

Naturalness: Flavor and Top quarks

Giuliano Panico



Barcelona

Top 2017, Braga – 21/9/2017

Top compositeness, Flavor and Naturalness

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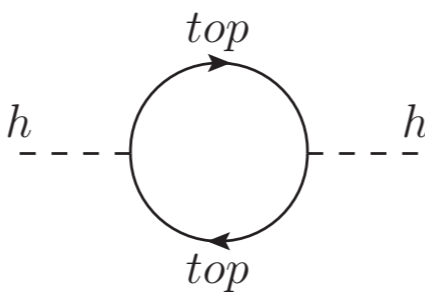
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Top and Naturalness

The **top quark** plays a central role for **Naturalness**

- ▶ it induces the largest SM loop corrections to the Higgs mass

$$\delta m_h^2|_{1-loop} \sim \text{diagram} \sim -\frac{y_{top}^2}{8\pi^2} \Lambda_{UV}^2 \gg 125 \text{ GeV}$$


In theories with a large cut-off $\Lambda_{UV} \gg \text{TeV}$ a sizable cancellation is needed to keep the Higgs mass small

$$m_h^2 = m_h^2|_{bare} + \delta m_h^2|_{1-loop} = 125 \text{ GeV}$$

Top and Naturalness

Solving the Naturalness Problem has been one of the **main guidelines** to go beyond the SM

The basic idea: new physics can screen the top loop

$$\delta m_h^2|_{1-loop} \sim \text{diagram with top loop} + \text{diagram with NP} \sim -\frac{y_{top}^2}{8\pi^2} \Lambda_{NP}^2 \lesssim \text{TeV}$$

Necessary ingredient: low new physics scale $\Lambda_{NP} \lesssim \text{TeV}$

► possibly within the LHC reach!

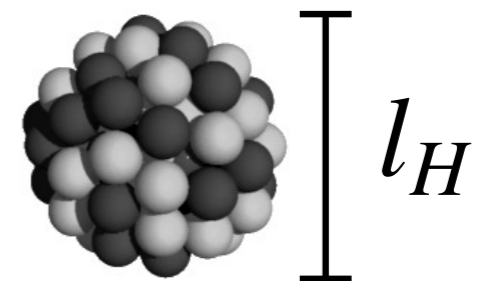
Residual tuning

$$\Delta \simeq \frac{\delta m_h^2|_{1-loop}}{m_h^2} \simeq \left(\frac{\Lambda_{NP}}{500 \text{ GeV}} \right)^2$$

The composite Higgs solution

A strongly-coupled solution: **Higgs as a composite state** [Georgi, Kaplan]

- ▶ corrections to m_h screened at the compositeness scale $\sim \text{TeV}$



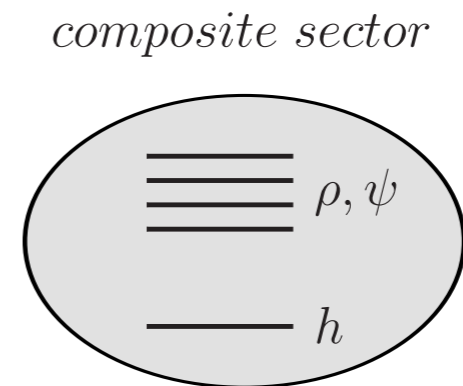
Compelling features:

- ▶ new strongly-coupled sector
- ▶ Higgs as a Goldstone boson from spontaneously broken global symmetry (useful to keep Higgs couplings and EW parameters under control)

The composite Higgs solution

Phenomenological consequences:

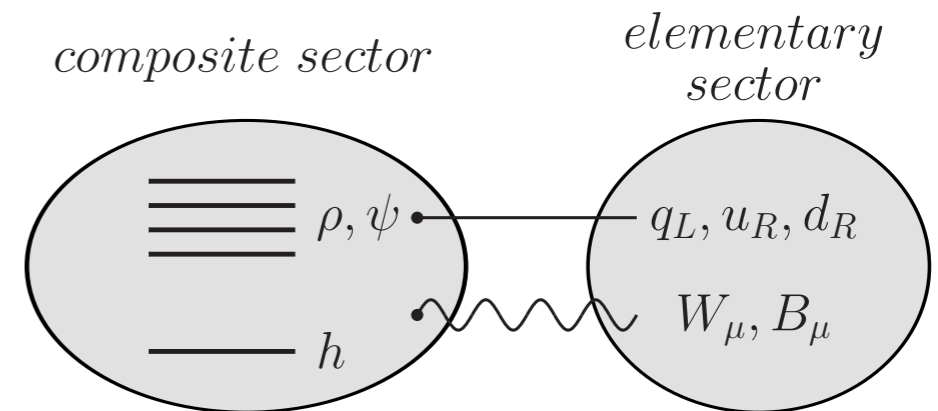
- ▶ deviations in Higgs couplings
- ▶ resonances at $m \sim \text{TeV}$
(massive vectors and heavy fermions)




The composite Higgs solution

Phenomenological consequences:

- ▶ deviations in Higgs couplings
- ▶ resonances at $m \sim \text{TeV}$
(massive vectors and heavy fermions)



Resonances are coupled with SM states

- ▶ largest mixing with top quark  **top partners**
sizable **top compositeness**
(deviations in top couplings)
- ▶ crucial role in naturalness \rightarrow **light** top partners

Top partners

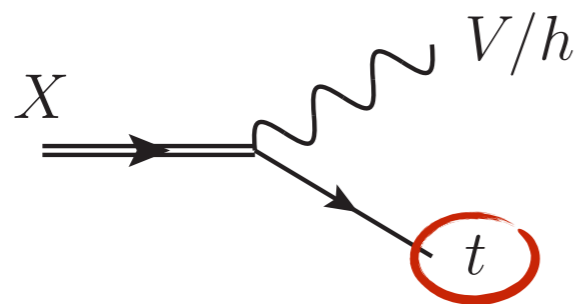
Top partners phenomenology

Main properties:

- ▶ colored states (usually QCD triplets)
- ▶ charged under EW (fill extended multiplets due to custodial symmetry)

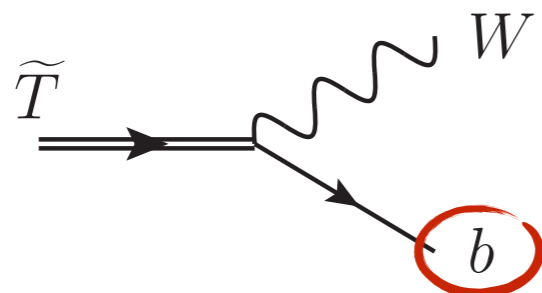
Minimal multiplets:

- ▶ custodial **fourplet** $\begin{pmatrix} T & X_{5/3} \\ B & X_{2/3} \end{pmatrix}$

