Flavor without symmetries

Alex Pomarol, UAB (Barcelona)

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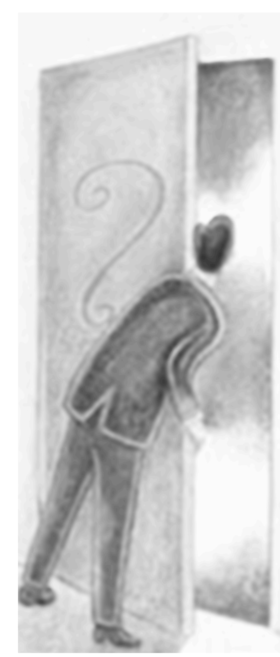
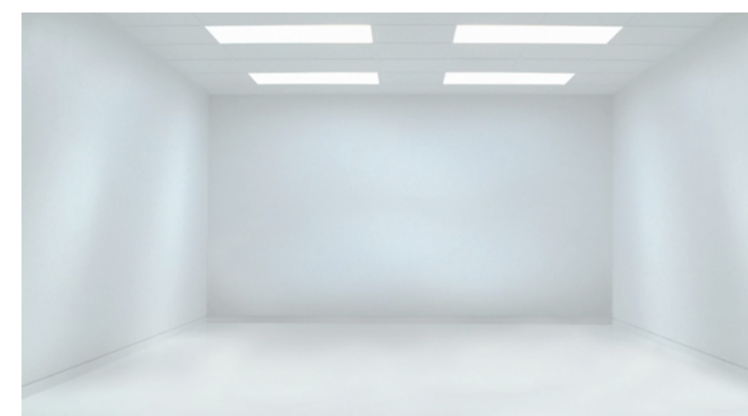
Apologizes: I am not going to talk on glances at the energy frontier





Flavor without symmetries

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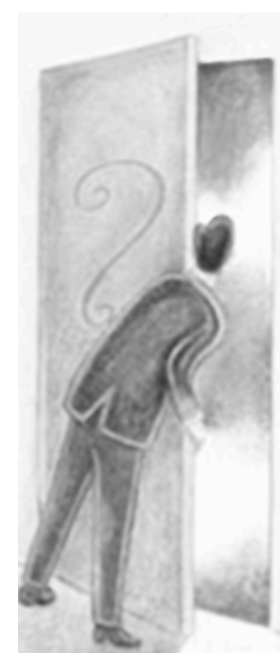
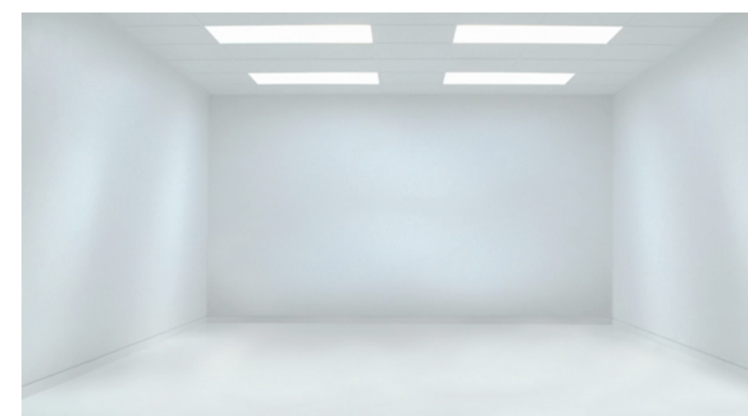
Apologizes: I am not going to talk on glances at the energy frontier

Interpreting other "null results": the absence of new flavor sources beyond the SM





After many years,

<u>no clear progress on the origin of flavor in the SM</u>:

Many ideas, but without sharp predictions

Localization in extra dimensions

Masses from loops

gauge flavor symmetries

Froggatt-Nielsen

... contrary to gauge couplings → predictions from GUTs

Higgs quartic → predictions from SUSY or Composite Higgs

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no clear progress on the origin of flavor in the SM:

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In BSMs for the hierarchy problem things are even worse (or more interesting), as generically predict new sources of flavor...

$$(\bar{f}_i\gamma^\mu f_j)(\bar{f}_l\gamma_\mu f_k) \longrightarrow$$ **ϵ_K, ϵ'/ϵ, ΔM_B, $B \to Xll$, ...**

not serious deviation seen!

“Cheap” way to avoid them:

☛ Demand similar BSM flavor-structure as in the SM:

Minimal Flavor Violation (MFV)

Flavor under control for new physics scale at ~TeV

but global symmetries are accidental

So, why/how they arise?

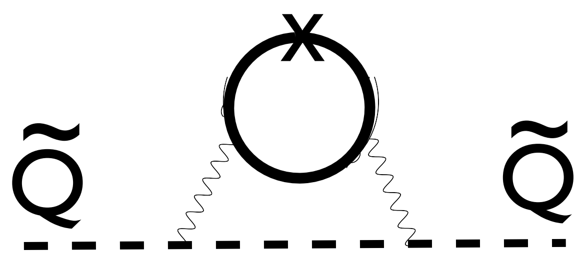
Symmetries from dynamics!

Symmetries from dynamics!

But only few examples known:

SUSY: Gauge Mediated Susy Breaking (GMSB)

soft-masses through gauge interactions (flavor blind)



but today minimal GMSB highly tuned to reproduce $m_h \sim 125$ GeV

Beyond minimal models… EDMs are sizable!

$$d_e \sim 10^{-28}\text{cm}\,\text{e}\left(\frac{M_S}{10\ \text{TeV}}\right)^2 \tan\beta$$

Symmetries from dynamics!

But only few examples known:

Composite Higgs:

More difficult, as we must address the origin of Yukawas:

Higgs associated to a composite operator: $\mathcal{O}_H \sim \bar{\psi}\psi$

As dimension of $\mathcal{O}_H$ is larger than 1 **($d_H>1$)**

Yukawas, $ff\mathcal{O}_H$, are irrelevant couplings!

We cannot push their origin to Planck-physics!

Symmetries from dynamics!

But only few examples known:

Composite Higgs:

Most interesting possibility:

Yukawas from linear mixing to operators of the strong sector:

$$\mathcal{L}_{\rm lin} = \epsilon_{f_i}\, \bar{f}_i\, \mathcal{O}_{f_i}$$ (portal of f_i to the strong sector)

↳ depending on the dimension of $\mathcal{O}_f$, we can have relevant or irrelevant couplings

☛ large or small mixings ϵ_f

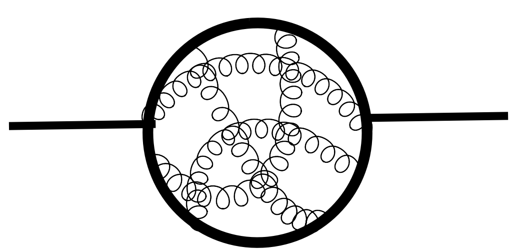
O(1) numbers (anomalous dimensions γ_i of $\mathcal{O}_{f_i}$)
can lead to large hierarchies:

From the RGE:

$$\epsilon_{f_i}(\Lambda_{IR}) \sim \left(\frac{\Lambda_{IR}}{M_P}\right)^{\gamma_i} \qquad \gamma_i = \mathrm{Dim}[\mathcal{O}_{f_i}] - 5/2 > 1$$

☛ small mixings at Λ_{IR}

The smaller mixing, the smaller the mass:

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

↳ coupling of the strong sector

Explicit example (for the top): arXiv:1502.00390

SU(4) strong sector

Fermions:
a) three $\Psi_{L,R} \in \mathbf{4}$ (fundamental)
b) five $\Upsilon \in \mathbf{6}$ (antisym. matrix)

$$\Psi\Upsilon\Psi = \mathcal{O}_{\rm top}$$

Operator that can be coupled to the top

Global sym.

