



$$m_* \gtrsim (3-8) g_* \varepsilon_{u/d}^2 \text{ TeV}$$

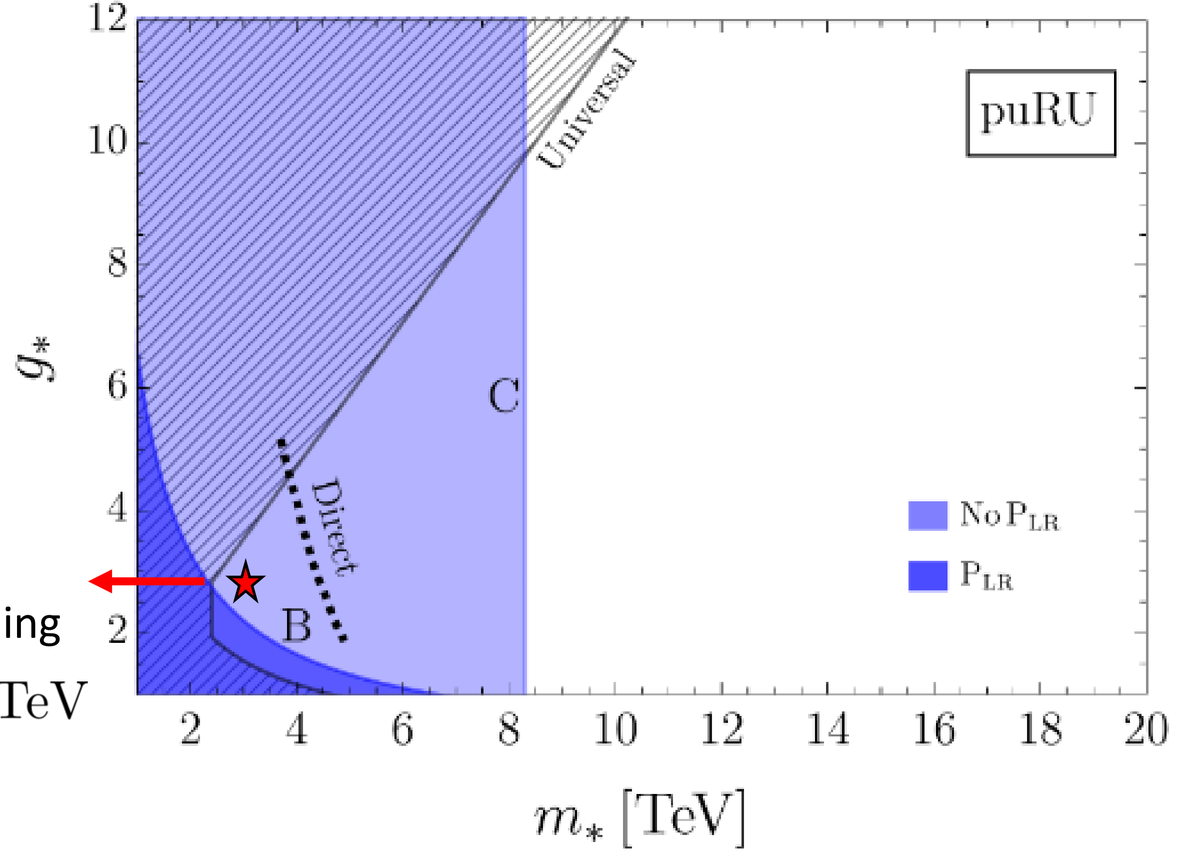
Tension is resolved!