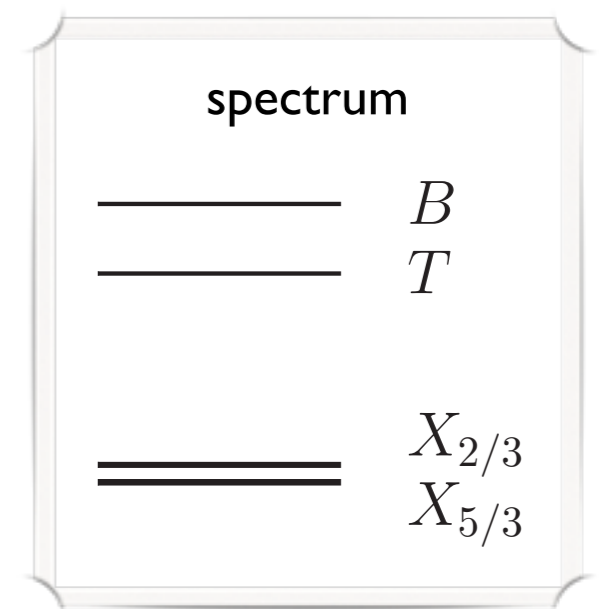


- ▶ sizable couplings to top
- ▶ exotic states are the lightest

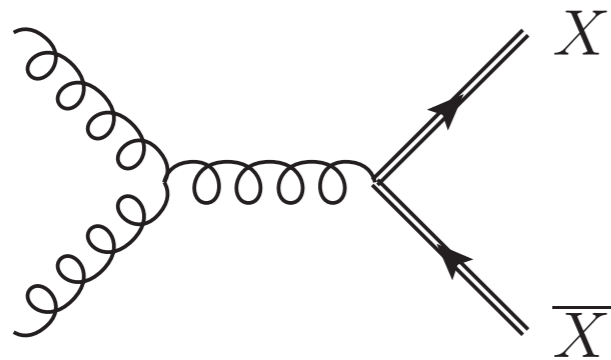
- ▶ custodial **singlet** \tilde{T}



- ▶ sizable couplings to bottom

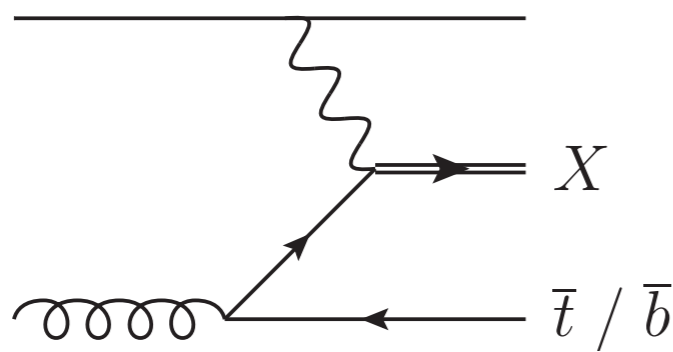


Top partners phenomenology



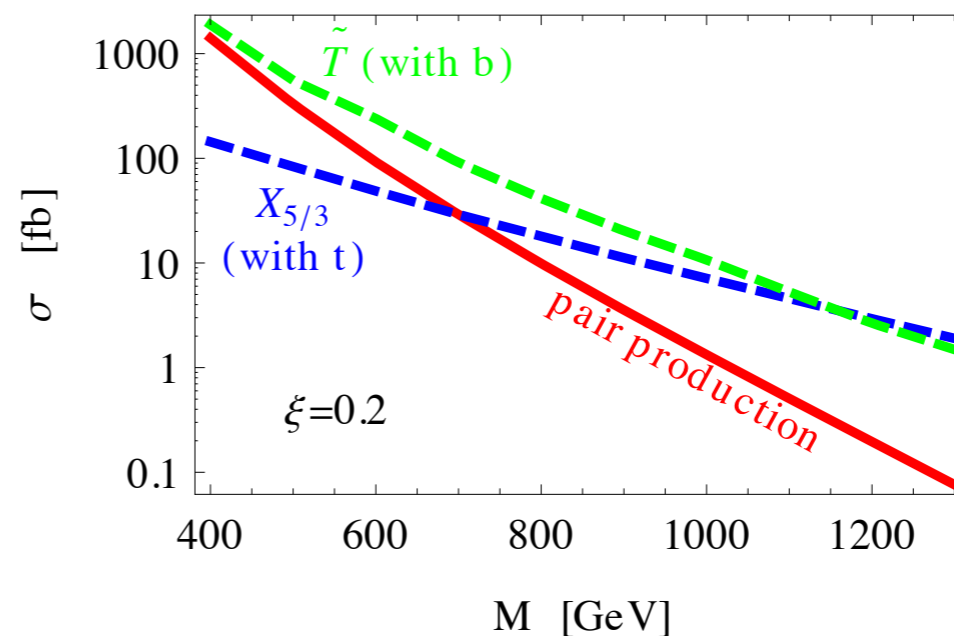
QCD pair production

- ▶ model independent
- ▶ more relevant at low mass



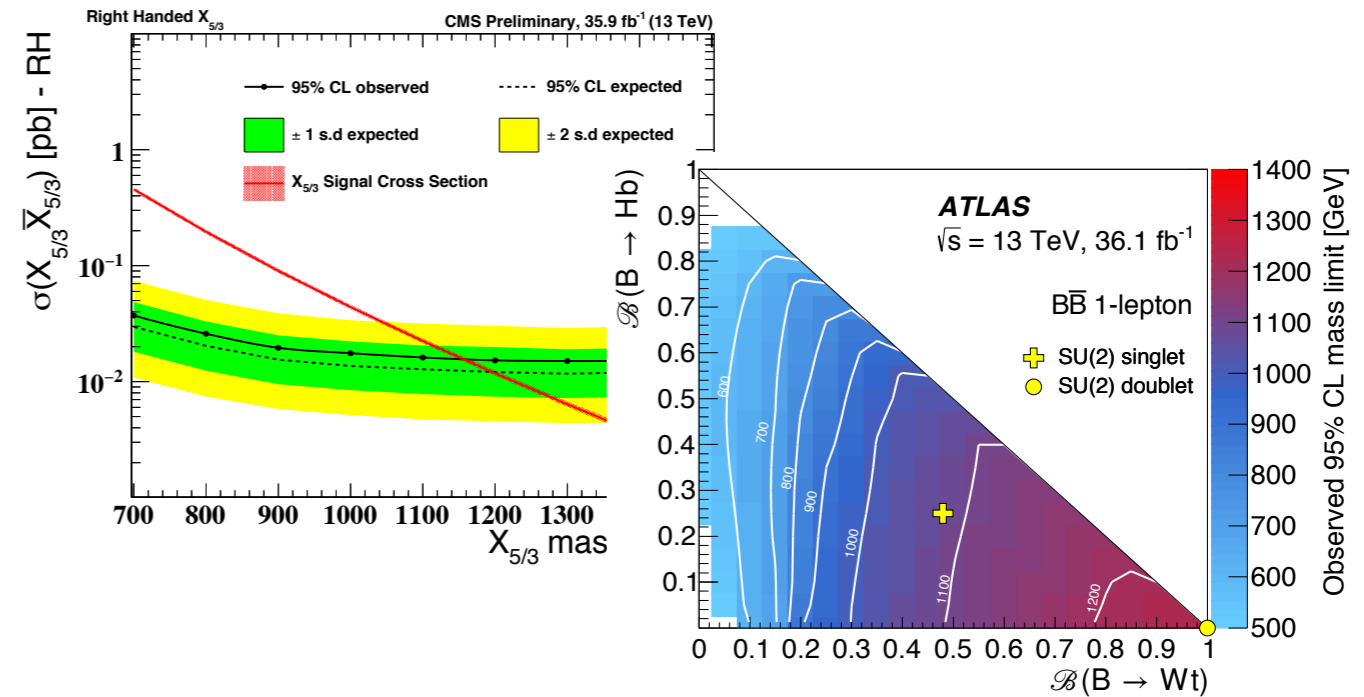
Single production with t or b

- ▶ model dependent
- ▶ potentially relevant at high masses
- ▶ production with b dominant when allowed



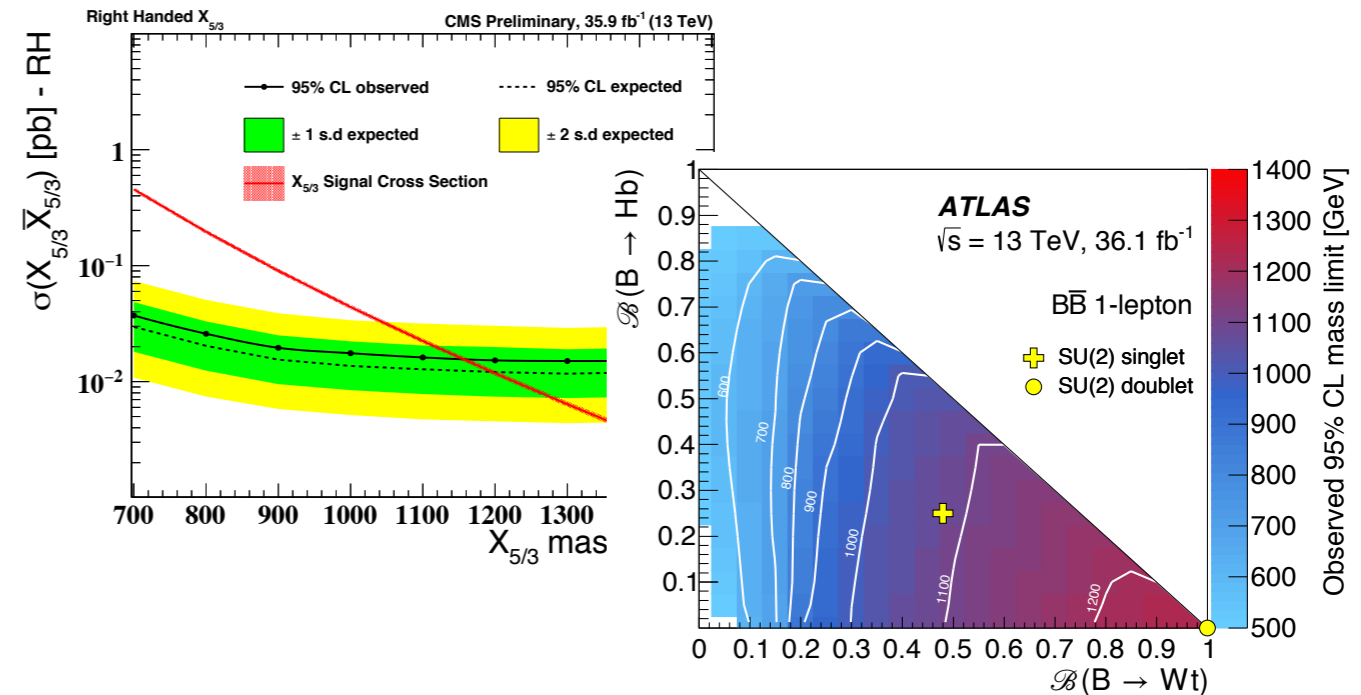
Bounds from direct searches

Current bounds slightly above the TeV scale

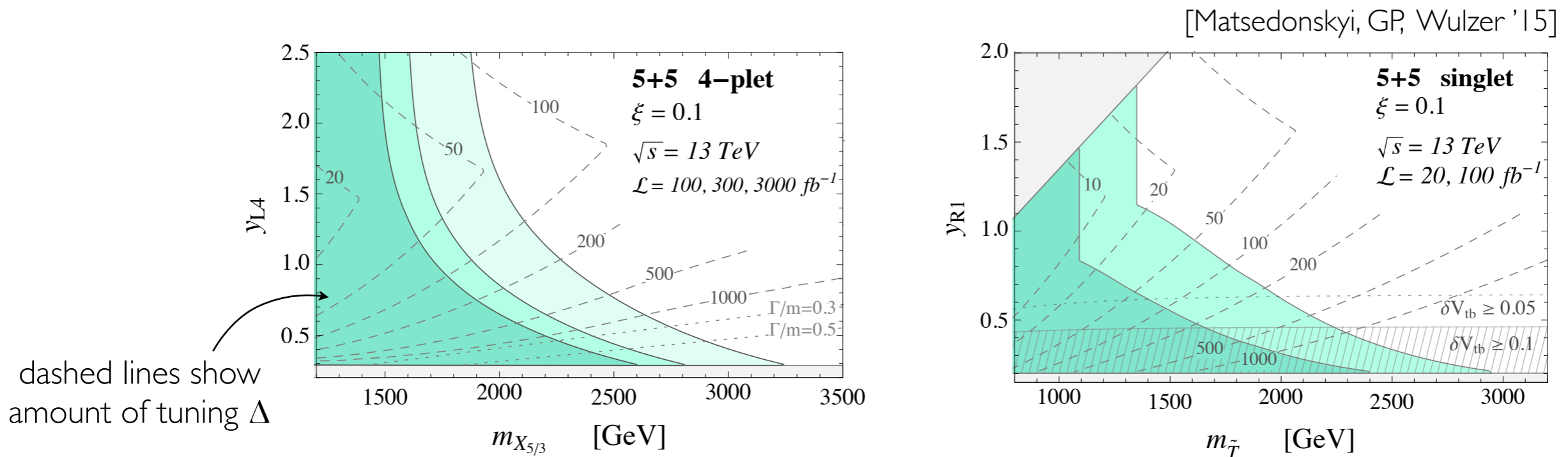


Bounds from direct searches

Current bounds slightly above the TeV scale



Future runs can test multi-TeV resonances



- completely probe parameter space with low tuning: $1/\Delta \gtrsim \text{few } \%$

Impact on explicit models

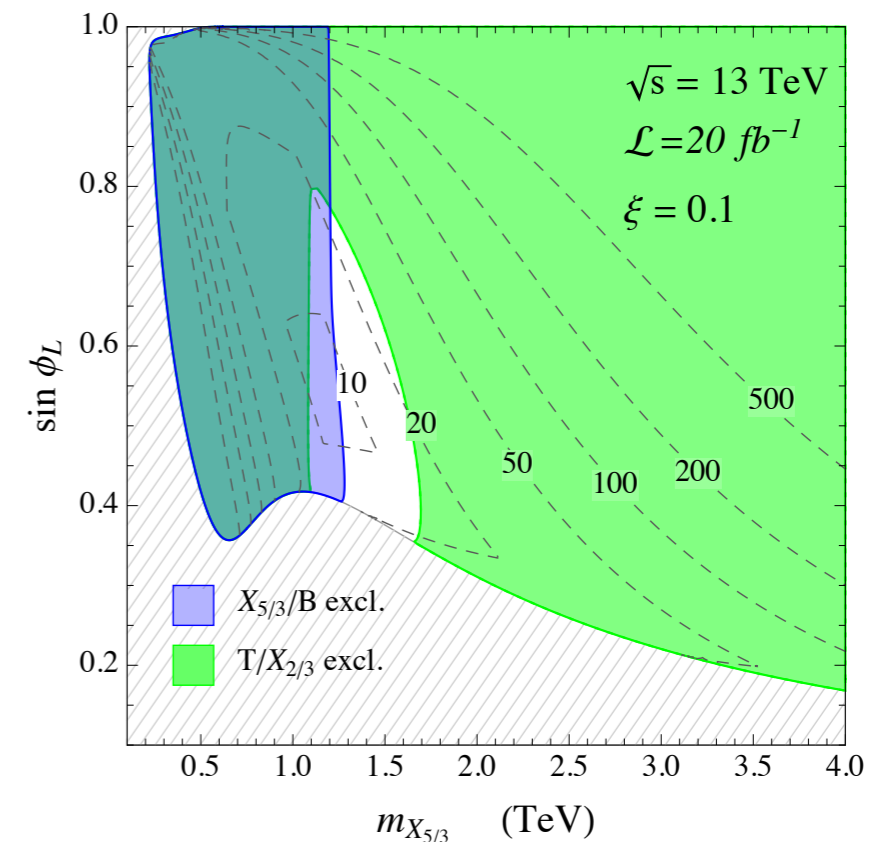
In a large class of minimal models (eg. MCHM_{4,5,10}) the mass of the lightest partner is tightly connected to the compositeness scale f

[Matsedonskyi, G. P., Wulzer; Marzocca, Serone, Shu; Pomarol, Riva]

$$\frac{m_H}{m_{top}} \gtrsim \frac{\sqrt{3}}{\pi} \frac{M_X}{f} \quad \Rightarrow \quad \xi \equiv \frac{v^2}{f^2} \lesssim \left(\frac{500 \text{ GeV}}{M_X} \right)^2$$

