Flavor hierarchies from dynamical scales

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based on GP and A. Pomarol 1603.06609
GP, M. Riembau and T. Vantalon 1712.06337

The SM and BSM flavor puzzle

The SM has a **peculiar flavor structure**: where does it come from?

... so far several ideas, but no compelling scenario

Moreover strong theoretical considerations (naturalness problem) suggest the necessity of **new physics** related to the EW scale

big effects are typically expected in **flavor physics** and **CP violation**
(sensitive to energy scales much higher than TeV)

... but basically **no deviations** seen experimentally!

How can we explain this?

The SM and BSM flavor puzzle

Popular solutions:

- Very high BSM scale $\sim 10^3\ \mathrm{TeV}$ $\longrightarrow$ give up on naturalness
- BSM flavor structure similar to SM:
  - flavor symmetries
  - CP invariance

The SM and BSM flavor puzzle

Popular solutions:

- ✦ Very high BSM scale $\sim 10^3$ TeV $\longrightarrow$ give up on naturalness
- ✦ BSM flavor structure similar to SM:
  - flavor symmetries
  - CP invariance

This seems a step back from SM!

in the SM global symmetries are **accidental!**

"[symmetries] are not fundamental at all, but they are just accidents, approximate consequences of deeper principles."

S. Weinberg, referring to isospin
in "Symmetry: 'A 'Key to Nature's Secrets'"

Looking for a dynamical flavor structure

Is it possible to obtain the **flavor structure**
as an **emergent feature?**

In this talk I will try to address this question in the context of **composite Higgs scenarios**

The basic picture

Higgs compositeness and flavor

Higgs compositeness forces flavor structure to be explained at "low" energy scales

✦ Higgs associated to a composite operator:

$$\mathcal{O}_H \sim \bar{\psi}\psi \qquad \Rightarrow \qquad dim[\mathcal{O}_H] > 1$$

→ Yukawa's $\bar{f}\mathcal{O}_H f$ are irrelevant couplings reduced by running

Sizable **top** Yukawa can only be generated at **low scale!**

$$dim[\mathcal{O}_H] \gtrsim 2 \quad \Rightarrow \quad \Lambda_t \lesssim 10 \text{ TeV}$$

Anarchic partial compositeness

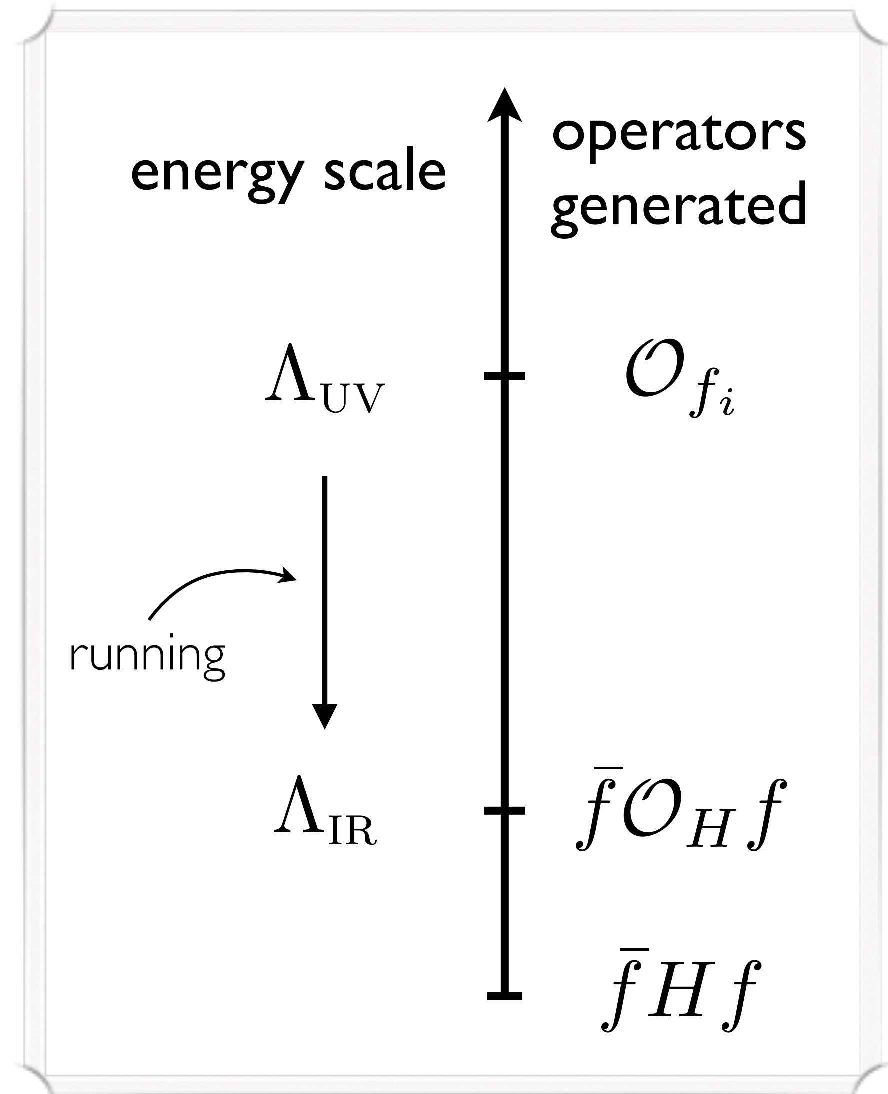
The standard **anarchic partial compositeness** flavor picture:

- Yukawa's from linear mixing to operators from the strong sector

$$\mathcal{L}_{lin} \sim \varepsilon_i \bar{f}_i \mathcal{O}_{f_i}$$

- size of IR mixings related to $dim[\mathcal{O}_{f_i}]$

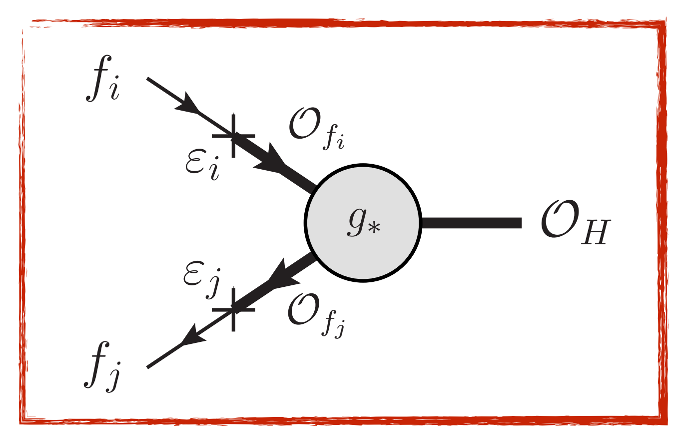
$$\varepsilon_{f_i}(\Lambda_{\rm IR}) \sim \left(\frac{\Lambda_{\rm IR}}{\Lambda_{\rm UV}}\right)^{dim[\mathcal{O}_{f_i}]-5/2}$$



→ smaller mixings give smaller Yukawa's

$$\mathcal{Y}_f \sim g_* \varepsilon_{f_i} \varepsilon_{f_j}$$

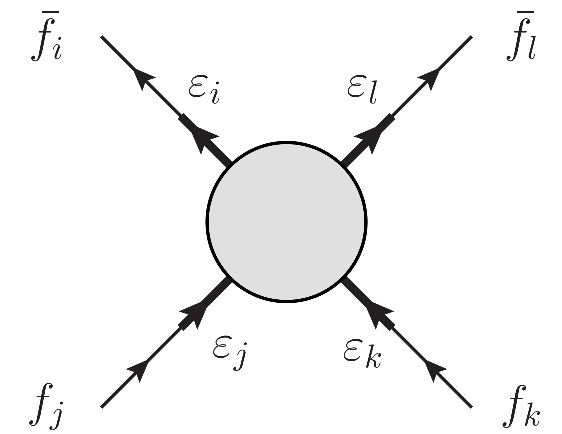
strong sector coupling



Flavor and CP-violation constraints

Strong bounds from $\Delta F = 2$ **transitions**

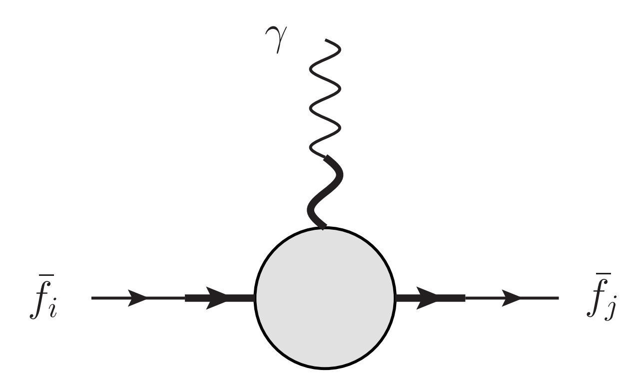
$$\mathcal{O}_{\Delta F=2} \sim \frac{g_*^2}{\Lambda_{\mathrm{IR}}^2} \varepsilon_i \varepsilon_j \varepsilon_k \varepsilon_l \bar{f}_i \gamma^\mu f_j \bar{f}_k \gamma_\mu f_l$$