$$G = SU(5) \times SU(3) \times SU(3)' \times U(1)_X \times U(1)'$$

$$\downarrow$$

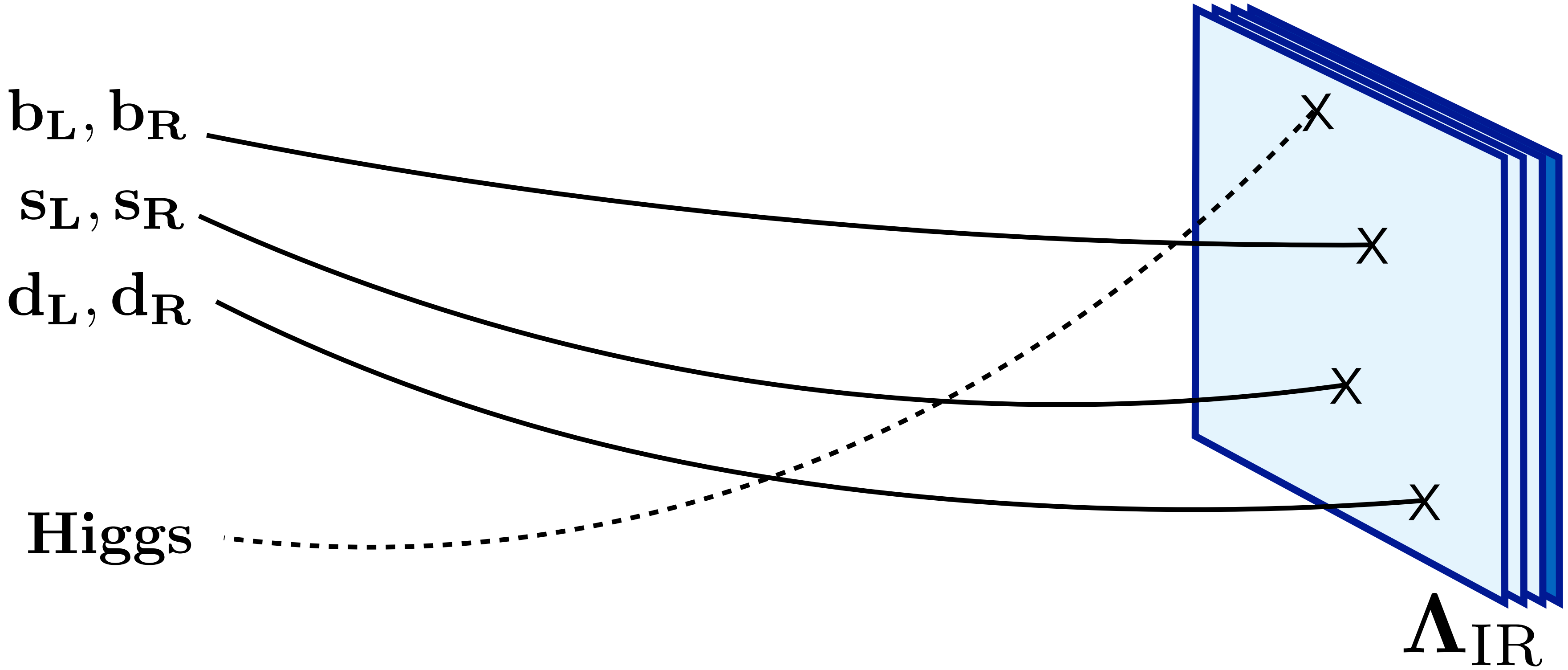
$$H = SO(5) \times SU(3)_{\rm color} \times U(1)_X$$

dimension at weak coupling: 9/2

dimension needed at strong coupling: 5/2 (γ= 2)

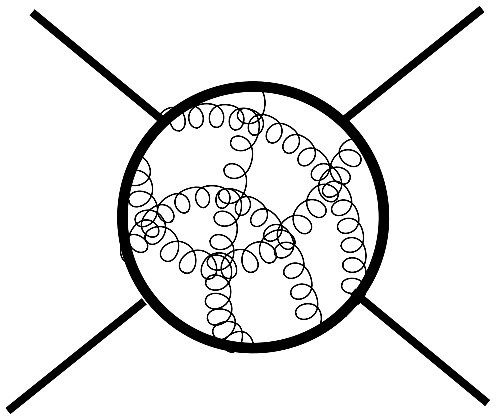
Possible? lattice could tell us!

AdS/CFT perspective



☛ easier from string theory?

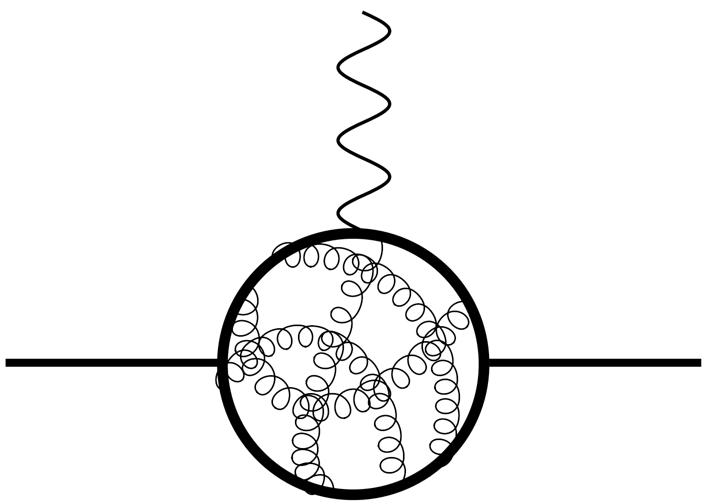
Flavor & CP-violation constraints



$$\frac{g_*^2}{\Lambda_{\rm IR}^2}\epsilon_{f_i}\epsilon_{f_j}\epsilon_{f_k}\epsilon_{f_l}\,\bar f_i\gamma^\mu f_j \bar f_k\gamma_\mu f_l$$

↳ scale of the strong sector: expected ~TeV

ϵ_K bound: $\boldsymbol{\Lambda}_{\rm IR} > \mathbf{10}\ \mathrm{TeV}$



$$\frac{g_*^2}{16\pi^2}\frac{g_* v}{\Lambda_{\rm IR}^2}\epsilon_{f_i}\epsilon_{f_j}\,\bar f_i\sigma_{\mu\nu}f_j\, gF^{\mu\nu}$$

EDM bound: $\boldsymbol{\Lambda}_{\rm IR} > \mathbf{100}\ \mathrm{TeV}\left(\frac{\mathbf{g}_*}{\mathbf{3}}\right)$

$\mu\to e\gamma$ bound: $\boldsymbol{\Lambda}_{\rm IR} > \mathbf{60}\ \mathrm{TeV}\left(\frac{\mathbf{g}_*}{\mathbf{3}}\right)$

arXiv:1106.6357

arXiv:1203.4220

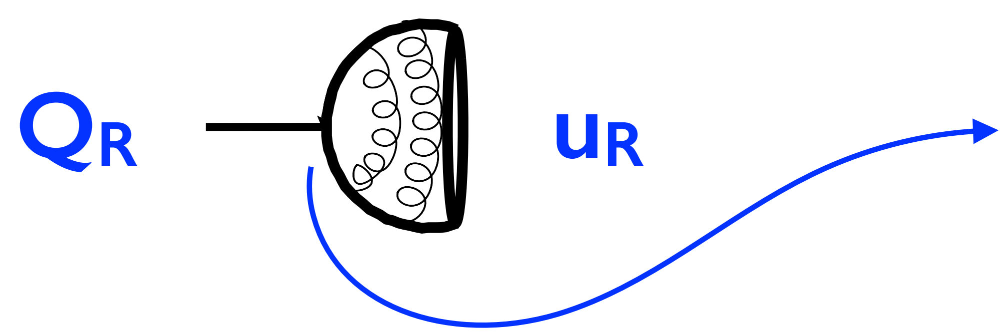
Other alternatives:

Consider some SM fermion fully composite:

For example: **Q_R u_R, d_R**

If arise from a strong sector with elementary fermions, it is not unconceivable to be flavor symmetric

All flavor mixings from left-handed:



$\propto Y_u$ ☛ **MFV**

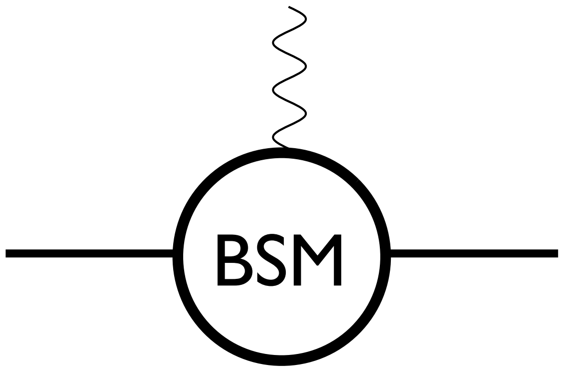
But also generated: $\frac{g_*^2}{\Lambda_{\rm IR}^2}(\bar{u}_R\gamma_\mu u_R)^2$

give deviation in dijets distributions, **pp → jj**: $\Lambda_{\rm IR} \gtrsim \mathbf{20}\ {\rm TeV}\left(\frac{\mathbf{g}_*}{\mathbf{3}}\right)$

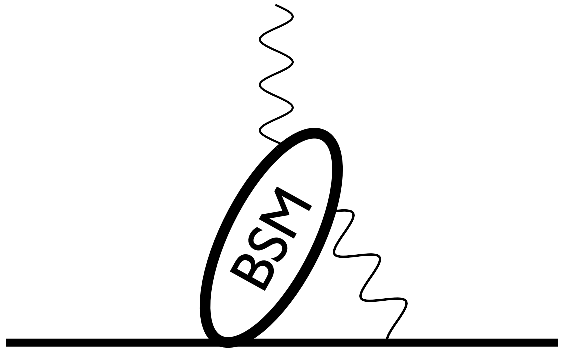
Towards suppressing EDMs:

Avoid linear mixing of light fermions to BSM:

$$\mathcal{L}_{\rm lin} = \epsilon_{f_i}\,\bar{f}_i\,\mathcal{O}_{f_i}$$



Bilinear mixing: $\mathcal{L}_{\rm bil} \sim \bar{f}_i \mathcal{O}_H f_j$



Not possible in the MSSM,
but possible in composite Higgs models

EDM at most at
two-loop!