Current exclusions:

- ▶ rule-out almost completely $\xi > 0.1$
- ▶ push minimal tuning below 10% level



Impact on explicit models

In a large class of minimal models (eg. MCHM_{4,5,10}) the mass of the lightest partner is tightly connected to the compositeness scale f

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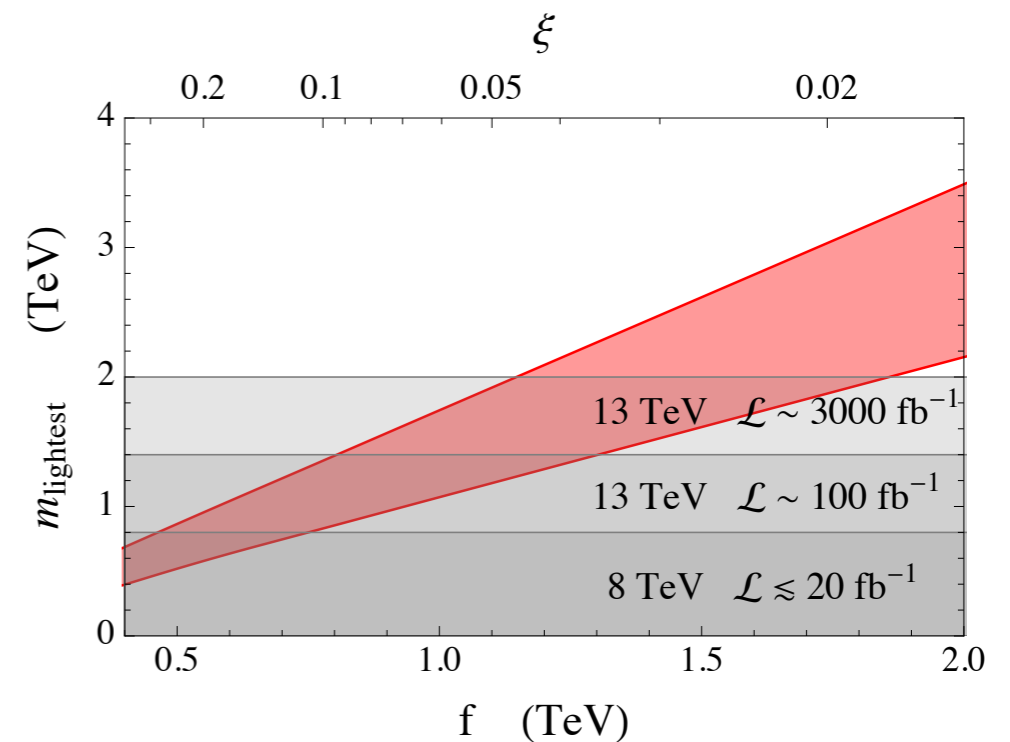
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Current exclusions:

- ▶ rule-out almost completely $\xi > 0.1$
- ▶ push minimal tuning below 10% level

High-luminosity reach:

- ▶ completely probe $\xi > 0.05$
- ▶ tuning below few %



Top couplings

The top couplings

Important consequences of top and Higgs compositeness are deviations in the **top couplings**

Main effects:

- ♦ modification of **top Yukawa**
(due to Higgs compositeness)
- ♦ modification of **gauge couplings**
(due to vector res. and mixing with partners)
- ♦ effective 4-fermion **contact interactions**
(mediated by heavy resonances)

Modification of Higgs couplings

The **Higgs compositeness** induces modification of **Higgs couplings**

- ◆ coupling to **gauge fields**

- ▶ universal, determined by symmetry: eg. $SO(5)/SO(4) \Rightarrow k_V = \sqrt{1 - \xi}$

- ◆ **Yukawa's**

- ▶ depends on partners quantum numbers: eg. $MCHM_5 \quad k_F = \frac{1 - 2\xi}{\sqrt{1 - \xi}}$
 $MCHM_4 \quad k_F = \sqrt{1 - \xi}$

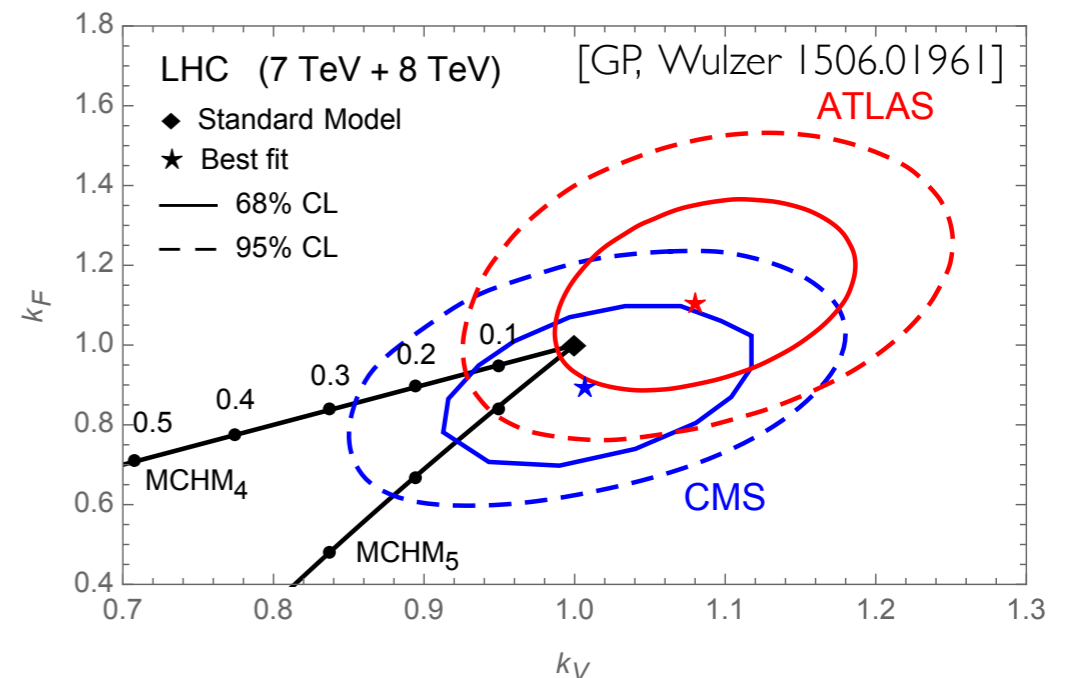
Couplings to gauge fields and quarks can be tested in Higgs physics

- ▶ current bounds $\xi \lesssim 0.1$

[ATLAS Collab. 1509.00672]

- ▶ possible deviation in top Yukawa

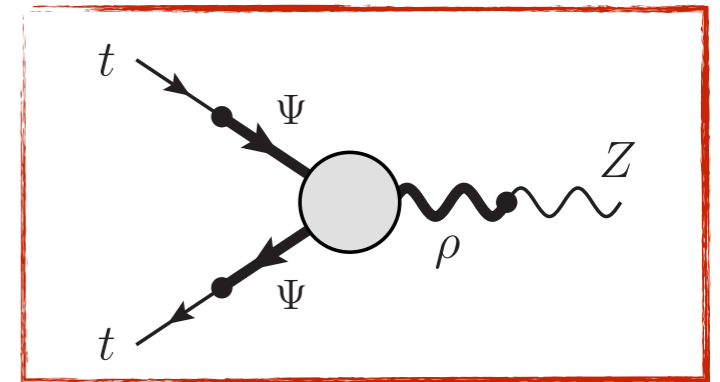
$$\delta y_{top} \lesssim 15 - 20\%$$



Modification of gauge couplings

Modifications in the **gauge couplings** are induced by vector resonances and top partners

$$\delta g_{Zt_L}, \delta g_{Zt_R} \sim \xi \lesssim 10\%$$



♦ modifications of $Z\bar{t}_R t_R$ coupling very difficult to test
(at present basically unconstrained)

♦ modifications of $Z\bar{t}_L t_L$ already constrained $|\delta g_{Zt_L}| \lesssim 8\%$

[Efrati, Falkowski, Soreq '15]

can have some impact on exclusions

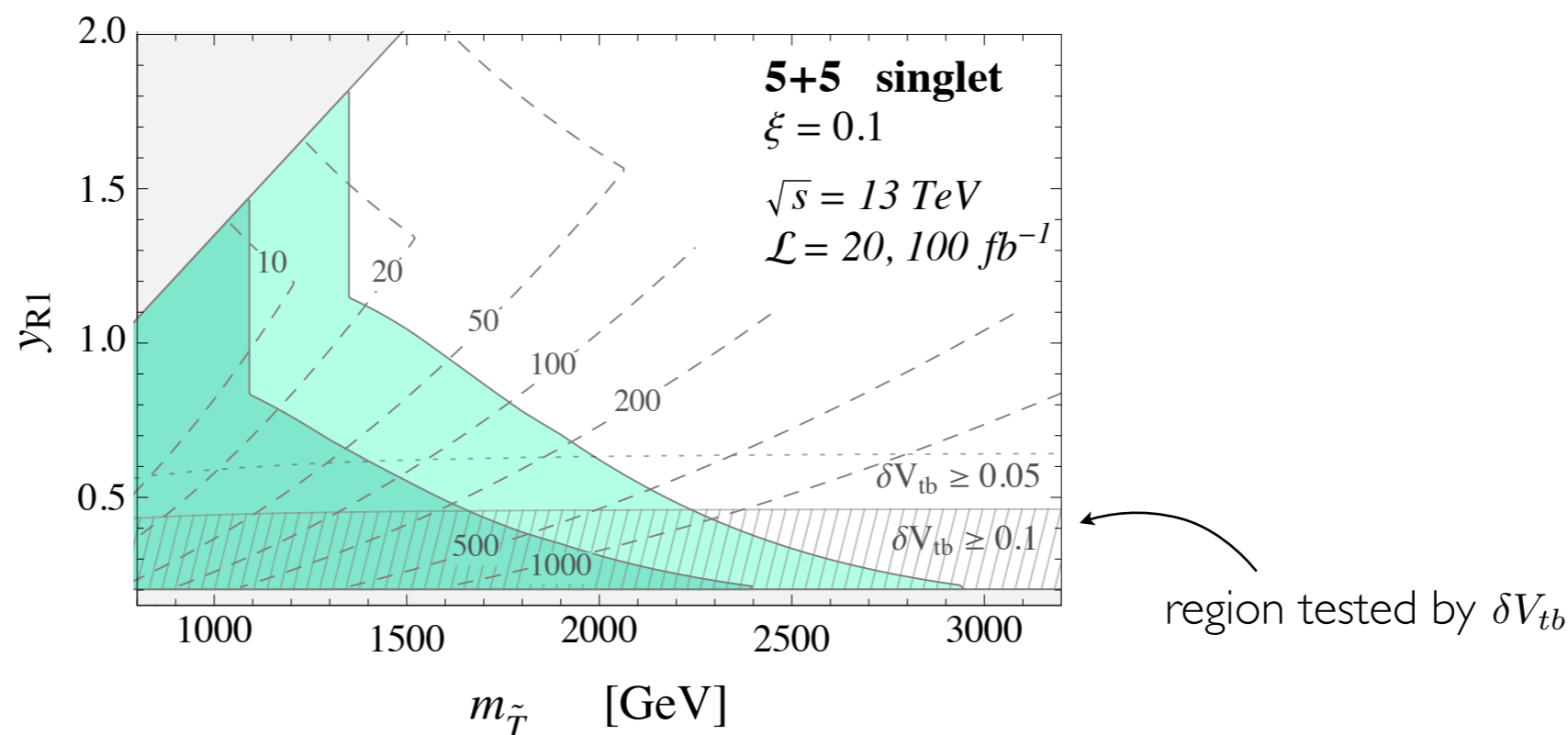
Z and W couplings

- ♦ strong relation between Z and W couplings
(assuming custodial symmetry for Zb_Lb_L coupling)