- bound from ε_K: $\Lambda_{\mathrm{IR}} \gtrsim 10\ \mathrm{TeV}$

... and especially from **CP-violation** and **lepton flavor violation**

$$\mathcal{O}_{dipole} \sim \frac{g_*}{16\pi^2} \frac{g_* v}{\Lambda_{\mathrm{IR}}^2} \varepsilon_i \varepsilon_j \bar{f}_i \sigma_{\mu\nu} f_j g F^{\mu\nu}$$

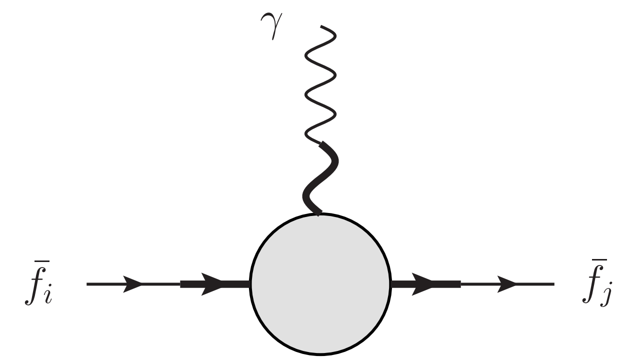


- bound from n EDM: $\Lambda_{\mathrm{IR}} \gtrsim 10\ \mathrm{TeV}(g_*/3)$
- bound from e EDM: $\Lambda_{\mathrm{IR}} \gtrsim 100\ \mathrm{TeV}(g_*/3)$
- bound from $\mu \to e\,\gamma$: $\Lambda_{\mathrm{IR}} \gtrsim 100\ \mathrm{TeV}(g_*/3)$

How to suppress EDM's

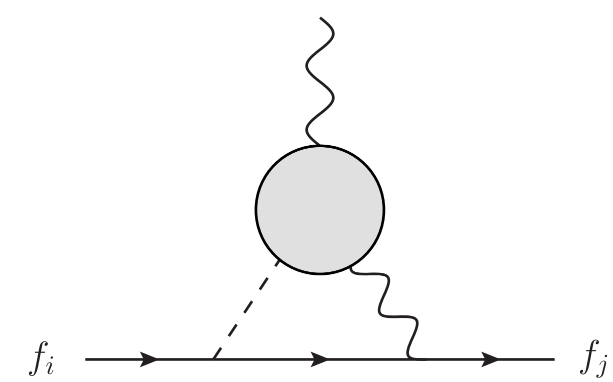
Large EDM's come from linear partial-compositeness mixings of light fermions

$$\mathcal{L}_{lin} \sim \varepsilon_i \bar{f}_i \mathcal{O}_{f_i}$$



Significant improvement if mixing through **bilinear operators**!

$$\mathcal{L}_{bilin} \sim \bar{f}_i \mathcal{O}_H f_j$$



- EDM's generated only at two loops

An explicit implementation

Portal interaction for light fermions "decouples" at high energy

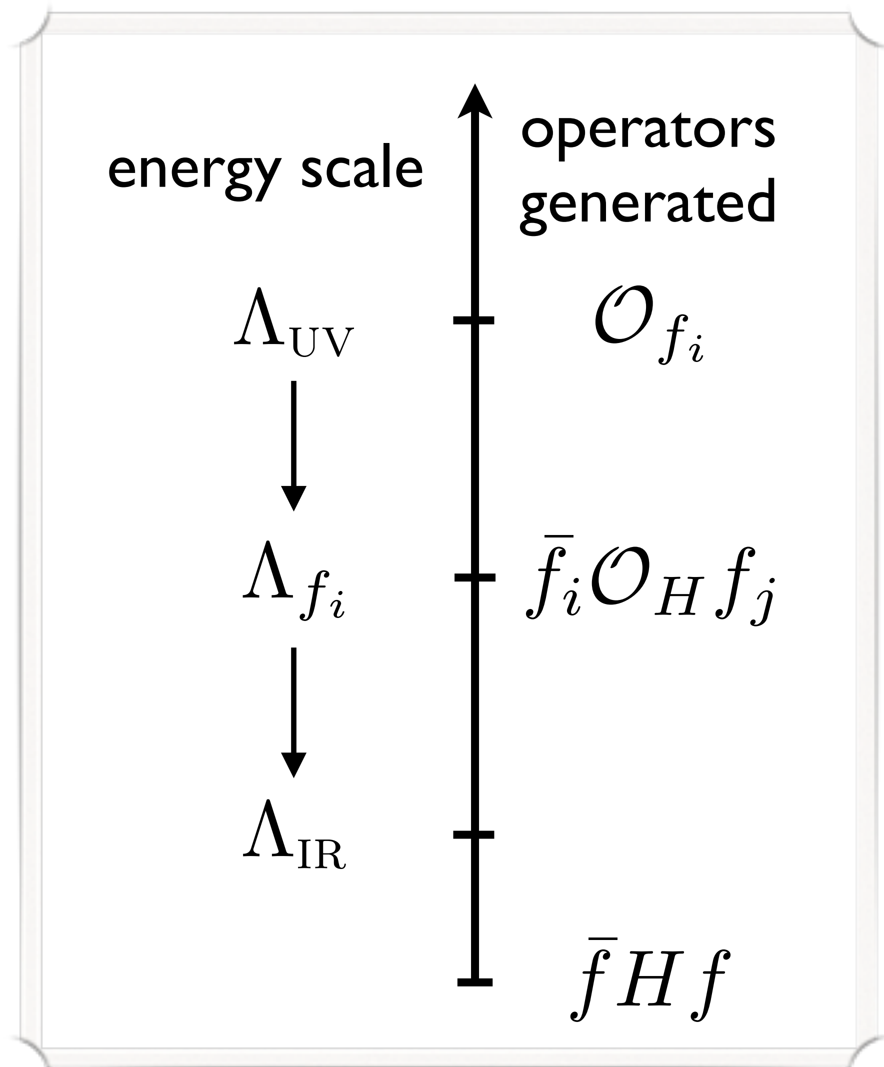
[GP and A. Pomarol '16]

[see also: Vecchi '12; Matsedonskyi '15; Cacciapaglia et al. '15]