Possibility considered here:

G.Panico, AP 1603.06609

(also related work by Matsedonskyi 15, Cacciapaglia etal 15)

$$\mathcal{L}_{\rm lin} = \epsilon_{f_i}\, \bar{f}_i\, \mathcal{O}_{f_i}$$

↳ portal decouples at higher energies:

E.g. if a constituent get a mass $\sim\Lambda_f$

↓

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

bilinear mixing generated at Λ_f

↳ Operator of the strong sector that at Λ_{IR} projects into the Higgs:

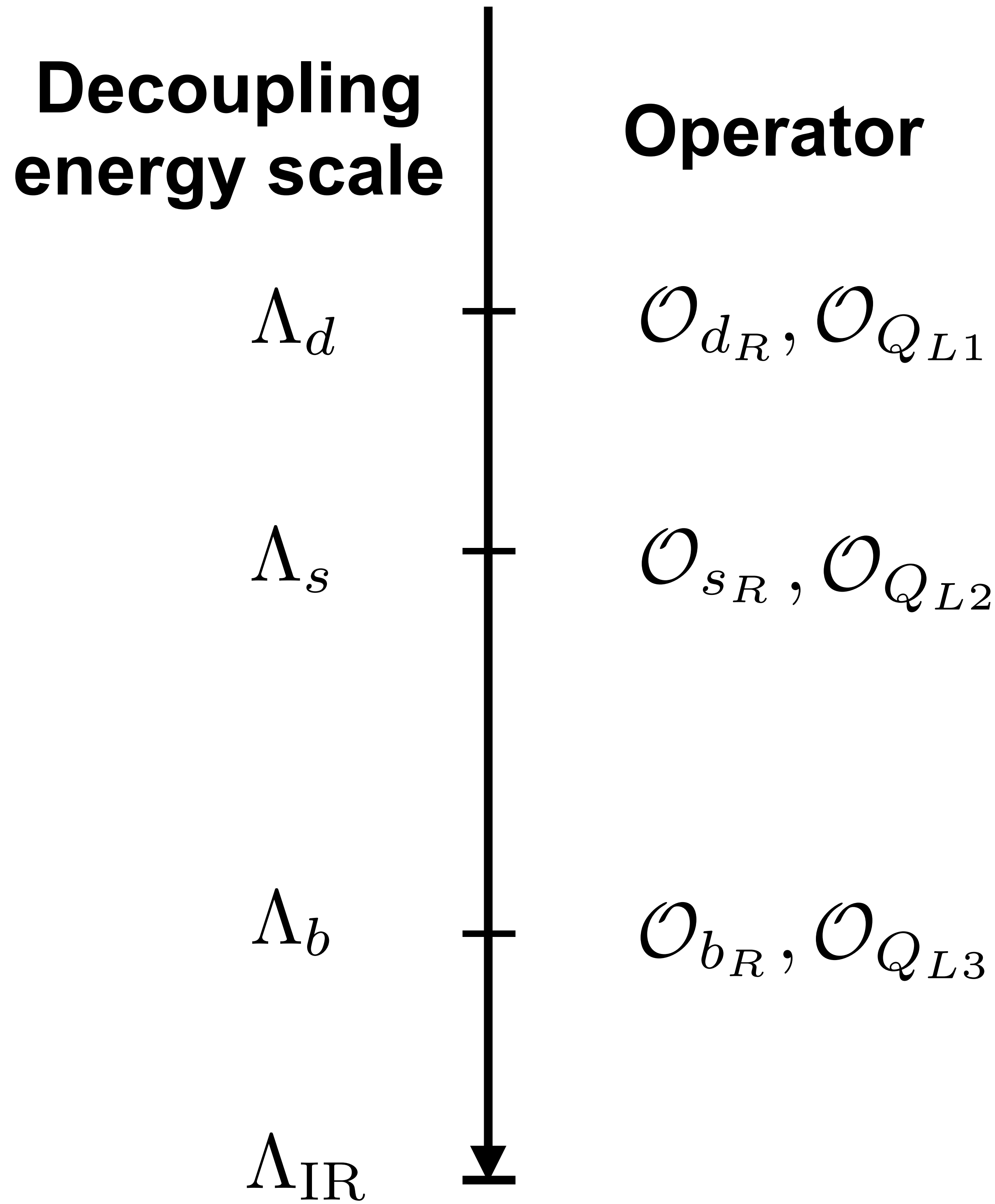
$$\langle 0|\mathcal{O}_H|H\rangle \neq 0$$

e.g. $\mathcal{O}_H \sim \bar{\psi}\psi$

The larger the scale of decoupling,

the smaller the fermion mass!

Down-quark sector



Envisaging from explicit examples:

SU(4) strong sector

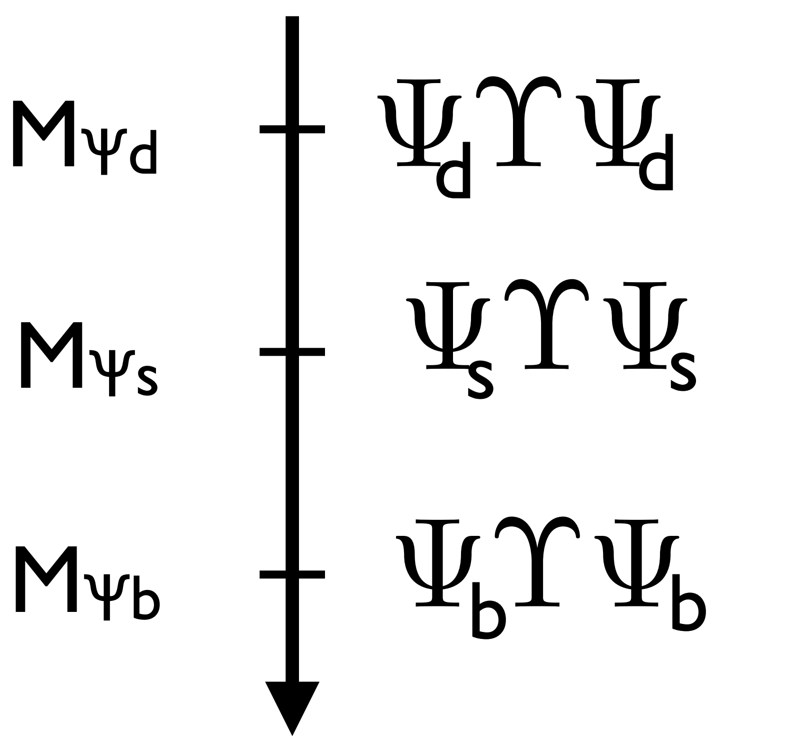
Fermions:

a) three $\Psi_{L,R} \in$ **4** (fundamental)