[del Aguila et al. '00;
Aguilar-Saavedra et al. '13;
Grojean, et al. '15]

$$\delta g_{Zt_L} = \delta V_{tb}^{\text{CKM}}$$

strong constraint on heavy top partners from δV_{tb} , can be competitive with direct bounds at LHC Run 2



Contact operators

4-top contact operators are induced by strong dynamics

$$\mathcal{O} = \frac{c}{f^2} (\bar{t} \gamma^\mu t)^2$$

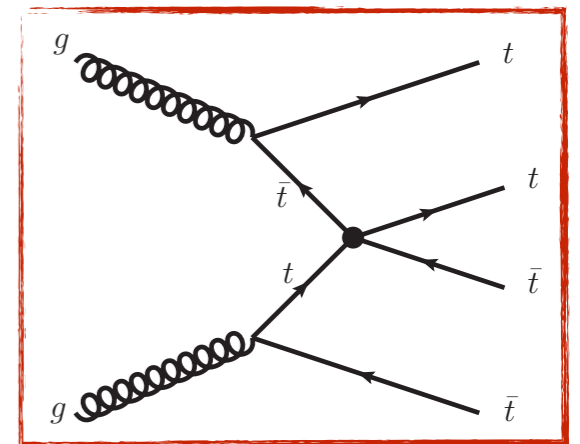
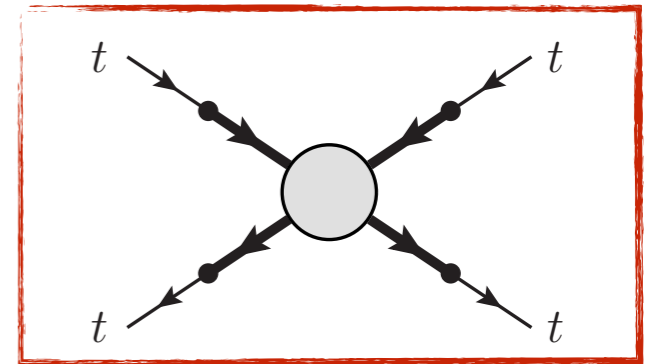
► $c \sim 1$ for fields with sizable compositeness

◆ can be tested in $\bar{t}t\bar{t}t$ production

current bounds on $\mathcal{O}_{RR} = (\bar{t}_R \gamma^\mu t_R)(\bar{t}_R \gamma_\mu t_R)$:

$$\frac{c_{RR}}{f^2} \lesssim \frac{1}{(590 \text{ GeV})^2}$$

[ATLAS Collab. ATLAS-CONF-2016-104]



Top and Flavor

Higgs compositeness and flavor

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

♦ Higgs associated to a composite operator:

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

→ 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

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

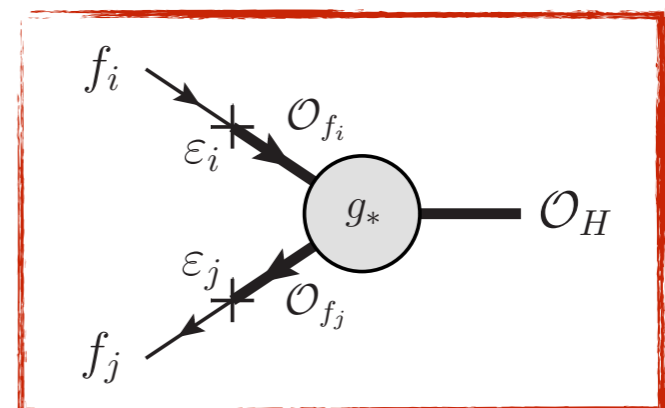
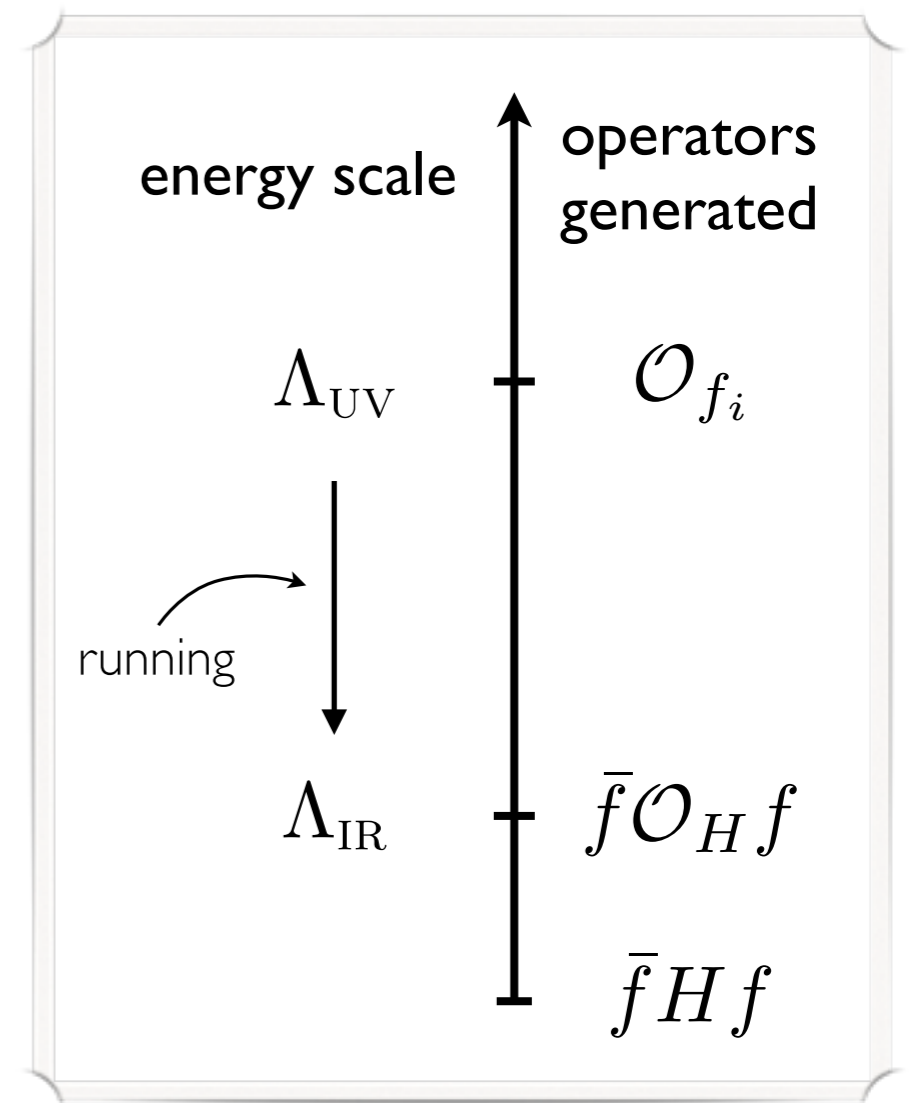
- size of IR mixings related to $\dim[\mathcal{O}_{f_i}]$

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

→ smaller mixings give smaller Yukawa's

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

strong sector coupling

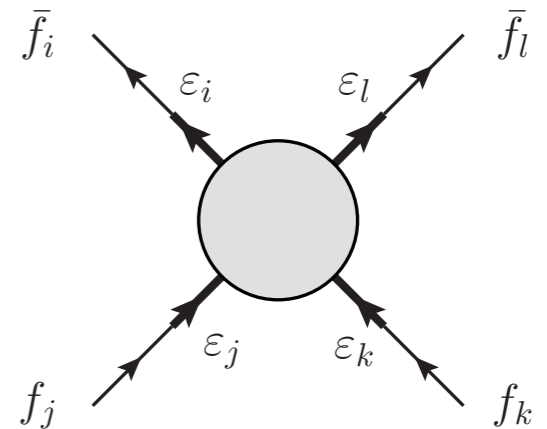


Flavor and CP-violation constraints

Strong bounds from $\Delta F = 2$ transitions

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

♦ bound from ε_K : $\Lambda_{\text{IR}} \gtrsim 10 \text{ TeV}$



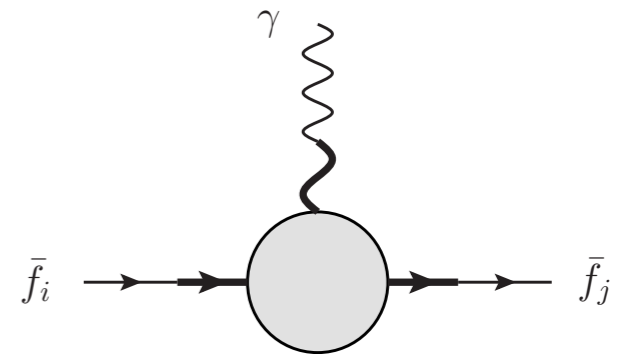
... and especially from **CP-violation** and **lepton flavor violation**

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

♦ bound from n EDM: $\Lambda_{\text{IR}} \gtrsim 10 \text{ TeV}(g_*/3)$

♦ bound from e EDM: $\Lambda_{\text{IR}} \gtrsim 100 \text{ TeV}(g_*/3)$

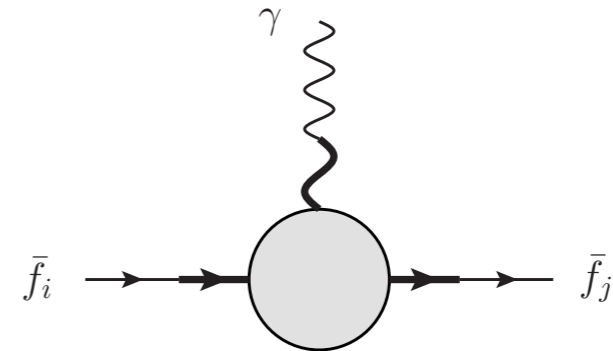
♦ bound from $\mu \rightarrow e \gamma$: $\Lambda_{\text{IR}} \gtrsim 100 \text{ TeV}(g_*/3)$



How to suppress EDM's

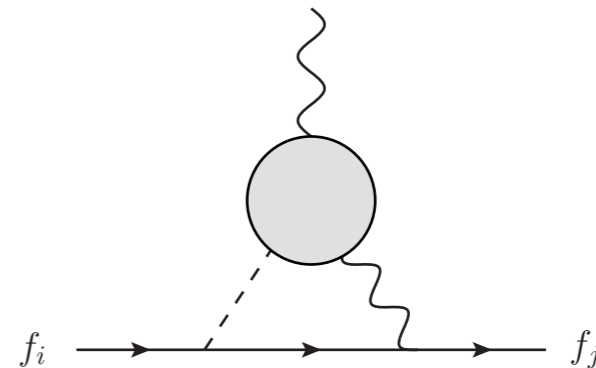
Large EDM's come from linear partial-compositeness mixings of light fermions

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



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

eg. if a constituent has a mass $\sim \Lambda_f$

[GP and A. Pomarol, 1603.06609]