$$\mathcal{L}_{lin} \sim \varepsilon_i \bar{f}_i \mathcal{O}_{f_i}$$

Bilinear mixing generated at scale Λ_f

$$\mathcal{L}_{bilin} \sim \bar{f}_i \mathcal{O}_H f_j$$

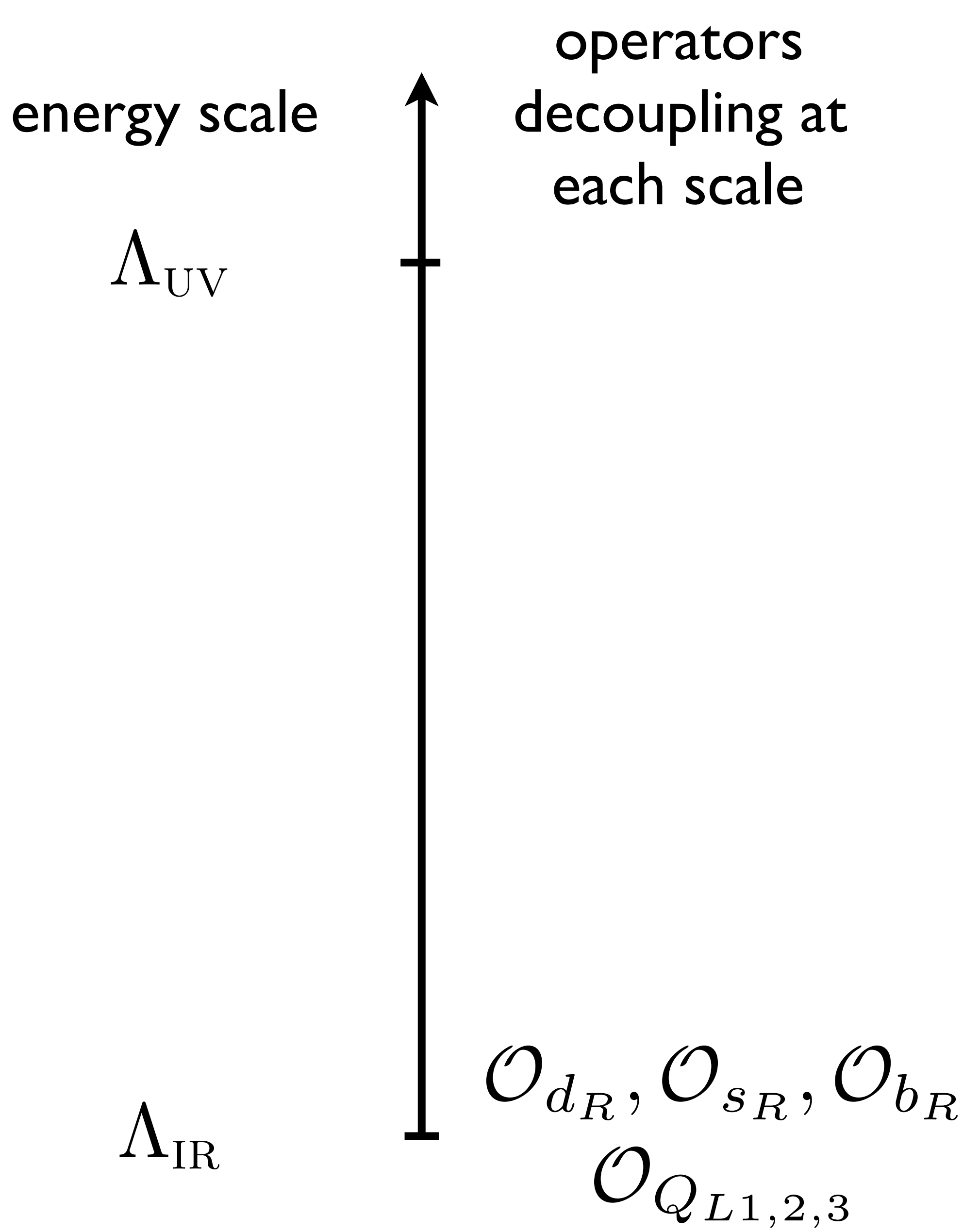


larger **decoupling scales** correspond to smaller fermion **masses**

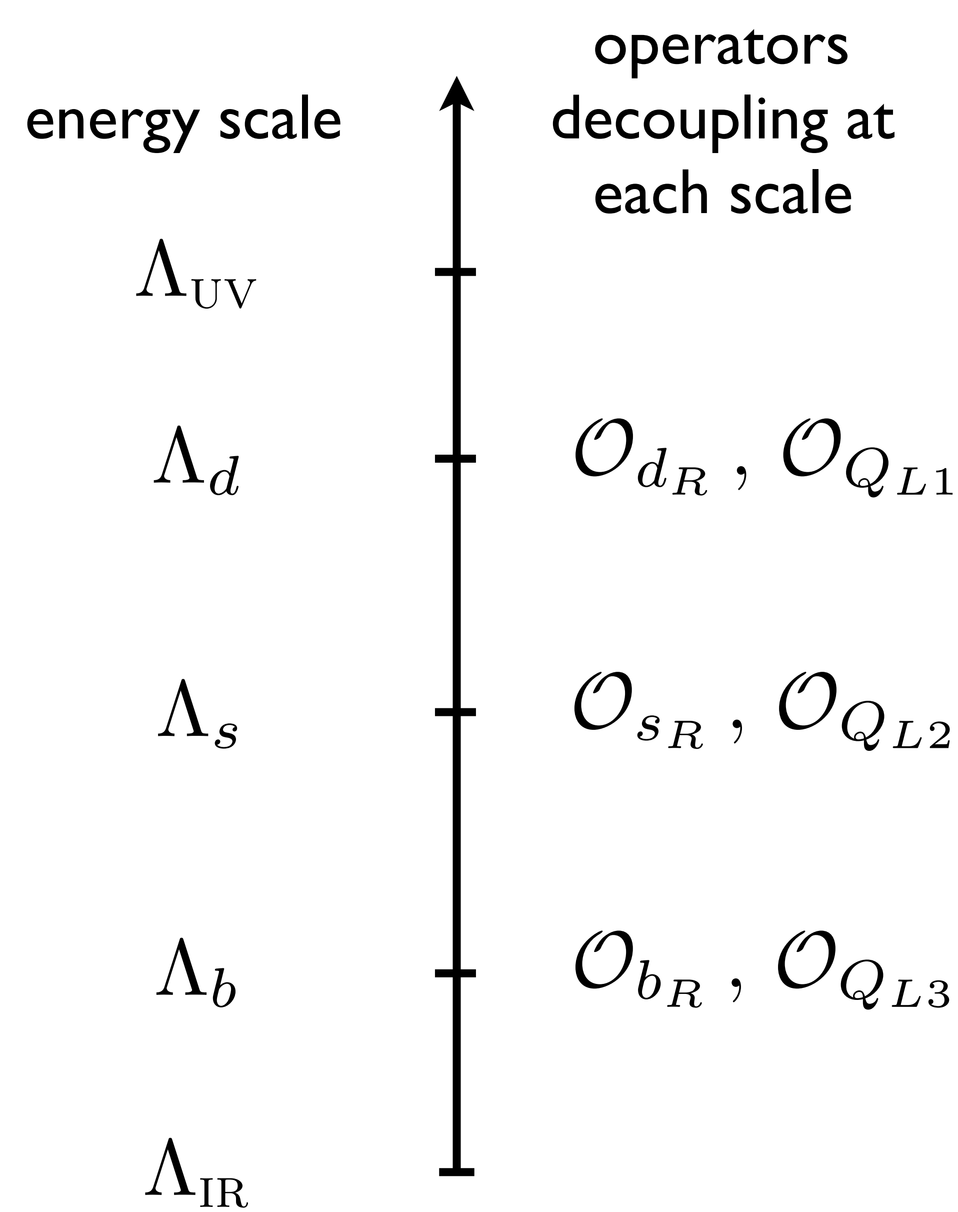
Anarchic vs Dynamical scales

Explicit example: The down-quark sector

Anarchic scenario



Dynamical scales



The emergent flavor structure

The emergent flavor structure

down-quark sector

decoupling energy scale | operators

Λ_d — $\mathcal{O}_{d_R}$, $\mathcal{O}_{Q_{L1}}$

Λ_s — $\mathcal{O}_{s_R}$, $\mathcal{O}_{Q_{L2}}$

Λ_b — $\mathcal{O}_{b_R}$, $\mathcal{O}_{Q_{L3}}$

Λ_{IR}

partial compositeness mixings

$$\mathcal{L}^{(3)}_{lin} = \varepsilon^{(3)}_{b_L}\overline{Q}_{L3}\mathcal{O}_{Q_{L3}} + \varepsilon^{(3)}_{b_R}\overline{b}_R\mathcal{O}_{b_R}$$

$$\Downarrow$$

below Λ_b

$$\mathcal{L}^{(3)}_{bilin} = \frac{1}{\Lambda_b^{d_H-1}}(\varepsilon^{(3)}_{b_L}\overline{Q}_{L3})\mathcal{O}_H(\varepsilon^{(3)}_{b_R}b_R)$$

$$\Downarrow$$

below Λ_{IR}

$$\mathcal{Y}_{down} = g_*\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \varepsilon^{(3)}_{b_L}\varepsilon^{(3)}_{b_R} \end{pmatrix}\left(\frac{\Lambda_{\mathrm{IR}}}{\Lambda_b}\right)^{d_H-1}$$

The emergent flavor structure

down-quark sector

decoupling energy scale	operators
Λ_d	$\mathcal{O}_{d_R}\,,\ \mathcal{O}_{Q_{L1}}$
Λ_s	$\mathcal{O}_{s_R}\,,\ \mathcal{O}_{Q_{L2}}$
Λ_b	$\mathcal{O}_{b_R}\,,\ \mathcal{O}_{Q_{L3}}$
$\Lambda_{\rm IR}$	

partial compositeness mixings

$$\mathcal{L}^{(2)}_{lin} = (\varepsilon^{(2)}_{b_L}\overline{Q}_{L3} + \varepsilon^{(2)}_{s_L}\overline{Q}_{L2})\mathcal{O}_{Q_{L2}} + (\varepsilon^{(2)}_{b_R}\overline{b}_R + \varepsilon^{(2)}_{s_R}\overline{s}_R)\mathcal{O}_{s_R}$$

below $\Lambda_{\rm S}$

$$\mathcal{L}^{(2)}_{bilin} = \frac{1}{\Lambda_d^{d_H-1}}(\varepsilon^{(2)}_{b_L}\overline{Q}_{L3} + \varepsilon^{(2)}_{s_L}\overline{Q}_{L2})\mathcal{O}_H(\varepsilon^{(2)}_{b_R}b_R + \varepsilon^{(2)}_{s_R}s_R)$$

below $\Lambda_{\rm IR}$

$$\mathcal{Y}_{down} = g_* \begin{pmatrix} 0 & 0 & 0 \\ 0 & \varepsilon^{(2)}_{s_L}\varepsilon^{(2)}_{s_R} & \varepsilon^{(2)}_{s_L}\varepsilon^{(2)}_{b_R} \\ 0 & \varepsilon^{(2)}_{b_L}\varepsilon^{(2)}_{s_R} & \end{pmatrix} \left(\frac{\Lambda_{\rm IR}}{\Lambda_s}\right)^{d_H-1}$$