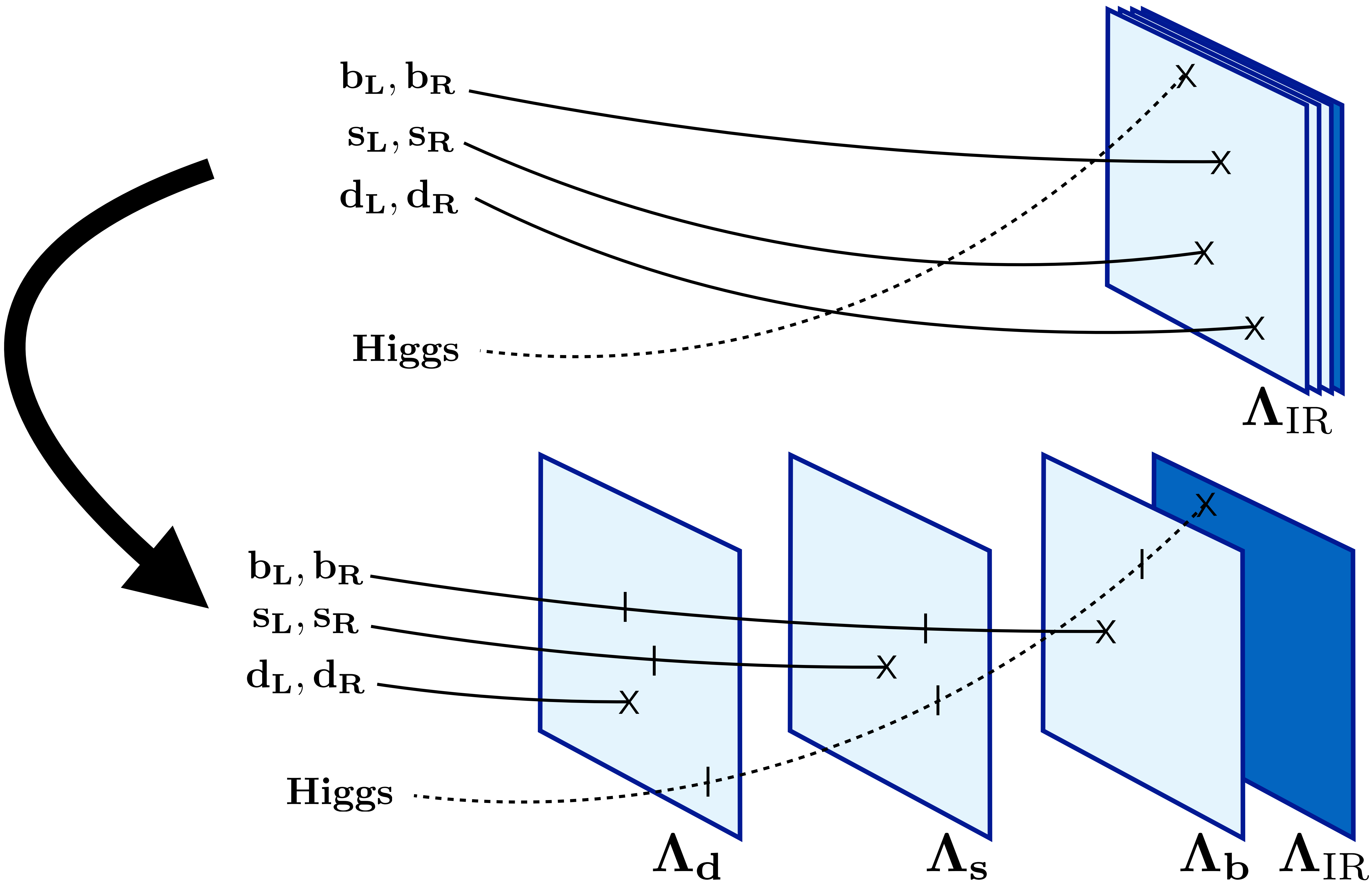
b) five $\Upsilon \in$ **6** (antisym. matrix)

$$\Psi \Upsilon \Psi = \mathcal{O}_{\rm top}$$

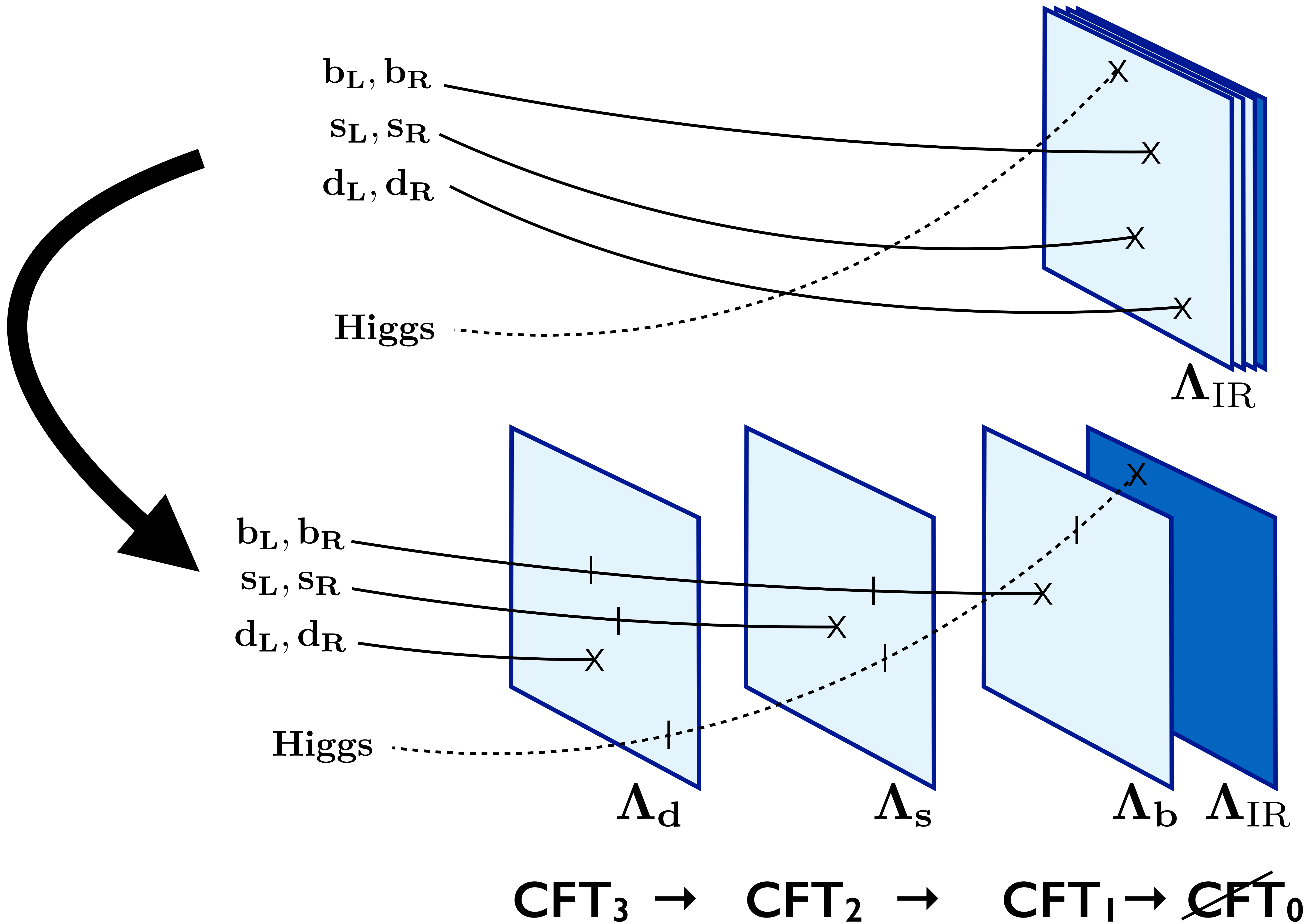
add more elementary fermions Ψ with explicit masses