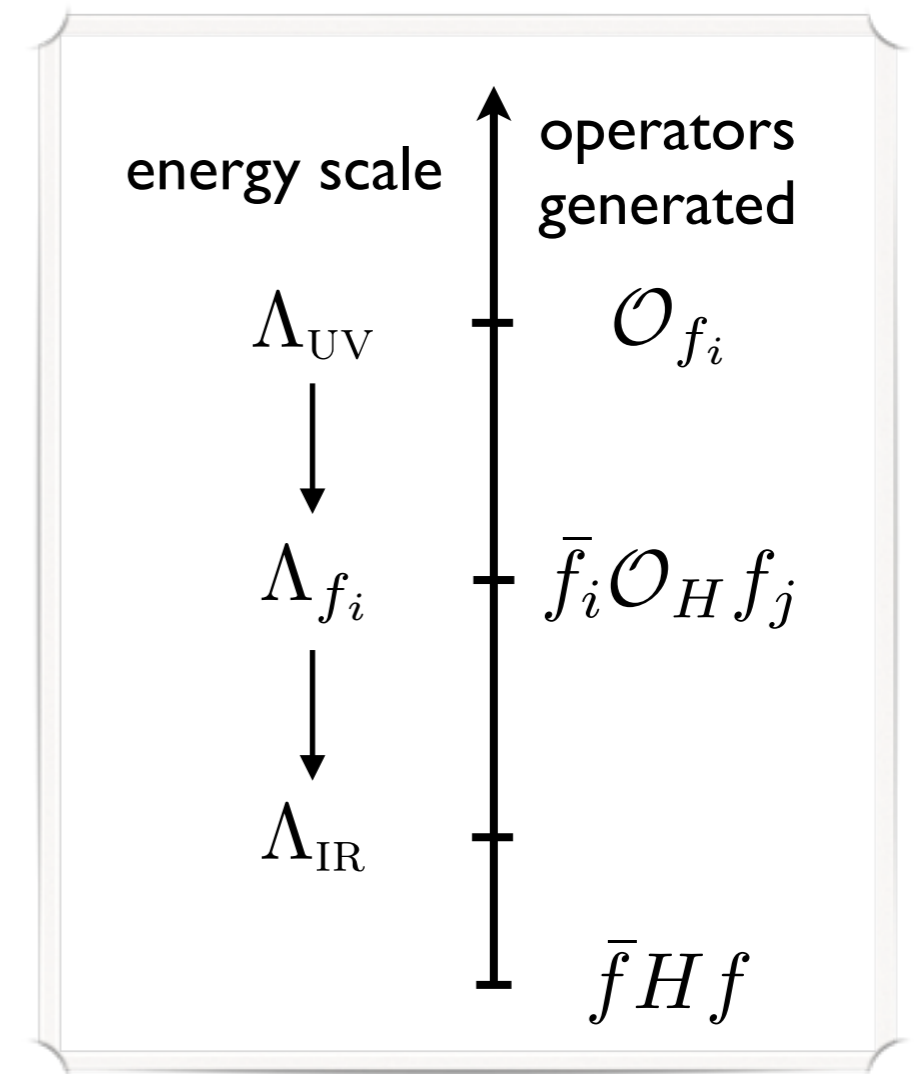
[also: Vecchi '12; Matsedonskyi '15; Cacciapaglia et al. '15]