The emergent flavor structure

down-quark sector

decoupling energy scale	operators
Λ_d	$\mathcal{O}_{d_R}\,,\ \mathcal{O}_{Q_{L1}}$
Λ_s	$\mathcal{O}_{s_R}\,,\ \mathcal{O}_{Q_{L2}}$
Λ_b	$\mathcal{O}_{b_R}\,,\ \mathcal{O}_{Q_{L3}}$
$\Lambda_{\rm IR}$	

partial compositeness mixings

$$\mathcal{L}^{(1)}_{lin} = (\varepsilon^{(1)}_{b_L}\overline{Q}_{L3} + \varepsilon^{(1)}_{s_L}\overline{Q}_{L2} + \varepsilon^{(1)}_{d_L}\overline{Q}_{L1})\mathcal{O}_{Q_{L1}}$$
$$+(\varepsilon^{(1)}_{b_R}\overline{b}_R + \varepsilon^{(1)}_{s_R}\overline{s}_R + \varepsilon^{(1)}_{d_R}\overline{d}_R)\mathcal{O}_{d_R}$$

$\Downarrow$

below Λ_d

$\Downarrow$

below $\Lambda_{\rm IR}$

$$\mathcal{Y}_{down} = g_* \begin{pmatrix} \varepsilon^{(1)}_{d_L}\varepsilon^{(1)}_{d_R} & \varepsilon^{(1)}_{d_L}\varepsilon^{(1)}_{s_R} & \varepsilon^{(1)}_{d_L}\varepsilon^{(1)}_{b_R} \\ \varepsilon^{(1)}_{s_L}\varepsilon^{(1)}_{d_R} & & \\ \varepsilon^{(1)}_{b_L}\varepsilon^{(1)}_{d_R} & & \end{pmatrix} \left(\frac{\Lambda_{\rm IR}}{\Lambda_d}\right)^{d_H-1}$$

The emergent flavor structure

The Yukawa matrix has an **“onion” structure**

$$\mathcal{Y}_{down} \simeq \begin{pmatrix} Y_d & \alpha_R^{ds} Y_d & \alpha_R^{db} Y_d \\ \alpha_L^{ds} Y_d & Y_s & \alpha_R^{sb} Y_s \\ \alpha_L^{db} Y_d & \alpha_L^{sb} Y_s & Y_b \end{pmatrix}$$

where the Yukawa’s are given by

$$Y_f \equiv g_* \varepsilon_{f_{Li}}^{(i)} \varepsilon_{f_{Ri}}^{(i)} \left(\frac{\Lambda_{\rm IR}}{\Lambda_f} \right)^{d_H - 1} \simeq m_f / v$$

- smaller Yukawa’s for larger decoupling scale
- mixing angles suppressed by Yukawa’s: $\theta_{ij} \sim Y_i / Y_j$

$\longrightarrow$ CKM mostly the rotation in the down-quark sector

Comparison with anarchic

bilinears

$$\begin{pmatrix} Y_d & \alpha_R^{ds} Y_d & \alpha_R^{db} Y_d \\ \alpha_L^{ds} Y_d & Y_s & \alpha_R^{sb} Y_s \\ \alpha_L^{db} Y_d & \alpha_L^{sb} Y_s & Y_b \end{pmatrix}$$

anarchic

$$\begin{pmatrix} Y_d & \sqrt{Y_d Y_s} & \sqrt{Y_d Y_b} \\ \sqrt{Y_d Y_s} & Y_s & \sqrt{Y_s Y_b} \\ \sqrt{Y_d Y_b} & \sqrt{Y_s Y_b} & Y_b \end{pmatrix}$$

The bilinear scenario predicts **smaller off-diagonal elements**

- particularly relevant for R rotations: suppressed w.r.t. anarchic

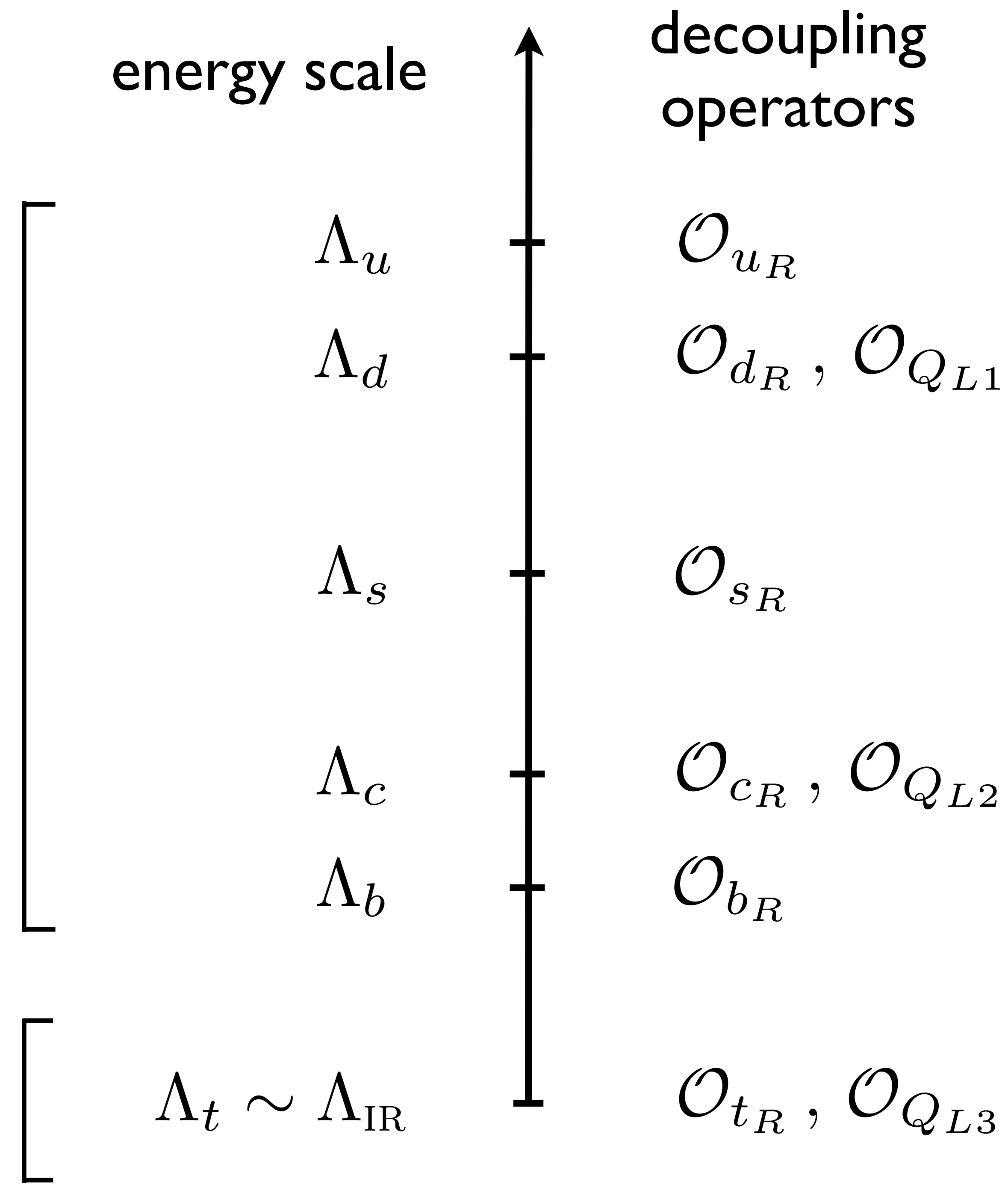
The hierarchy of scales

High scale suppresses flavor effects

- small contributions to FCNC's
- negligible EDM's

Main flavor effects from top

- unavoidable if top is composite!