AdS/CFT perspective

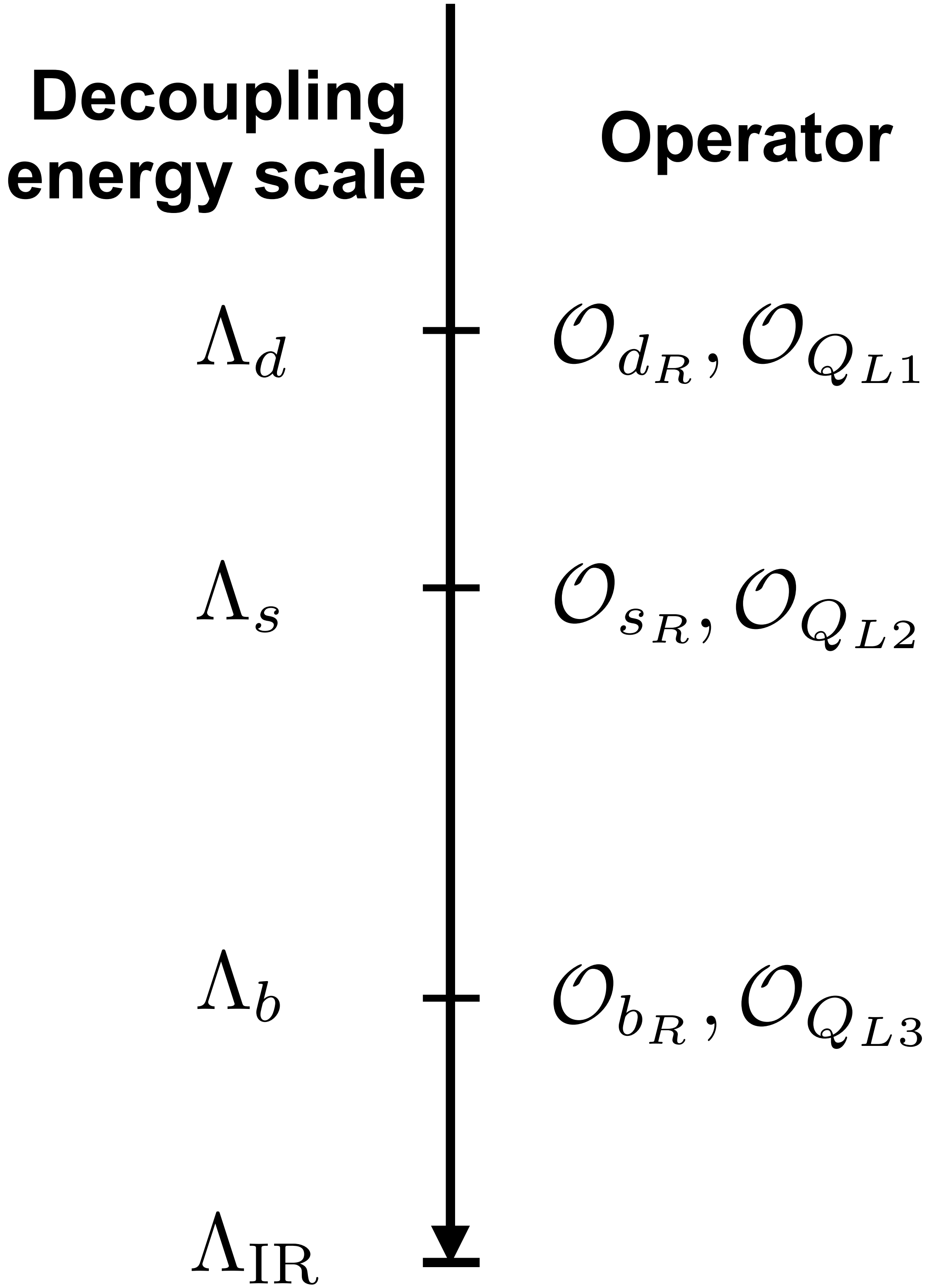


AdS/CFT perspective



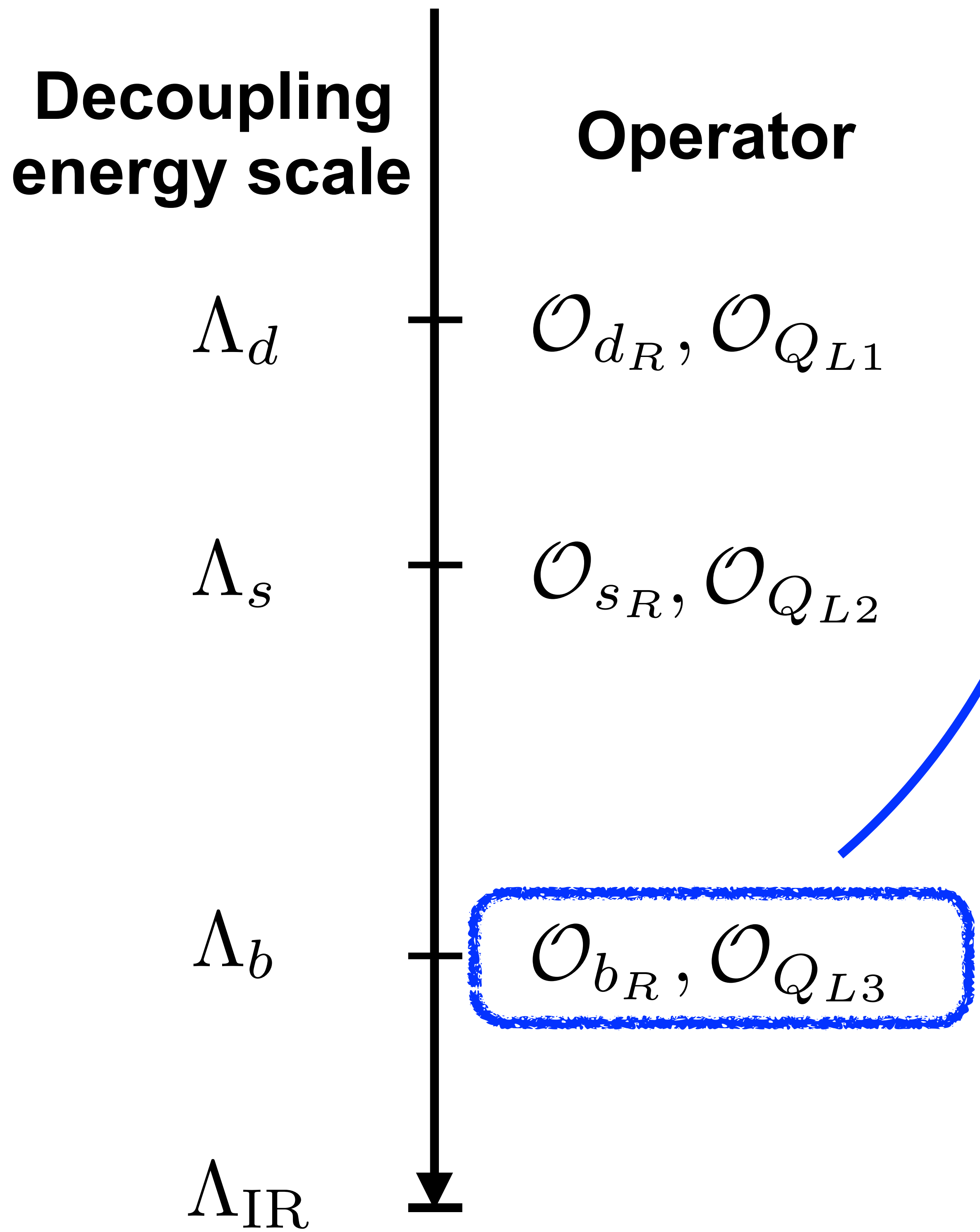
Arising flavor structure

Down-quark sector



Arising flavor structure

Down-quark sector



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

below Λ_b:

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

below $\Lambda_{\rm IR}$:

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

Arising flavor structure

Down-quark sector

Decoupling energy scale	Operator
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}	

$$\mathcal{L}_{\text{lin}}^{(2)} = (\epsilon_{b_L}^{(2)} \bar{Q}_{L3} + \epsilon_{s_L}^{(2)} \bar{Q}_{L2})\, \mathcal{O}_{Q_{L2}} + (\epsilon_{b_R}^{(2)} b_R + \epsilon_{s_R}^{(2)} s_R)\, \mathcal{O}_{s_R}$$

below Λ_s:

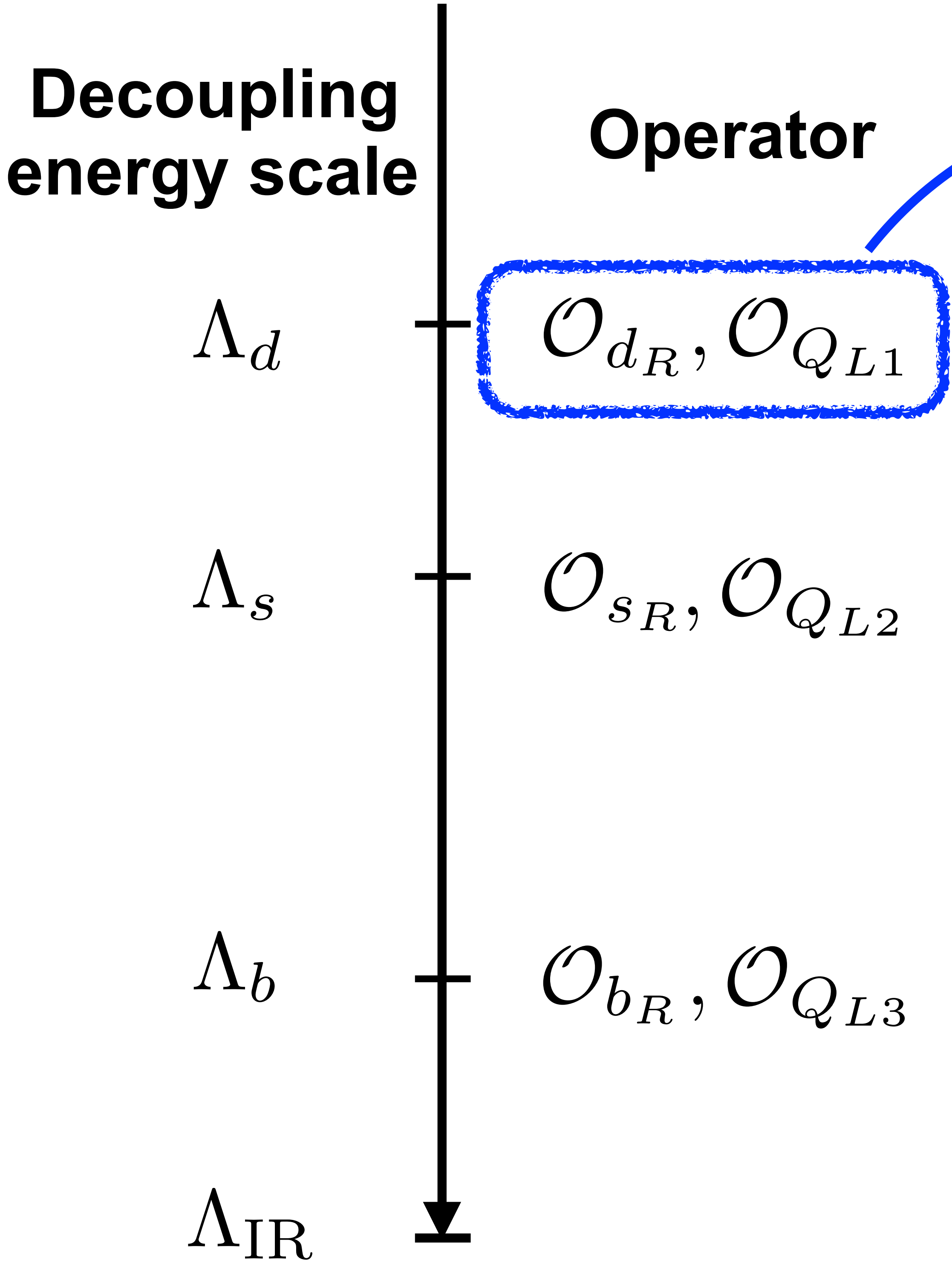
$$\mathcal{L}_{\text{bil}}^{(1)} = \frac{1}{\Lambda_d^{d_H-1}} (\epsilon_{b_L}^{(1)} \bar{Q}_{L3} + \epsilon_{s_L}^{(1)} \bar{Q}_{L2} + \epsilon_{d_L}^{(1)} \bar{Q}_{L1}) \mathcal{O}_H (\epsilon_{b_R}^{(1)} b_R + \epsilon_{s_R}^{(1)} s_R + \epsilon_{d_R}^{(1)} d_R)$$