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



Bilinear mixing generated at scale Λ_f

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

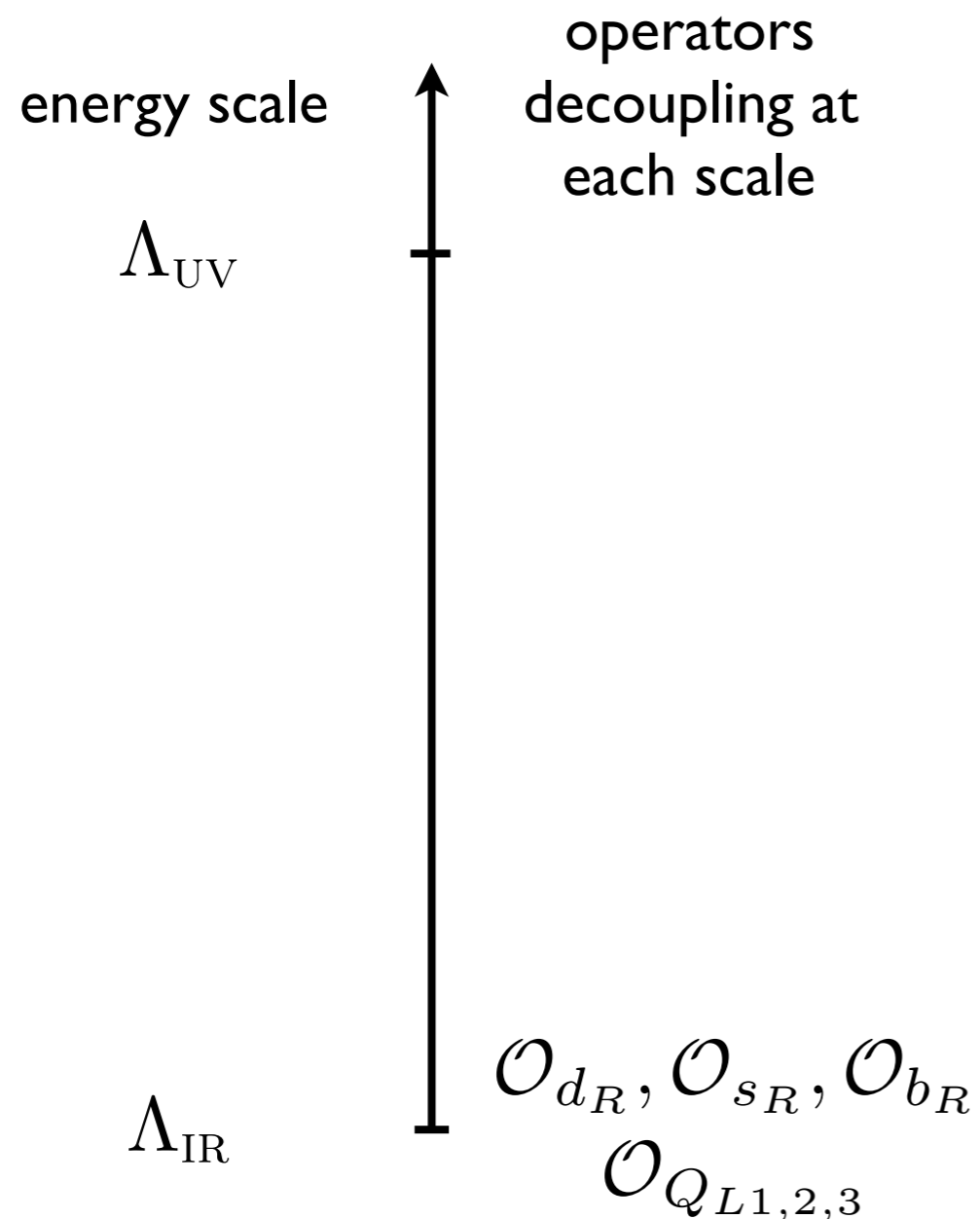


larger **decoupling scales** correspond to smaller fermion **masses**

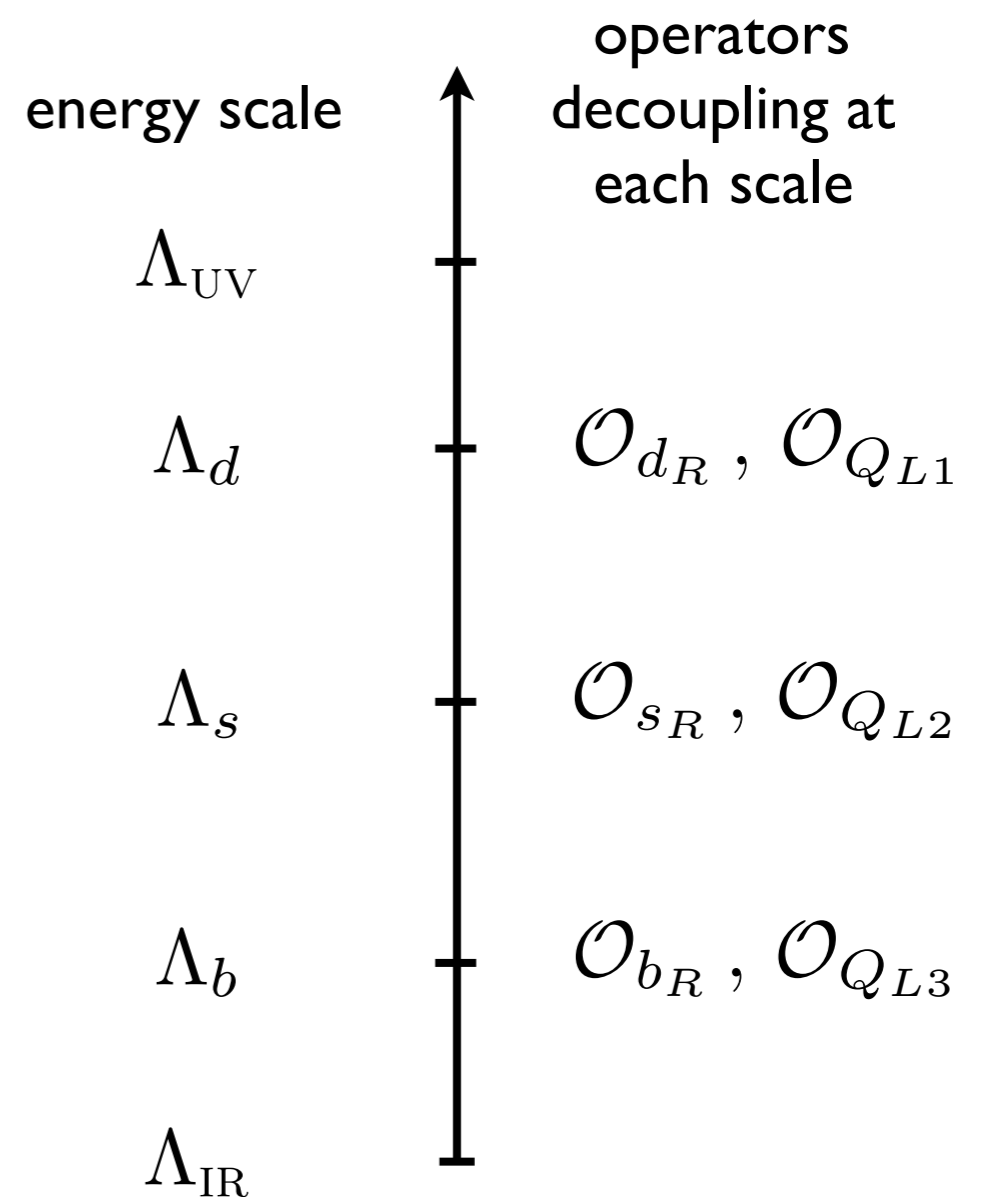
Anarchic vs Dynamical scales

Explicit example: The down-quark sector

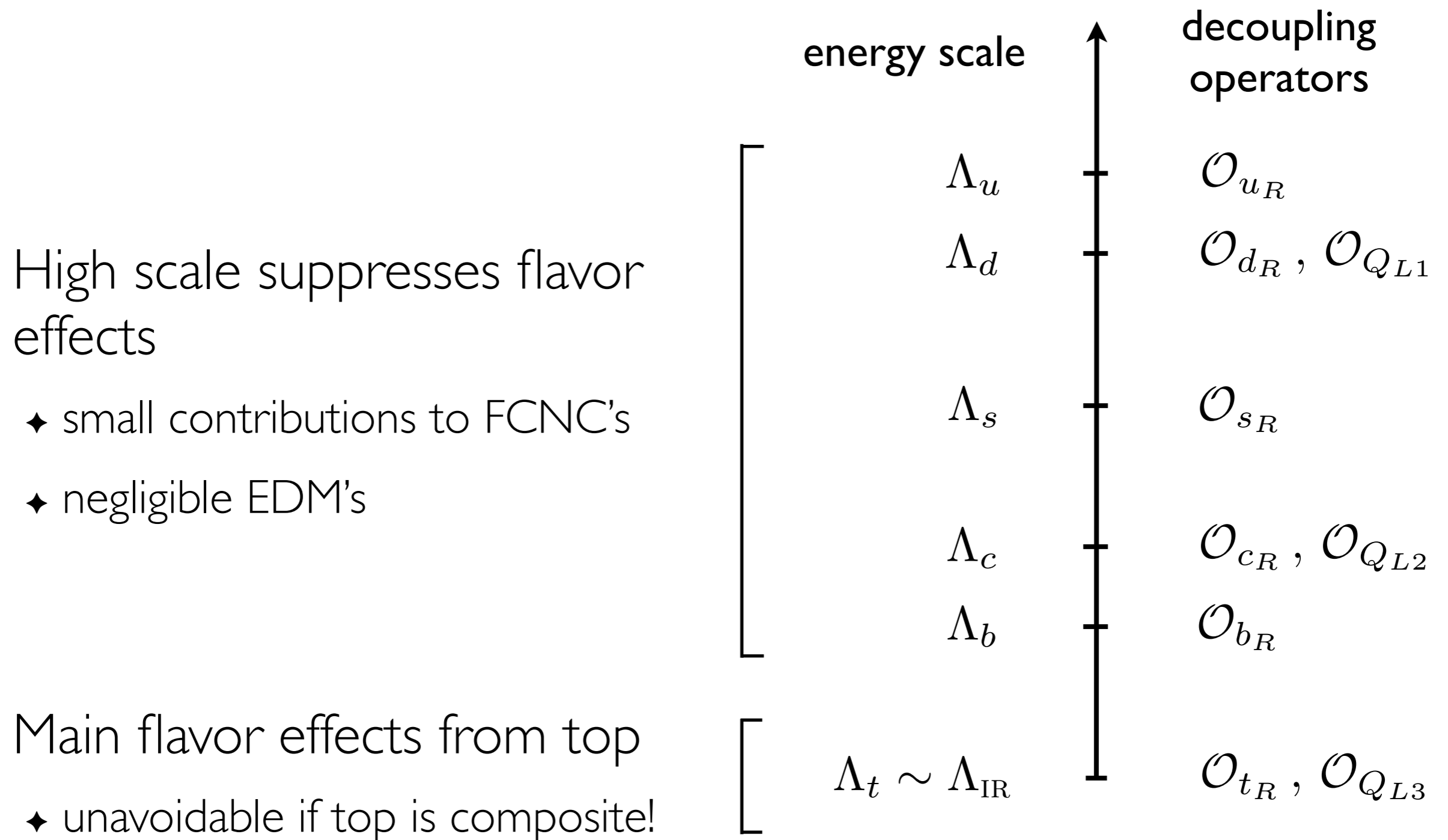
Anarchic scenario



Dynamical scales



The hierarchy of scales



$\Delta F = 2$ transitions

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

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

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



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

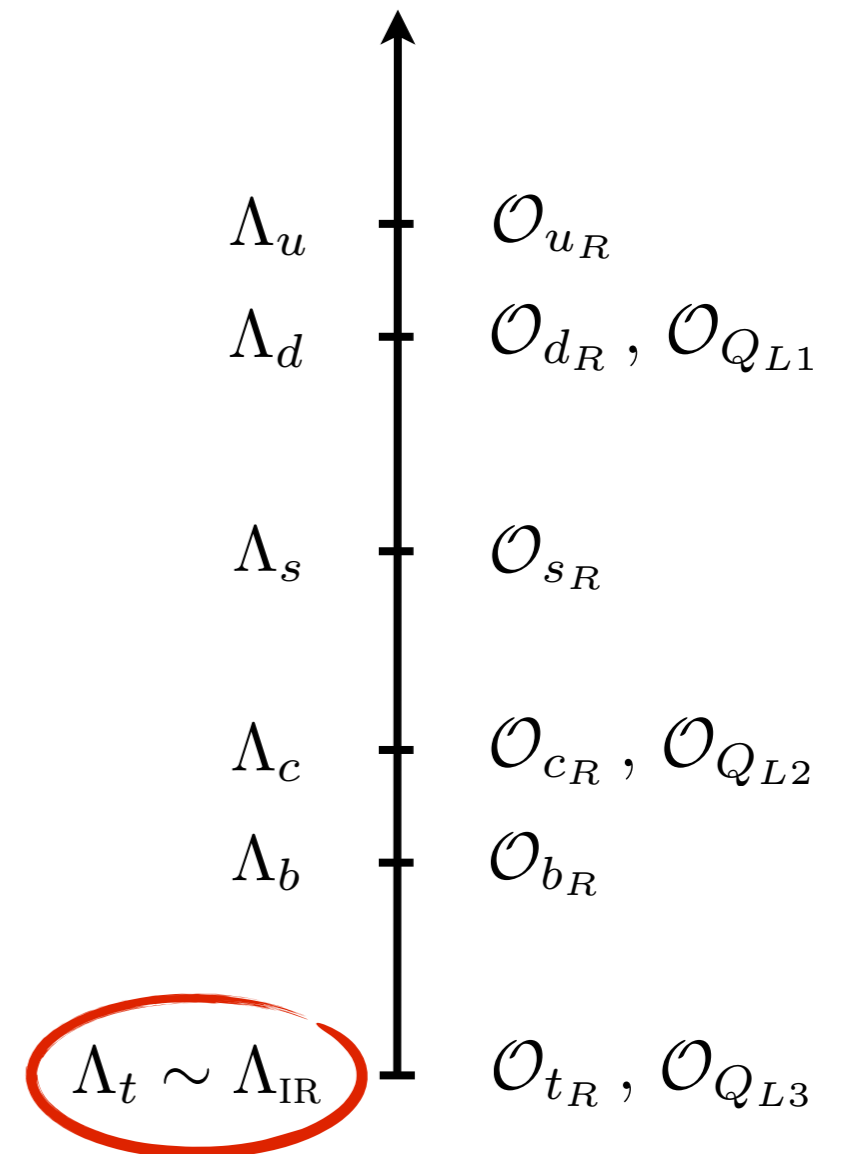
corrections to ε_K , ΔM_{B_d} , ΔM_{B_s}

- 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

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



$\Delta F = 1$ transitions

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

$\Delta F = 1$ operators

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



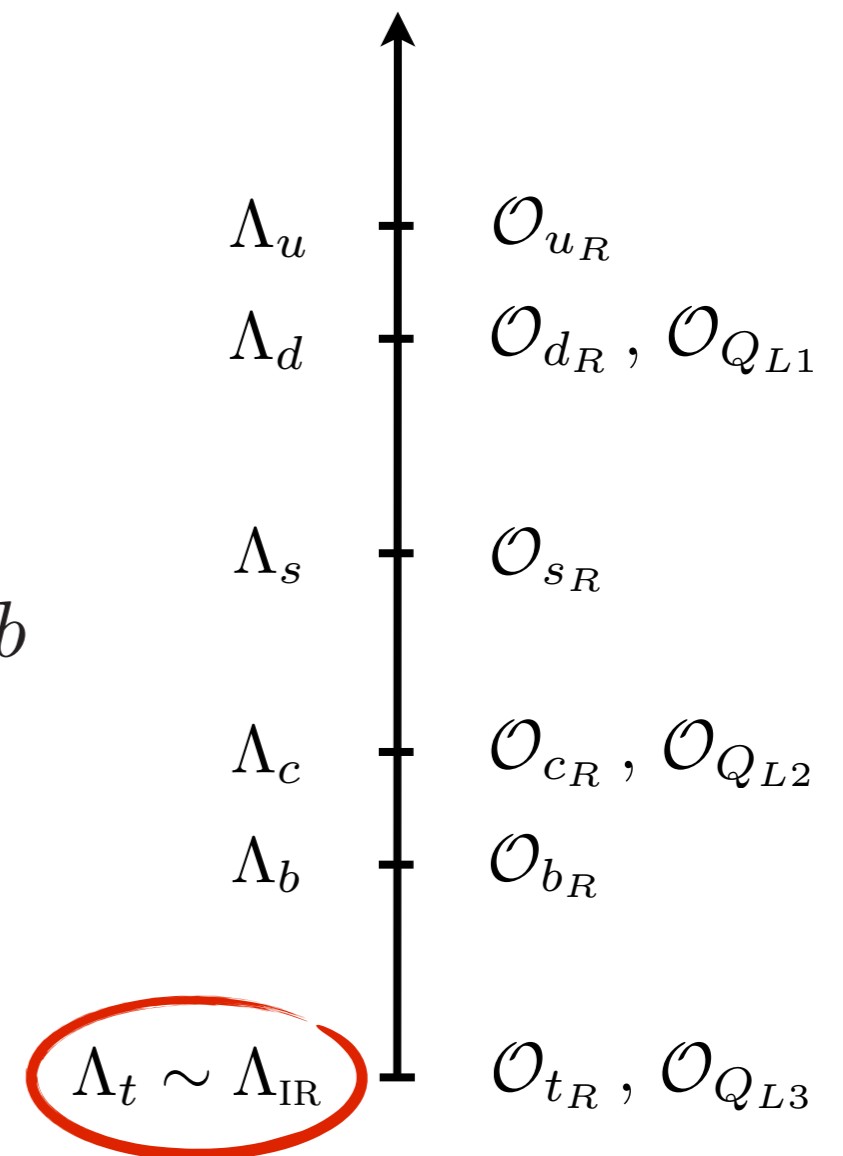
rotation to physical basis
 $V_L \sim V_{\text{CKM}}$

corrections to $K \rightarrow \mu\mu, \varepsilon'/\varepsilon, B \rightarrow X\ell\ell, Z \rightarrow b\bar{b}$

- correlated and close to experimental bounds

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

- can be suppressed by left-right symmetry



EDM's

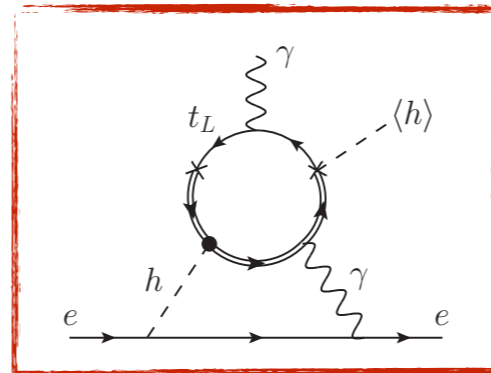
Top partial compositeness at Λ_{IR} gives rise to EDM's