Flavor and CP-violating effects

$\Delta F = 1$ transitions

Top partial compositeness at $\Lambda_{\rm IR}$ gives rise to flavor effects

$\Delta F = 1$ operators

$$\sim \frac{g_* Y_t}{\Lambda_{\rm IR}} \overline{Q}_{L3} \gamma^\mu Q_{L3}\, i\, H^\dagger \overleftrightarrow{D}_\mu H$$

$$\Big\downarrow$$

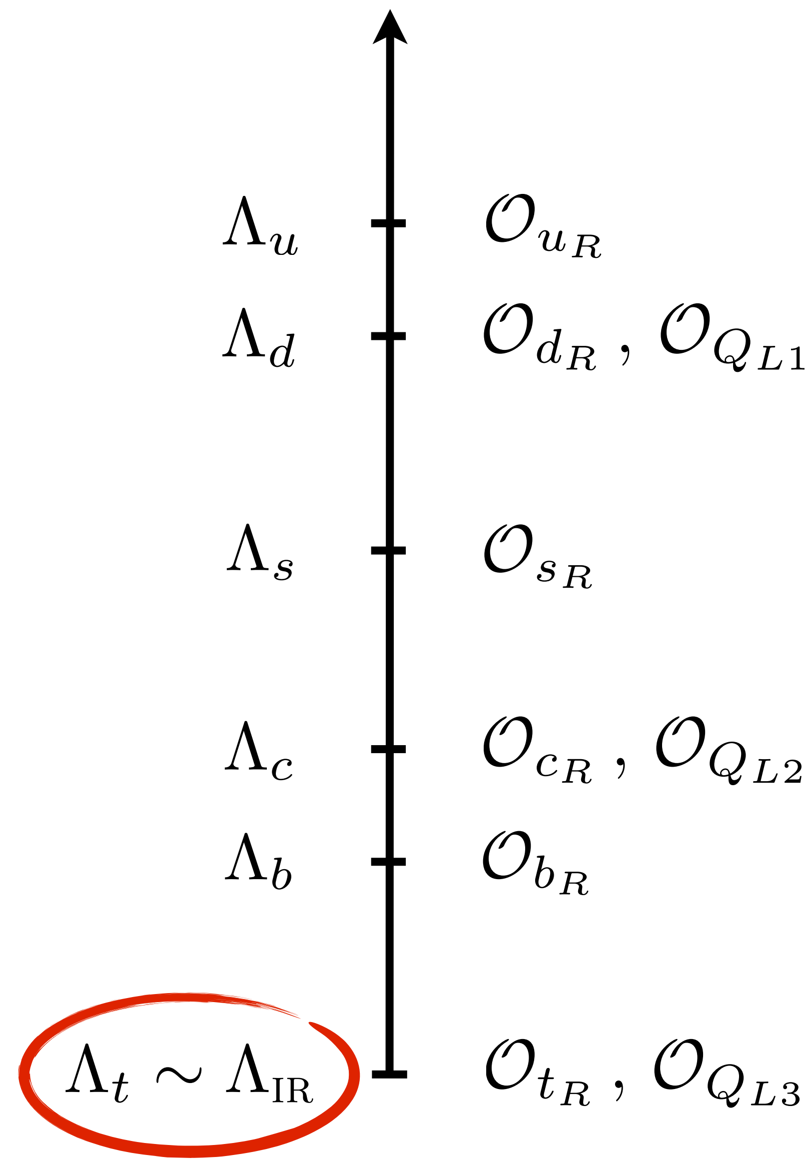
rotation to physical basis
$V_L \sim V_{\rm CKM}$

corrections to $K \to \mu\mu, \varepsilon'/\varepsilon, B \to X\ell\ell, Z \to bb$

- correlated and close to experimental bounds

$$\Lambda_{\rm IR} \gtrsim 4 - 5\ \text{TeV}$$

- can be suppressed by left-right symmetry



$\Delta F = 2$ transitions

Top partial compositeness at Λ_{IR} gives rise to flavor effects

$\boxed{\Delta F = 2 \text{ operators}}$

$$\sim \frac{Y_t^2}{\Lambda_{\text{IR}}^2} (\overline{Q}_{L3} \gamma^\mu Q_{L3})^2$$

rotation to physical basis
$V_L \sim V_{\text{CKM}}$

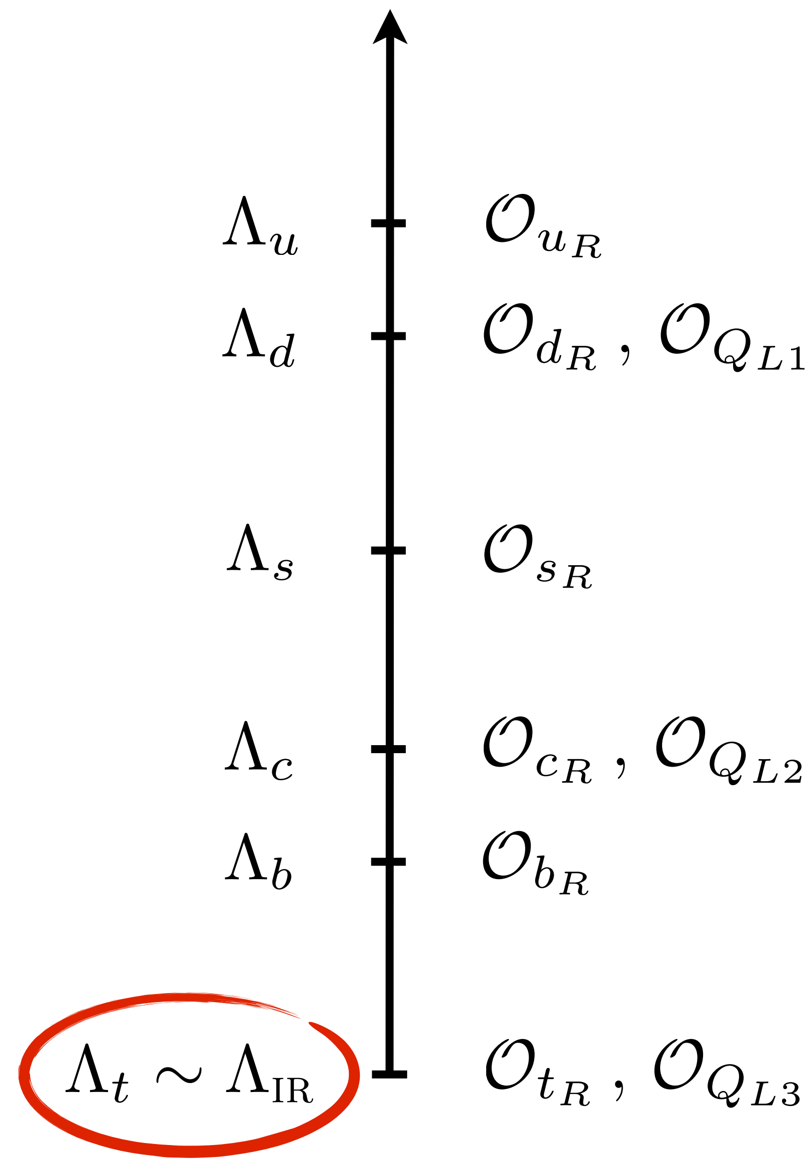
corrections to $\varepsilon_K \, , \, \Delta M_{B_d} \, , \, \Delta M_{B_s}$

- correlated: interesting prediction

$$\frac{\Delta M_{B_d}}{\Delta M_{B_s}} \simeq \left. \frac{\Delta M_{B_d}}{\Delta M_{B_s}} \right|_{\text{SM}}$$

- close to experimental bounds

$$\Lambda_{\text{IR}} \gtrsim 2 - 3 \text{ TeV}$$



Effects at higher scales

Top partial compositeness at $\Lambda_{\rm IR}$ gives rise to flavor effects

$\Delta F = 2$ **operators**

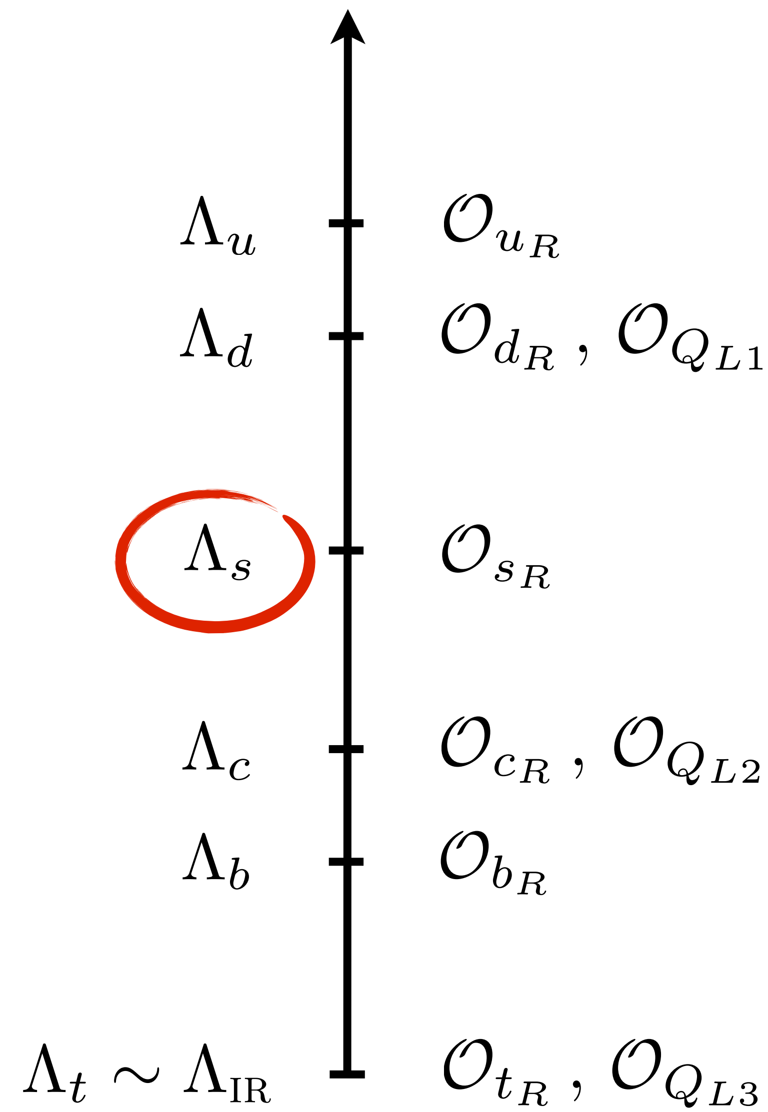
$$\sim \frac{g_*^2}{\Lambda_s^2}(\overline{Q}_{L2} s_R)(\overline{s}_R Q_{L2})$$