below Λ_{IR}:

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

Arising flavor structure

Down-quark sector



below $\Lambda_{\rm IR}$:

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

Arising flavor structure

"onion" structure:

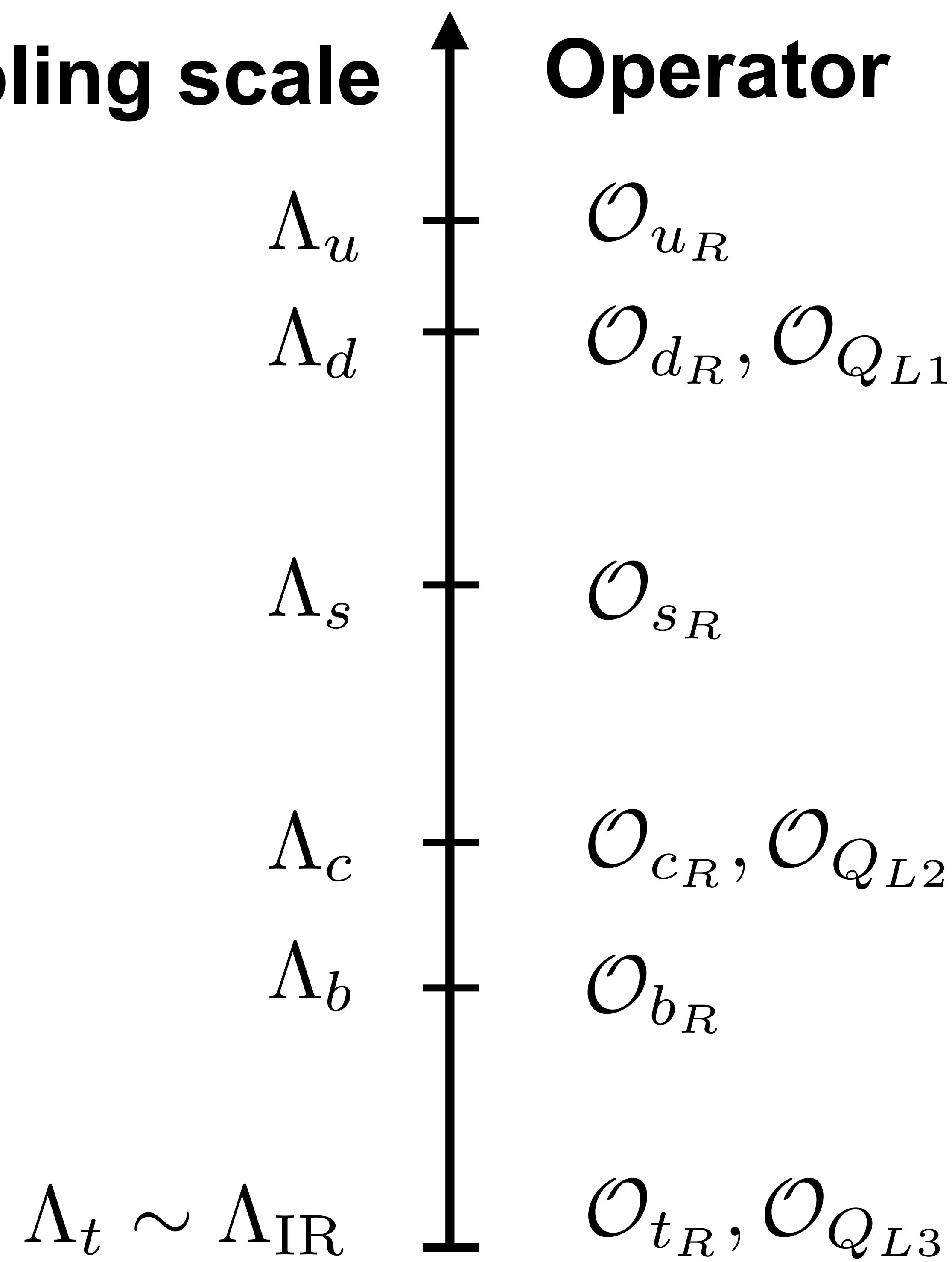
$$\mathcal{Y}_{\rm down} \simeq \begin{pmatrix} Y_d & \alpha_R^{ds} Y_d & \alpha_R^{db} Y_d \\ \alpha_L^{ds} Y_d & Y_s & \alpha_R^{sb} Y_s \\ \alpha_L^{db} Y_d & \alpha_L^{sb} Y_s & Y_b \end{pmatrix}$$

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

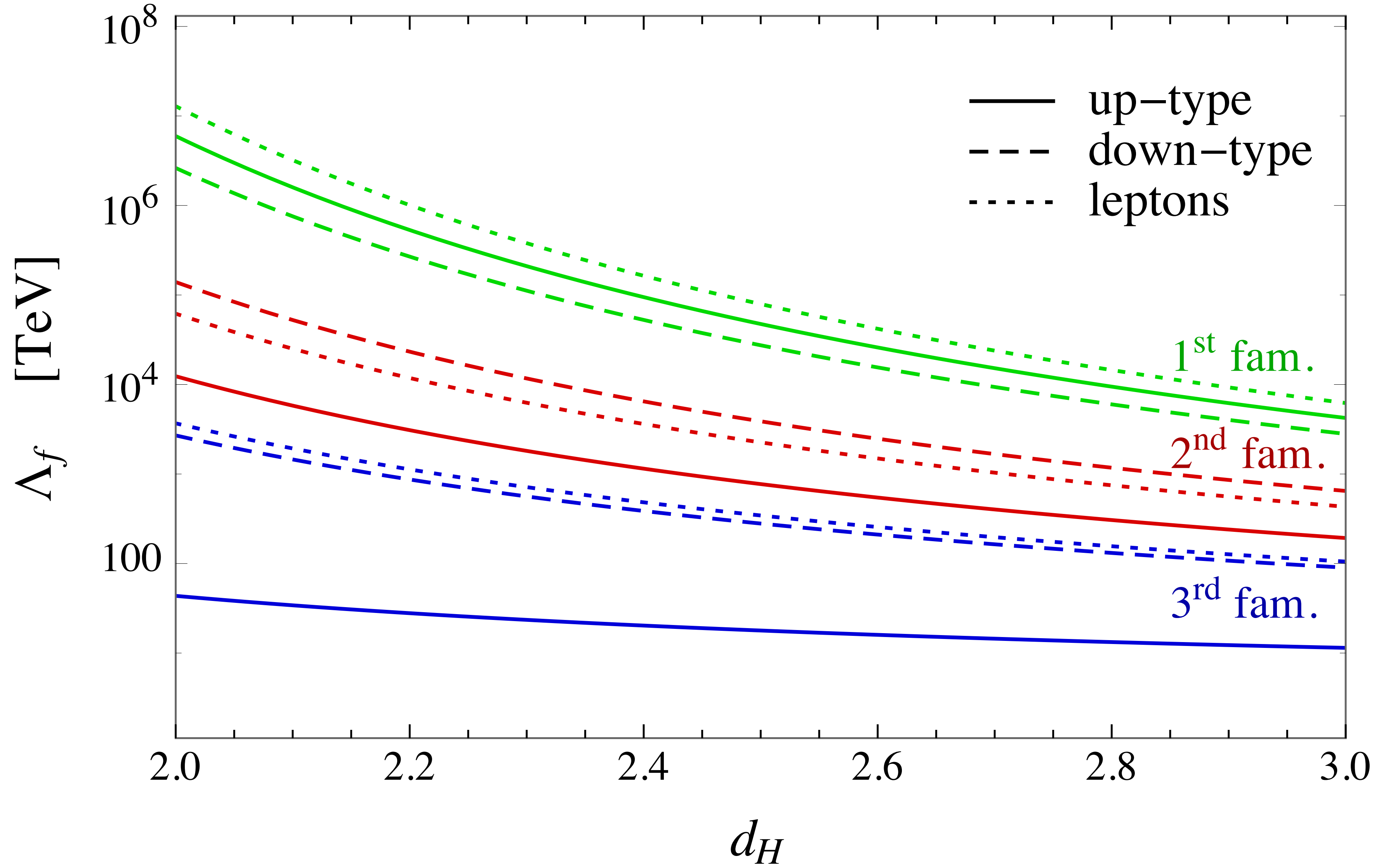
- Smaller Yukawas for large decoupling scale!
- Mixing angles suppressed by Yukawas: $\theta_{ij} \sim Y_i / Y_j$

CKM mostly the rotation in the down-quark sector!