- ♦ EDM's for u, d and e suppressed by

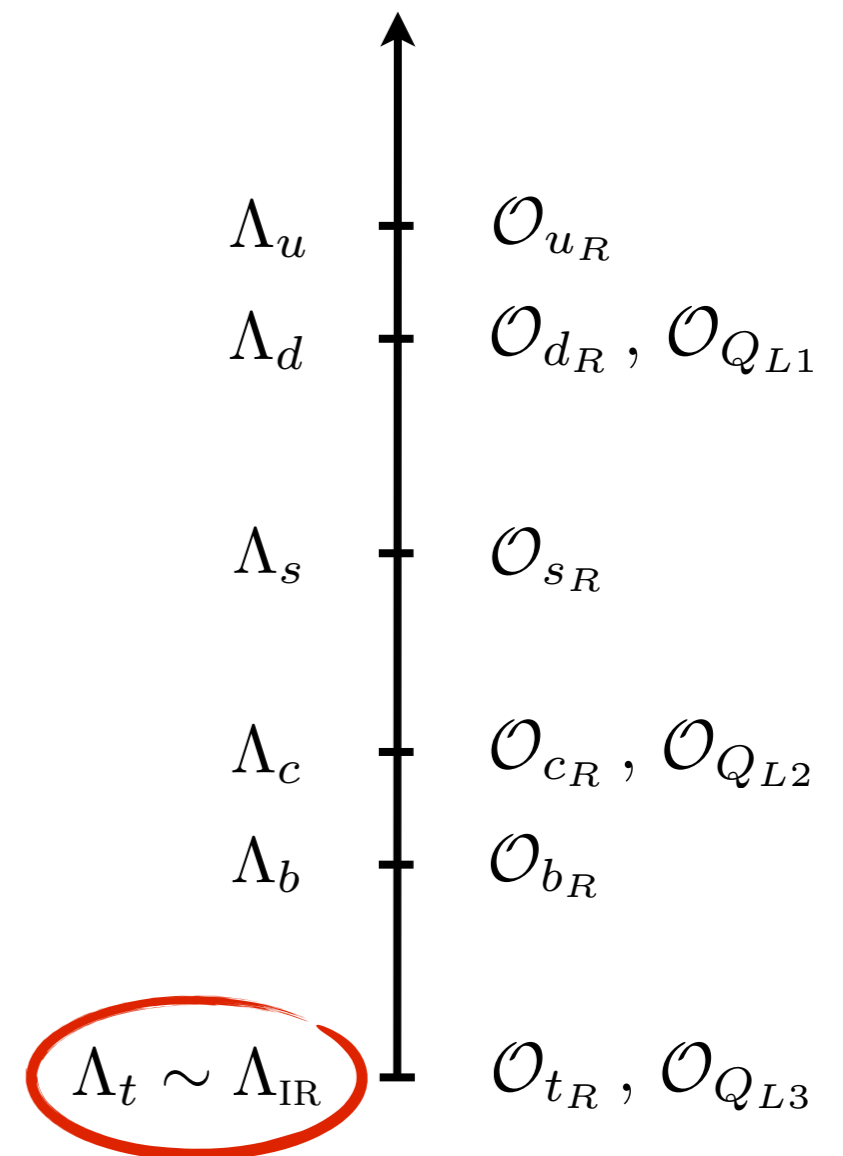
$$\Lambda_{u,d,e} > 10^6 \text{ TeV}$$

- ♦ sizable **neutron EDM**
(through top EDM)

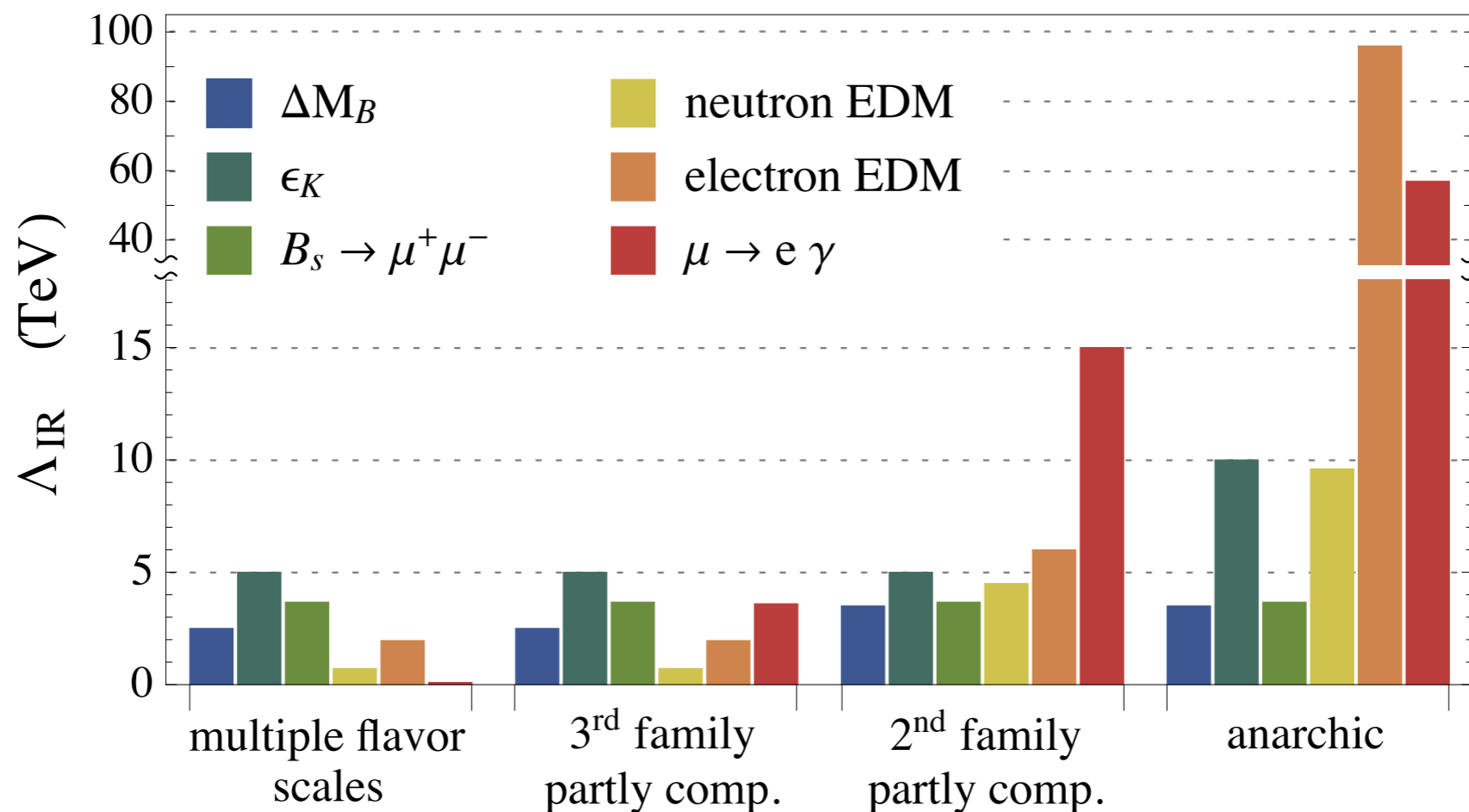
- ♦ sizable **electron EDM**
(from two-loop Barr-Zee)



n and e EDM's lead to the
bound $\Lambda_{\text{IR}} \gtrsim \text{TeV}$



Summary of bounds



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

Conclusions

Conclusions

The **top quark** plays a crucial role in composite Higgs models

- ♦ largest mixing with the new strongly-coupled sector
- ♦ portal to access new physics

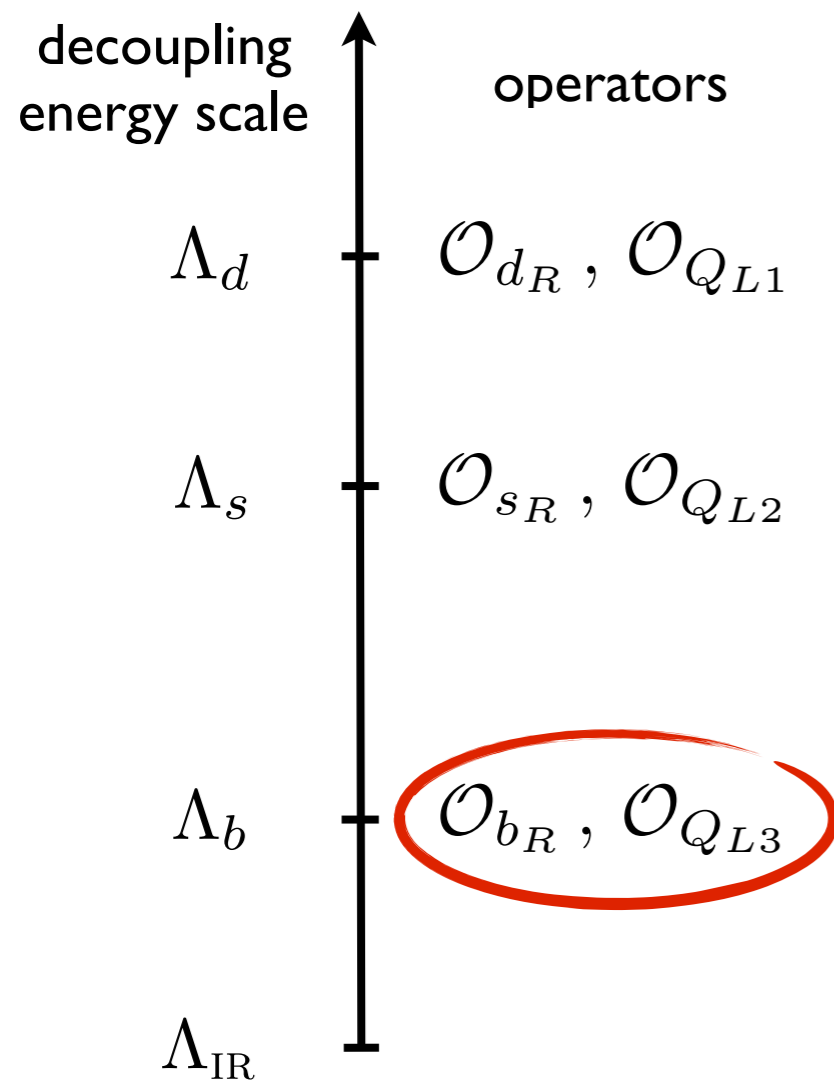
Main phenomenological handles

- ♦ light top partners (charged under QCD and decaying to 3rd gen.)
- ♦ modification of top couplings (Yukawa, gauge couplings, contact interactions)
- ♦ flavor structure (top quark controls flavor- and CP-violation)