rotation to physical basis
$V_L \sim V_{\rm CKM}$

corrections to ε_K

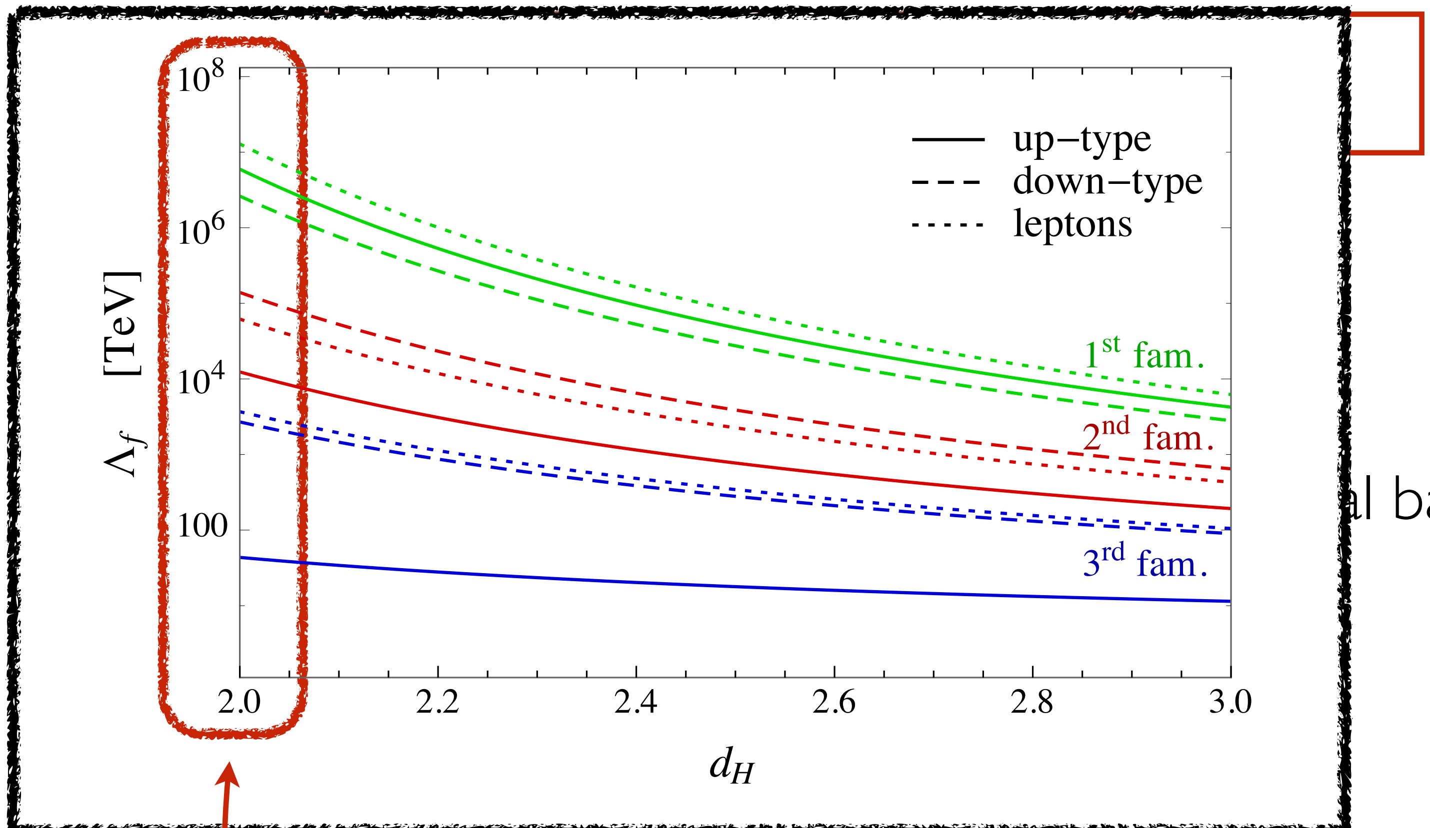
- close to experimental bounds for

$$\Lambda_s \sim 10^5 \ \mathrm{TeV}$$

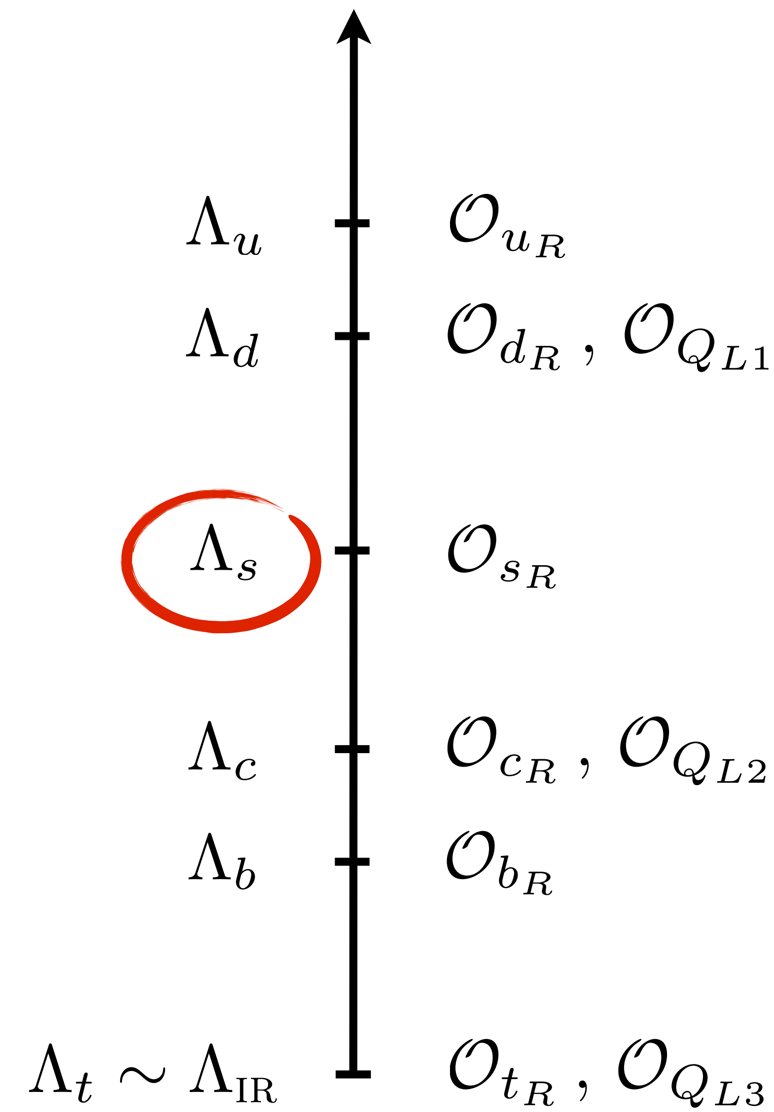


Effects at higher scales

Top partial compositeness at $\Lambda_{\rm IR}$ gives rise to flavor effects



al basis



- close to experimental bounds for

$$\Lambda_s \sim 10^5\ \text{TeV}$$

$$\Downarrow$$

realized if Higgs dimension $d_H \sim 2$

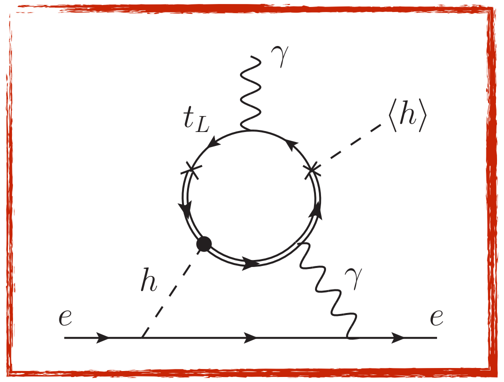
EDMs

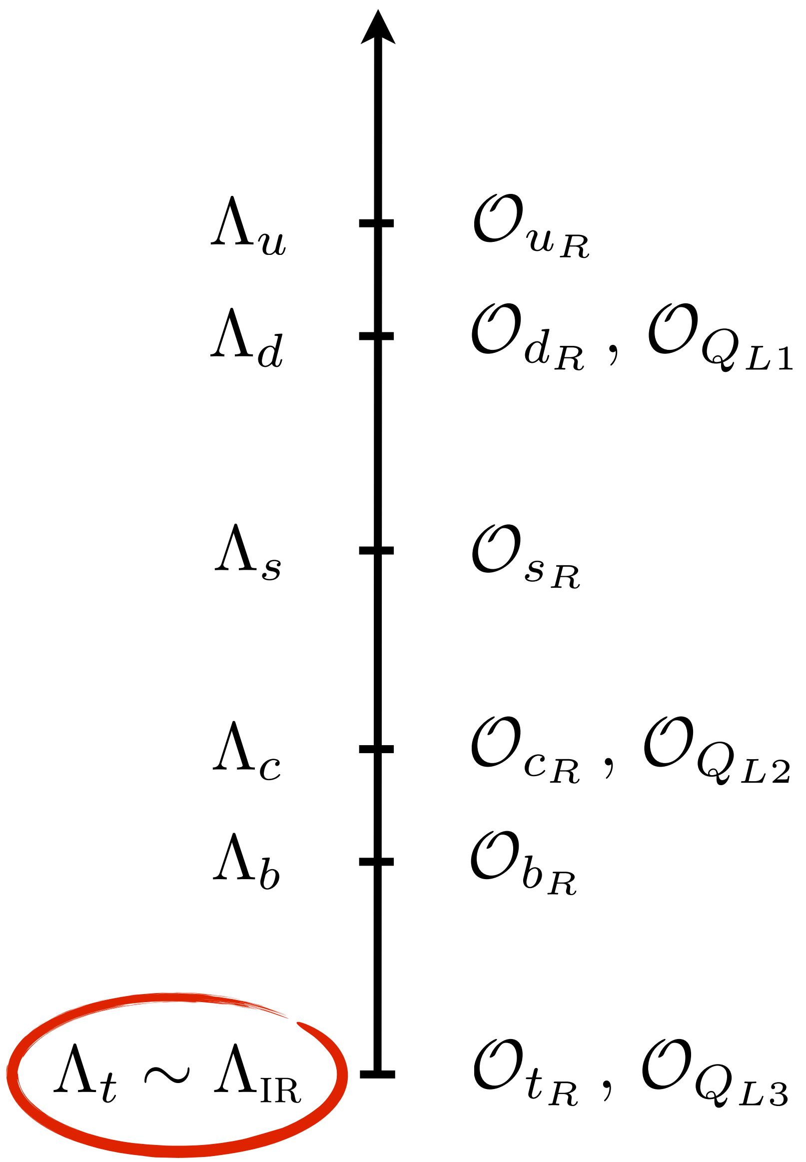
Top partial compositeness at $\Lambda_{\rm IR}$ gives rise to EDM's

- one-loop EDMs for light fermions suppressed by

$$\Lambda_{u,d,e} > 10^6 \ \mathrm{TeV}$$