Similarly for the up-quark sector (and lepton sector)



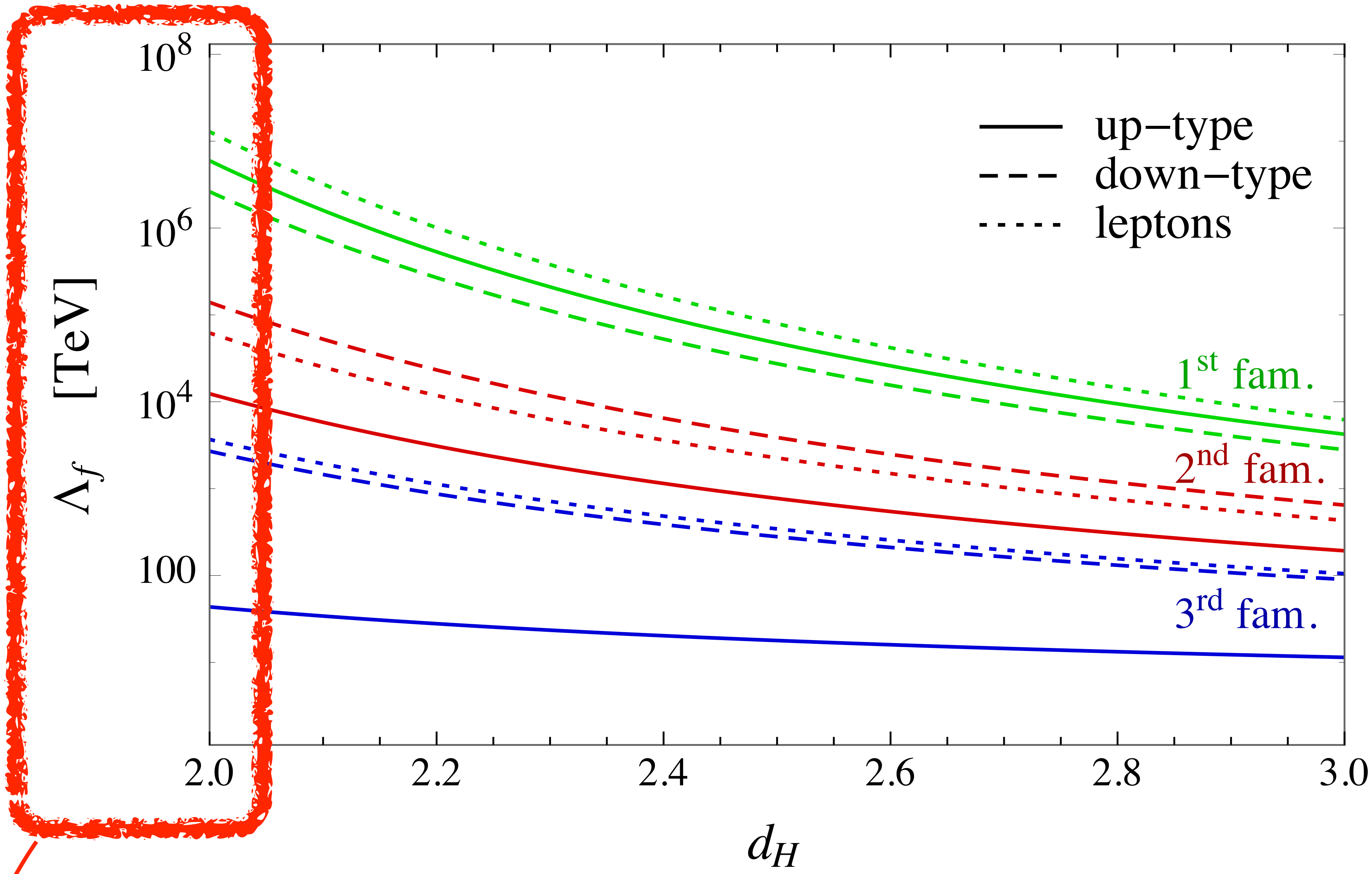
Scales of decoupling:



dimension of the Higgs operator

$$(\mathcal{O}_H \sim \bar{\Upsilon}\Upsilon)$$

Scales of decoupling:



dimension of the Higgs operator

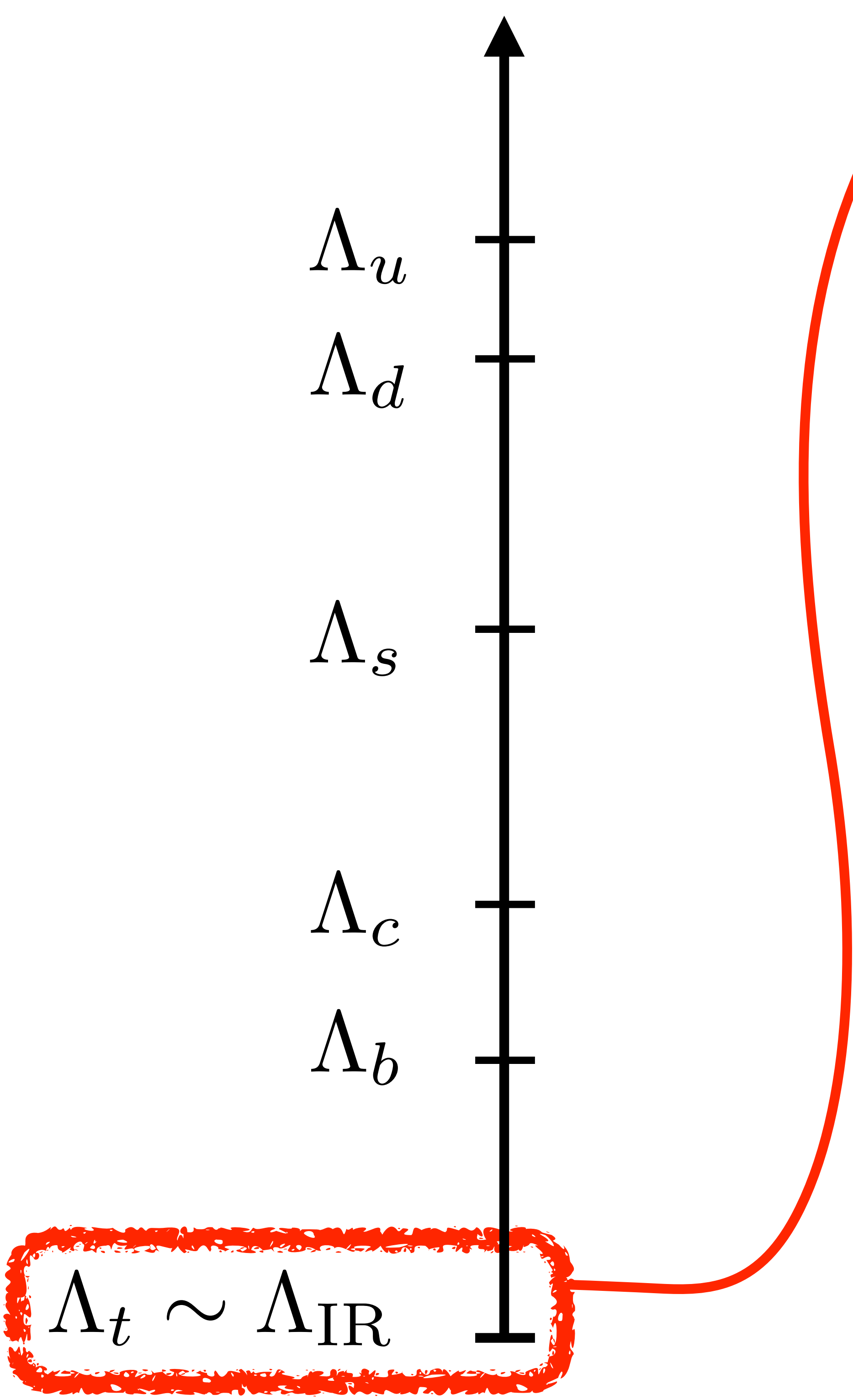
$(\mathcal{O}_H \sim \bar{\Upsilon}\Upsilon)$

d_H~2 needed to pass FCNC

("walking TC": d_H~2 instead of ~3)