ΔF = 2 (Bd)



$$m_* \gtrsim \frac{7}{g_* \varepsilon_t^2} \text{ TeV}$$

Partial Universality

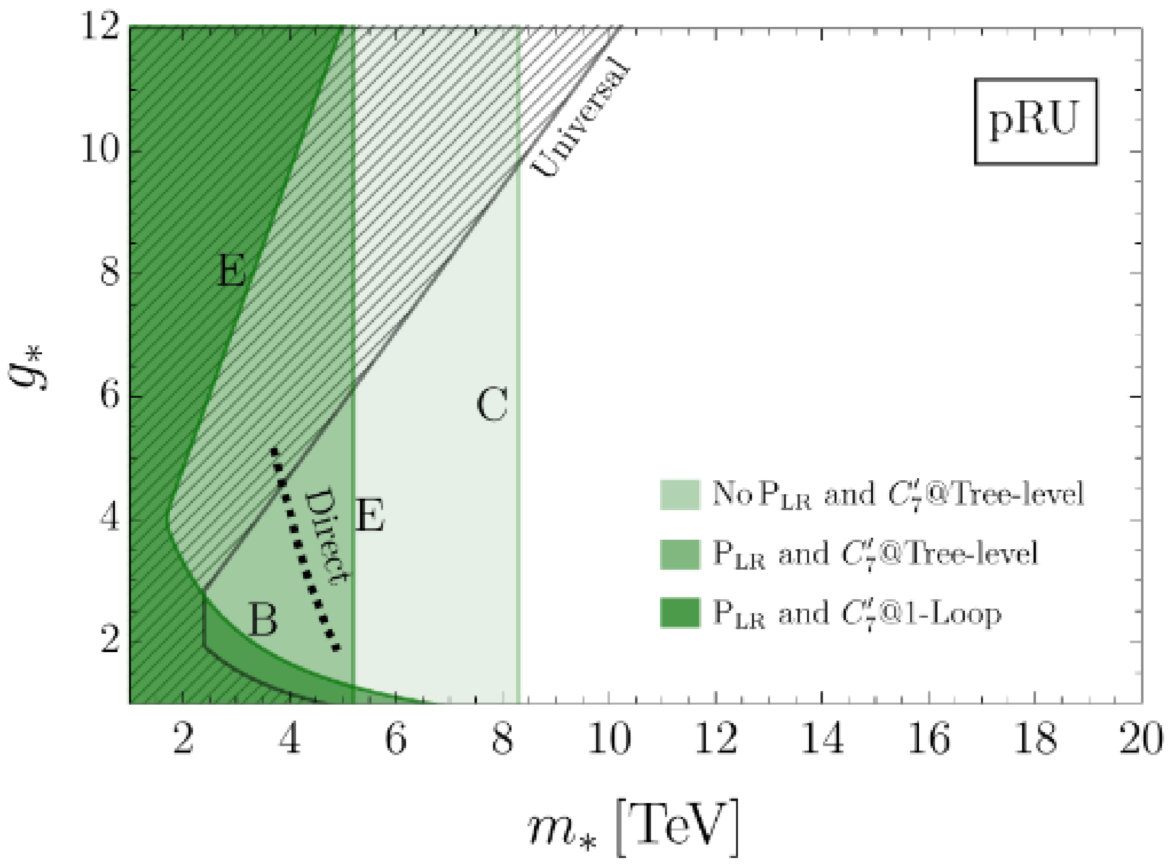


5-10%
Higgs tuning

$m_* \sim 2.5$ TeV