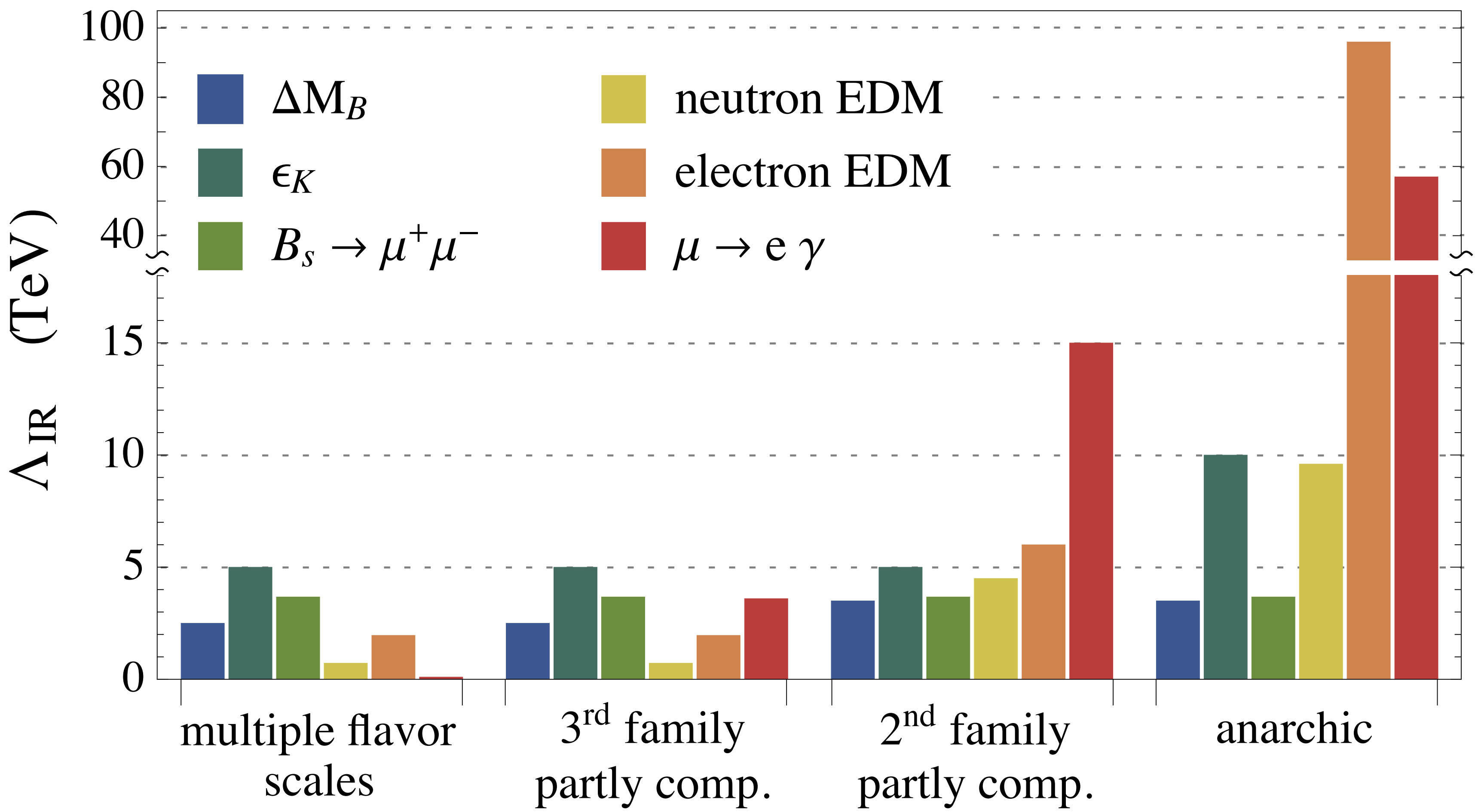
… but sizable **neutron** and **electron EDM** from two-loop Barr-Zee diagrams





n and e EDMs lead to the bound $\Lambda_{\rm IR} \gtrsim \mathrm{TeV}$

Summary of the bounds



- huge improvement with respect to the anarchic case (especially in the lepton sector)
- several effects close to experim. bounds for $\Lambda_{\rm IR} \sim \mathit{few}$ TeV

Next generation EDM bounds

Experimental bounds on EDMs will soon greatly improve

- ✦ electron EDM

ACME		*ACME II*		*ACME III*
$\lvert d_e \rvert < 9.4 \cdot 10^{-29} e\,\mathrm{cm}$	$\longrightarrow$	$\lvert d_e \rvert \lesssim 0.5 \cdot 10^{-29} e\,\mathrm{cm}$	$\longrightarrow$	$\lvert d_e \rvert \lesssim 0.3 \cdot 10^{-30} e\,\mathrm{cm}$