Backup

The emergent flavor structure

down-quark sector



partial compositeness mixings

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



below Λ_b

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



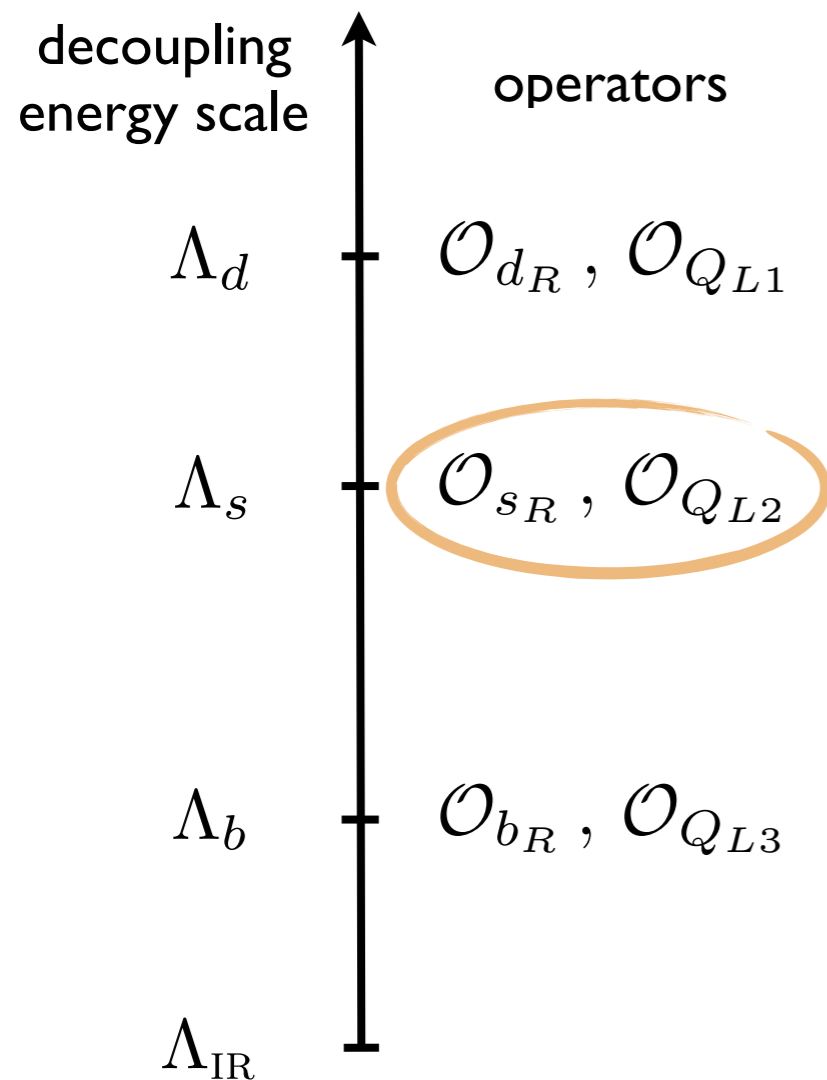
below Λ_{IR}

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

♦ bottom Yukawa

The emergent flavor structure

down-quark sector



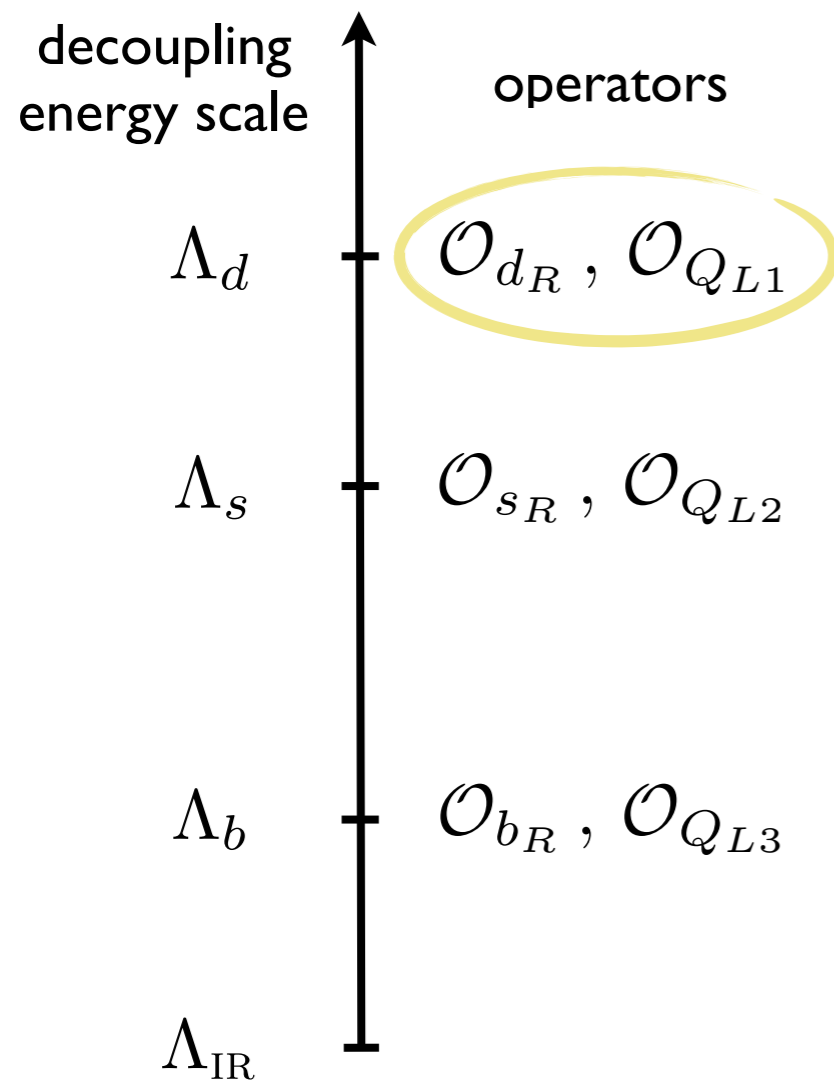
contribution from Λ_s

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

♦ strange Yukawa and mixing with 3rd generation

The emergent flavor structure

down-quark sector



contribution from Λ_d

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

- ♦ down Yukawa and mixing with 2nd and 3rd generation

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

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

- smaller Yukawa's for larger decoupling scale
- mixing angles suppressed by Yukawa's: $\theta_{ij} \sim Y_i / Y_j$
 - CKM mostly the rotation in the down-quark sector

Comparison with anarchic

bilinears

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

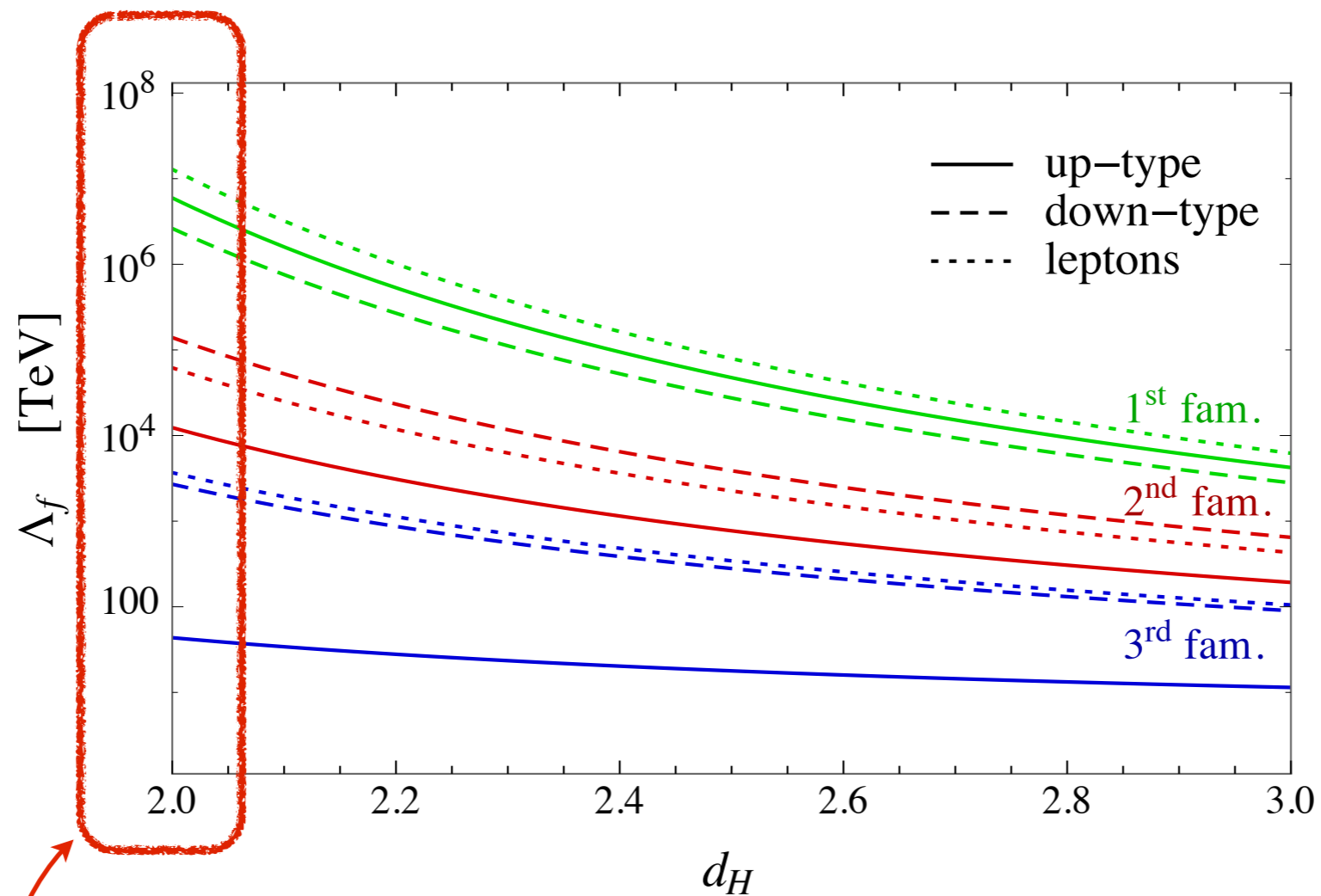
anarchic

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

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

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

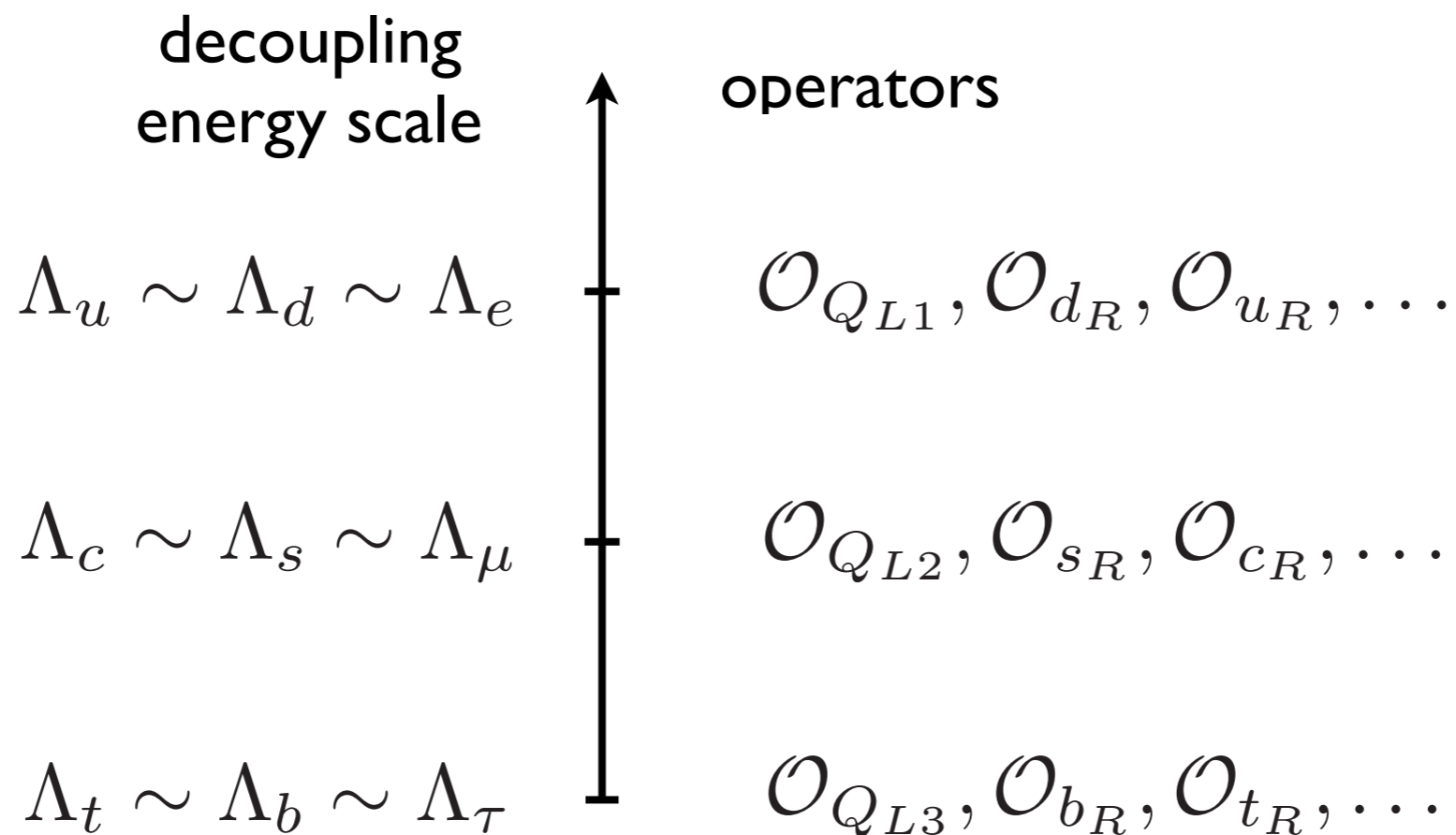
Scales of decoupling



$d_H \sim 2$ needed to pass FCNC

One scale for each family

More economical construction by associating one scale to each generation



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

Neutrino masses

♦ Majorana masses realization:

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

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:

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

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