$g_* \sim 3$

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

Partial Universality



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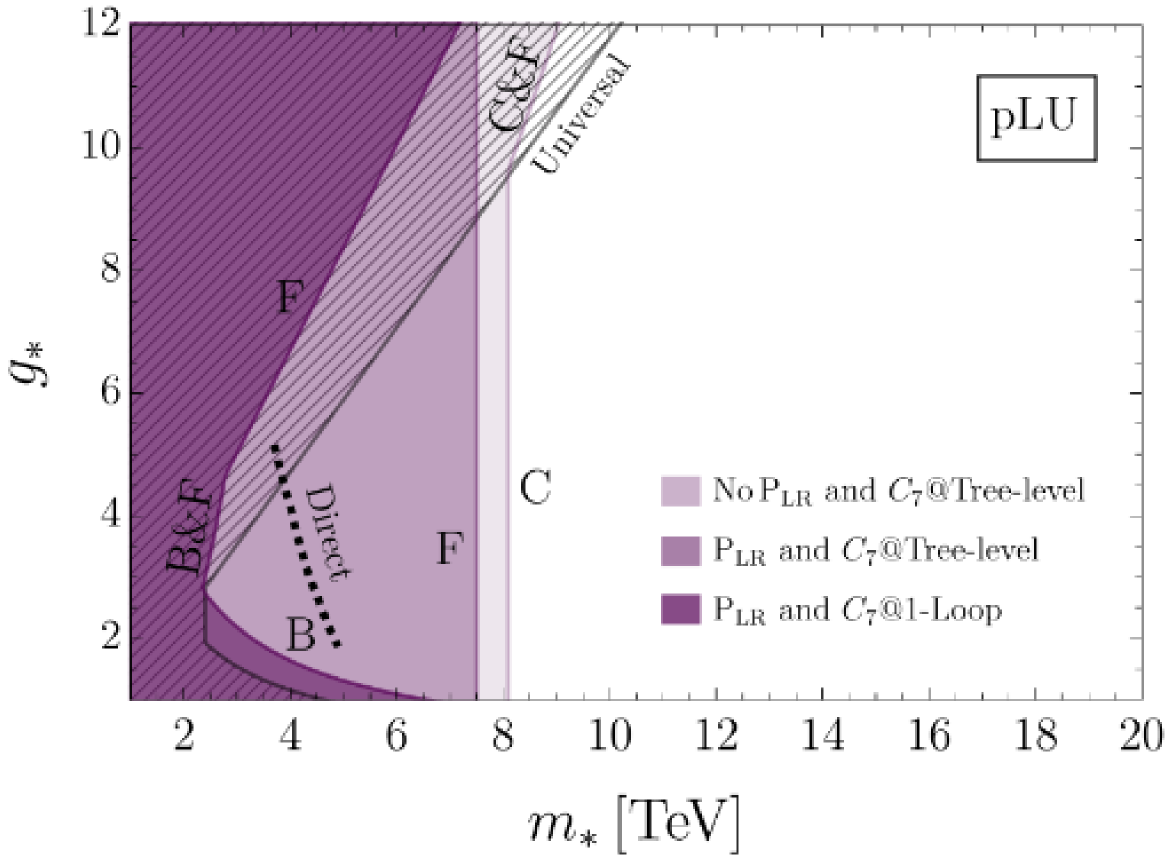