- ✦ neutron EDM

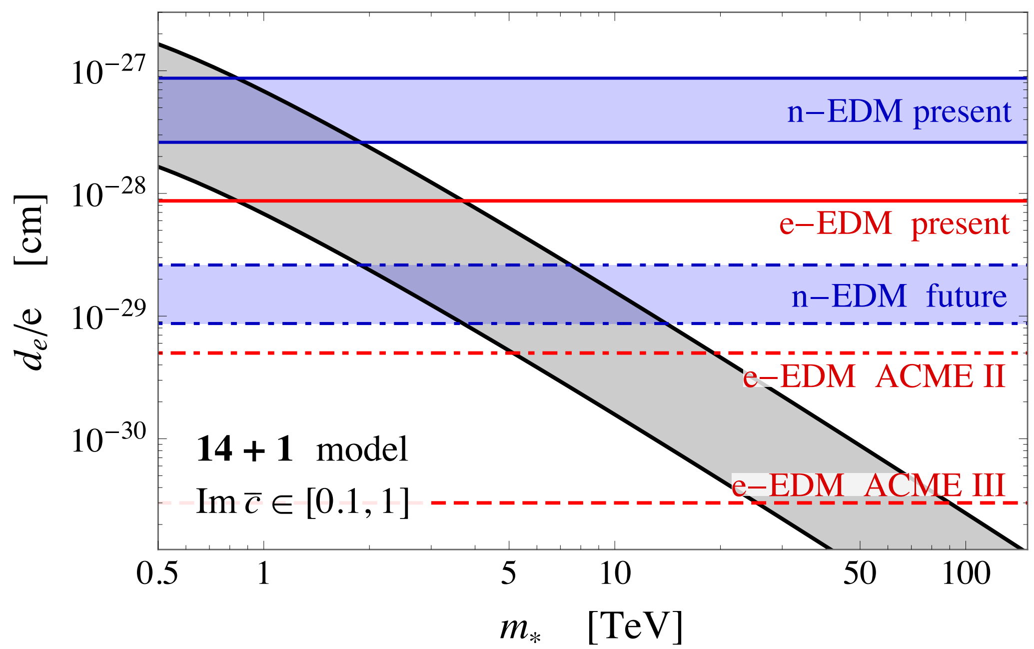
$$|d_n| < 2.9 \cdot 10^{-26} e\,\mathrm{cm} \longrightarrow |d_n| \lesssim 10^{-27} e\,\mathrm{cm}$$

- ‣ EDMs will become some of the strongest bounds on BSM, indirectly probing new physics well above the 10 TeV scale

EDM probes of top partners

Near-future bounds could probe partner masses well above 10 TeV

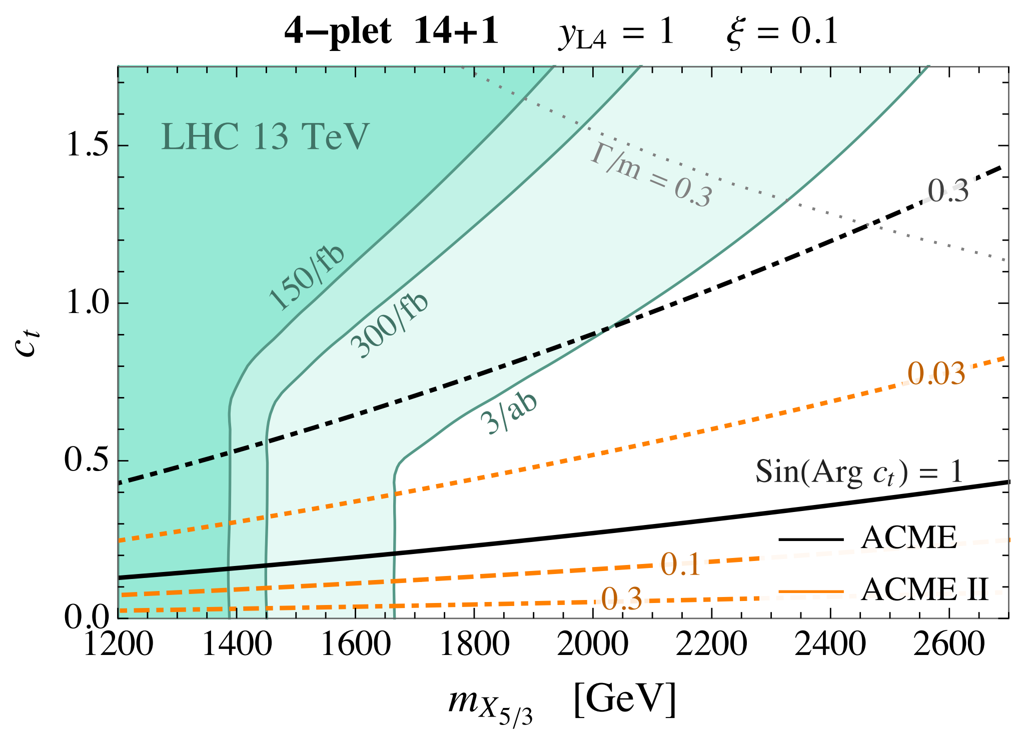
[GP, M. Riembau, T. Vantalon '17]

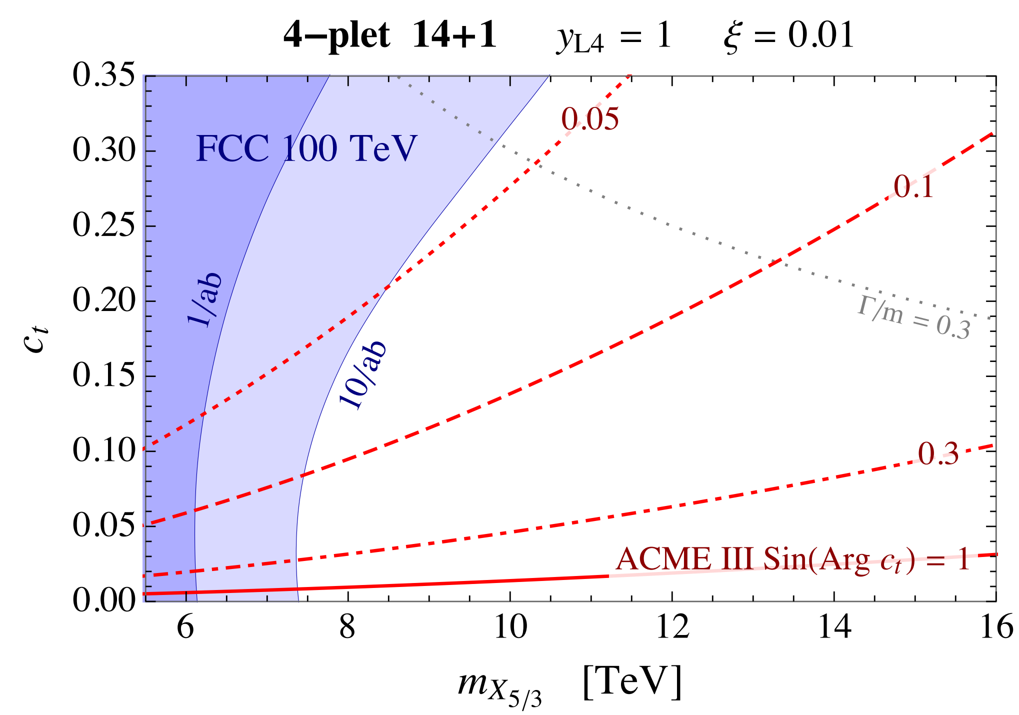


EDM probes of top partners

EDM bounds competitive with direct searches at LHC and even FCC_{100}

[GP, M. Riembau, T. Vantalon '17]





Conclusions

Conclusions

The **flavour structure** of the SM could be an **emergent feature:**

- ✦ Yukawa hierarchies linked to dynamically generated mass scales

Successful implementation in composite Higgs scenarios

- ✦ modification of partial compositeness
- ✦ flavor from mixing with the composite dynamics at different scales
  (at low energy equivalent to bilinear mixings)
- ✦ compatibility with flavour bounds + several new physics effects around the corner

Backup

One scale for each family

More economical construction by associating one scale to each generation

decoupling energy scale	operators
$\Lambda_u \sim \Lambda_d \sim \Lambda_e$	$\mathcal{O}_{Q_{L1}}, \mathcal{O}_{d_R}, \mathcal{O}_{u_R}, \ldots$
$\Lambda_c \sim \Lambda_s \sim \Lambda_\mu$	$\mathcal{O}_{Q_{L2}}, \mathcal{O}_{s_R}, \mathcal{O}_{c_R}, \ldots$
$\Lambda_t \sim \Lambda_b \sim \Lambda_\tau$	$\mathcal{O}_{Q_{L3}}, \mathcal{O}_{b_R}, \mathcal{O}_{t_R}, \ldots$

- ✦ Yukawa differences within each generation due to different mixings
- ✦ Only main difference: $\mu \to e\gamma$ close to exp. bounds

Neutrino masses

- **Majorana masses** realization:

$$\frac{1}{\Lambda_\nu^{2d_H-1}}\overline{L}^c\mathcal{O}_H\mathcal{O}_H L \quad \longrightarrow \quad m_\nu \simeq \frac{g_*^2 v^2}{\Lambda_{\rm IR}}\left(\frac{\Lambda_{\rm IR}}{\Lambda_\nu}\right)^{2d_H-1}$$

for $d_H \sim 2$ dimension-7 operators:

$$m_\nu \sim 0.1 - 0.01 \text{ eV} \quad \Rightarrow \quad \Lambda_\nu \sim 0.8 - 1.5 \times 10^8 \text{ GeV} \sim \Lambda_e$$

- **Dirac masses** realization:

$$\frac{1}{\Lambda_\nu^{d_H-1}}\mathcal{O}_H\overline{L}\nu_R$$

for $d_H \sim 2$ dimension-5 operators as in SM