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The future

Label	Observable
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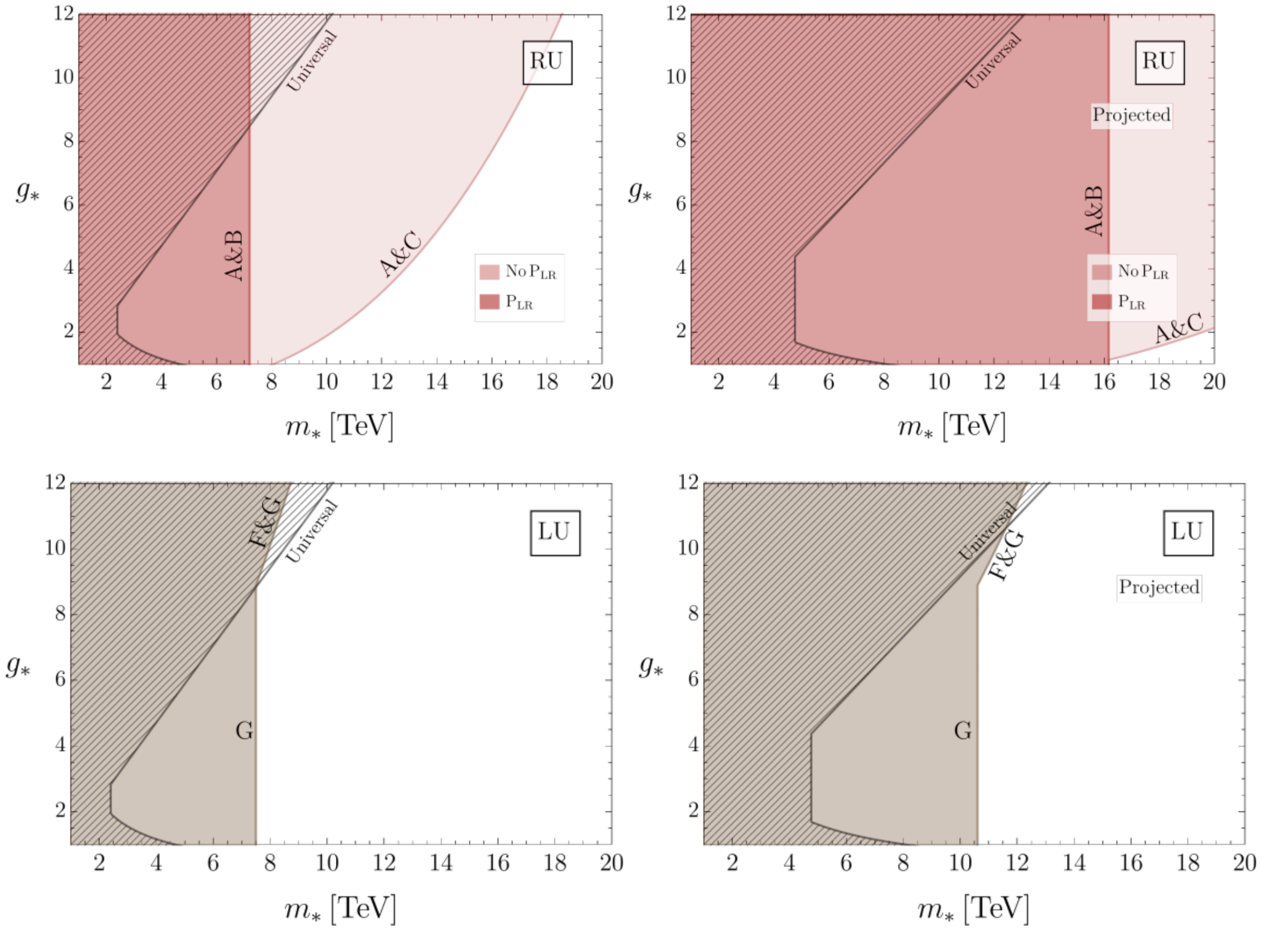

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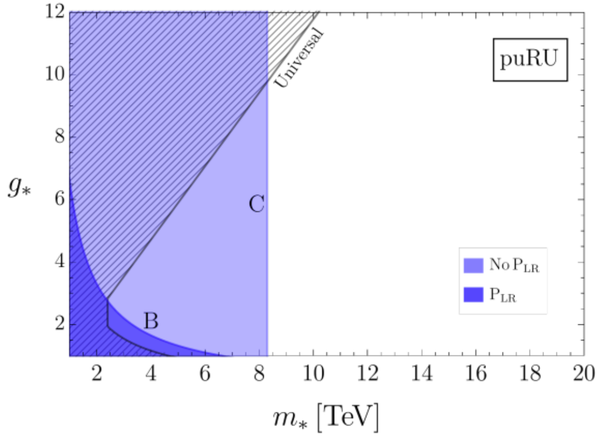

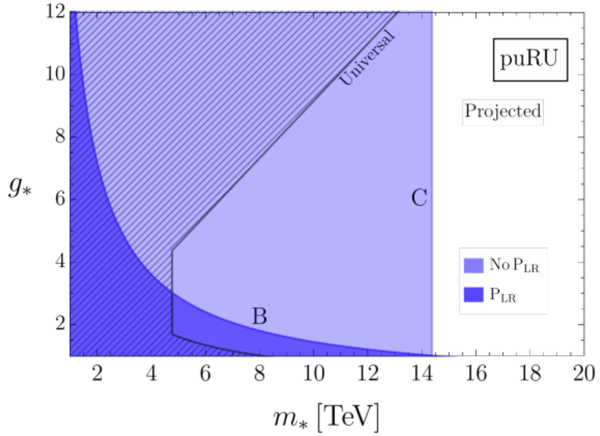

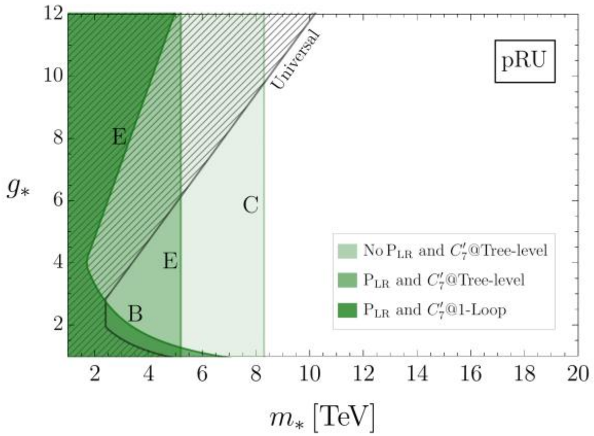

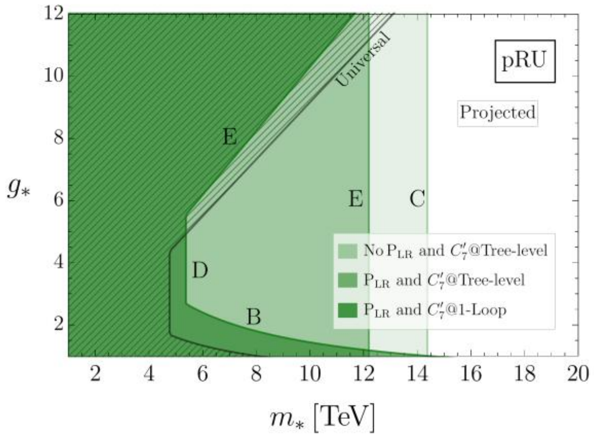

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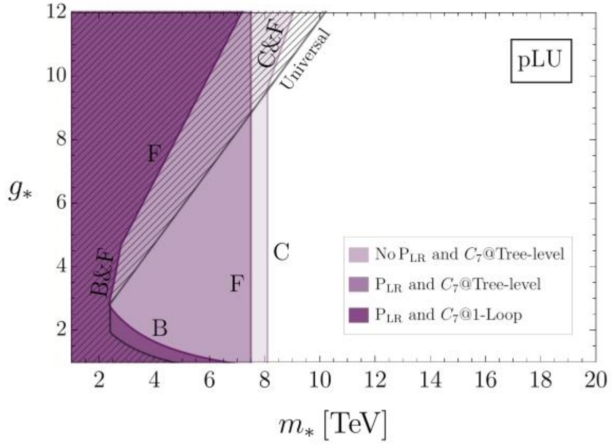

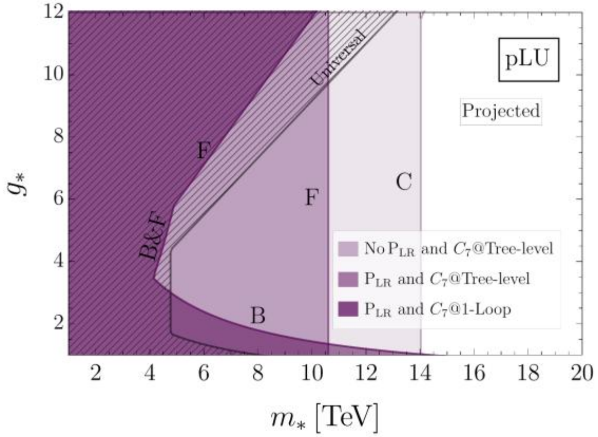

Summary

- **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**
- **Low-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