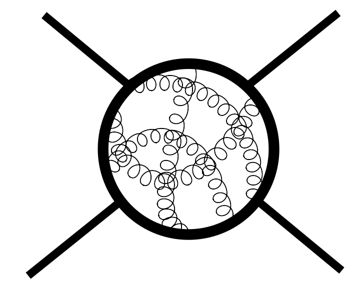
Flavor and CP-violating effects

Different effects at different scales:



Effects from the top

$\Delta F = 2$ transitions



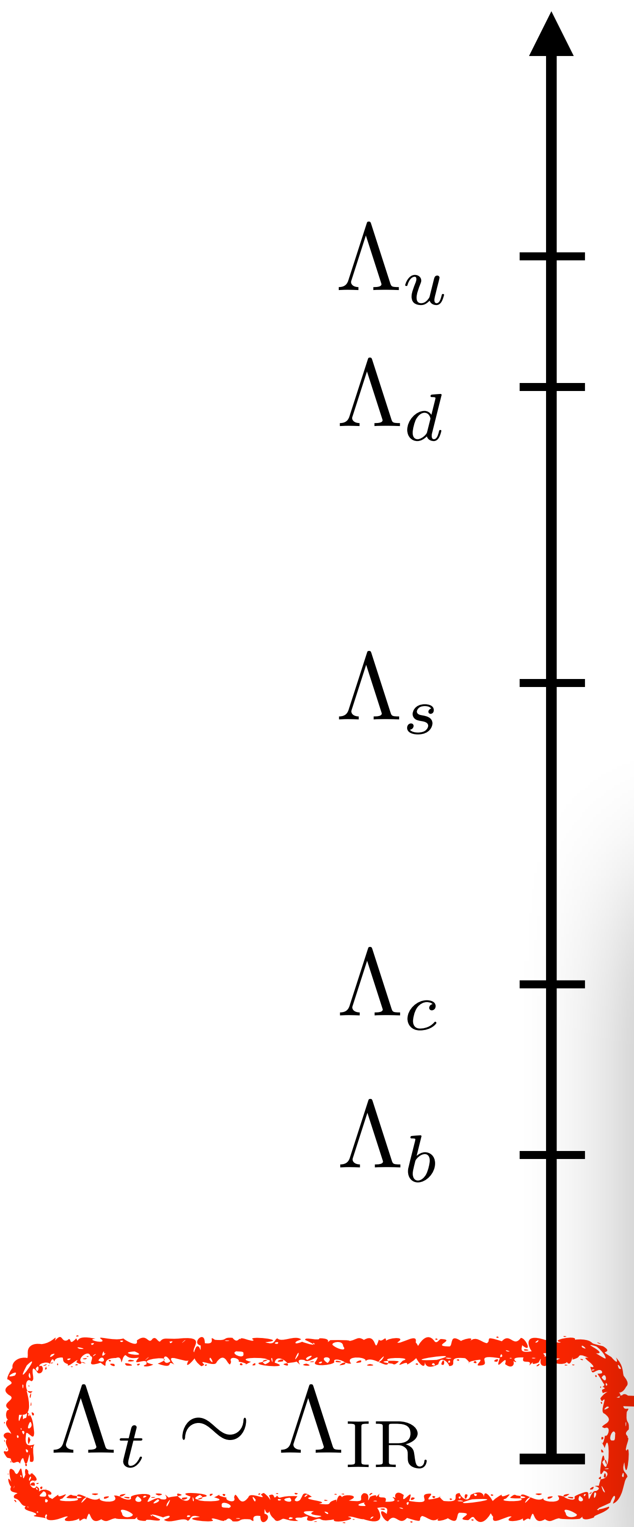
$$\sim \frac{Y_t^2}{\Lambda_{\rm IR}^2} \; (\overline{Q}_{L3}\gamma^\mu Q_{L3})^2$$

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

ϵ_K, ΔM_{B_d}, ΔM_{B_s}

correlated and all close to the experimental value for **$\Lambda_{\rm IR}$~2-3 TeV**

Different effects at different scales:



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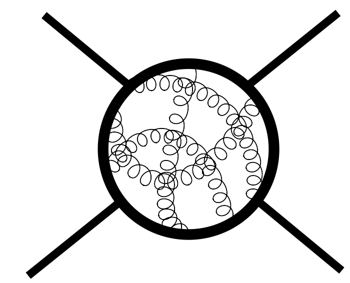
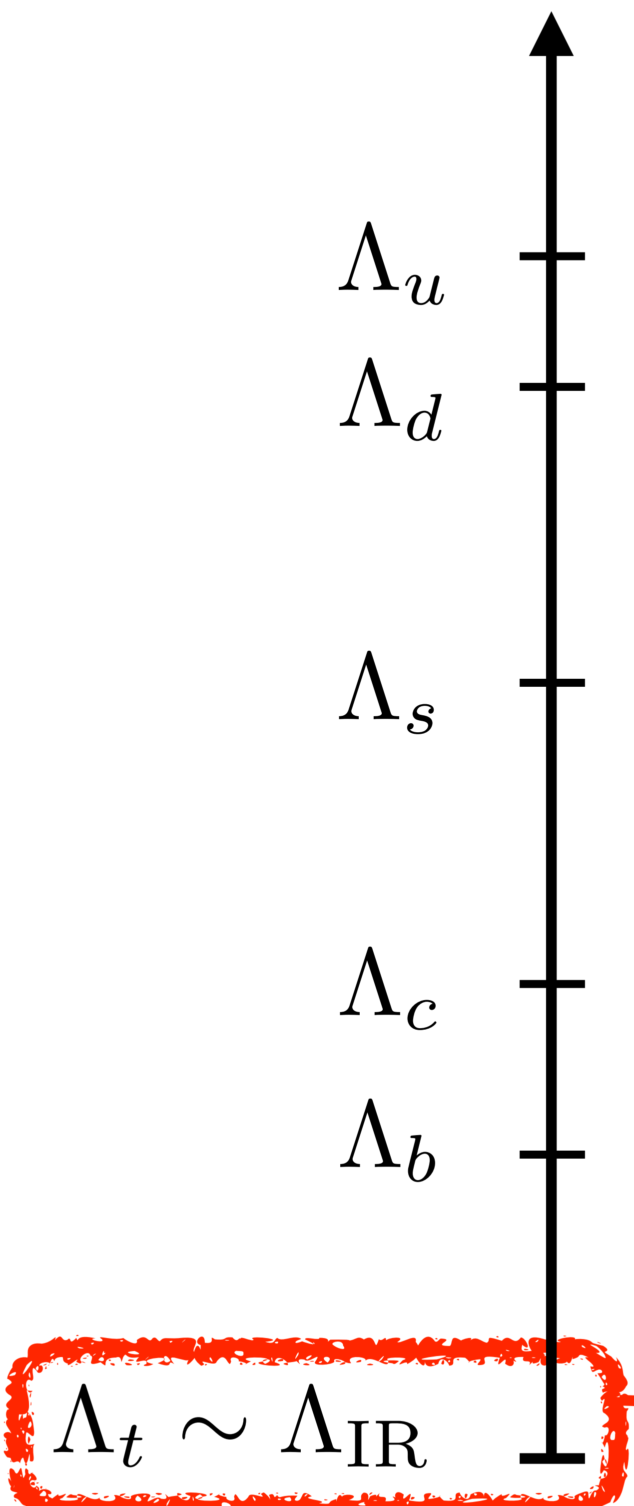


$$\sim \frac{Y_t^2}{\Lambda_{\rm IR}^2} \; (\overline{Q}_{L3}\gamma^\mu Q_{L3})^2$$

Interesting predictions:

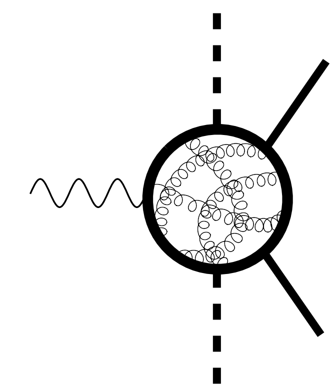
- Only CKM phase
- $$\frac{\Delta M_{B_d}}{\Delta M_{B_s}} \simeq \frac{\Delta M_{B_d}}{\Delta M_{B_s}}\Big|_{\rm SM}$$

Different effects at different scales:



Effects from the top

$\Delta F = 1$ transitions



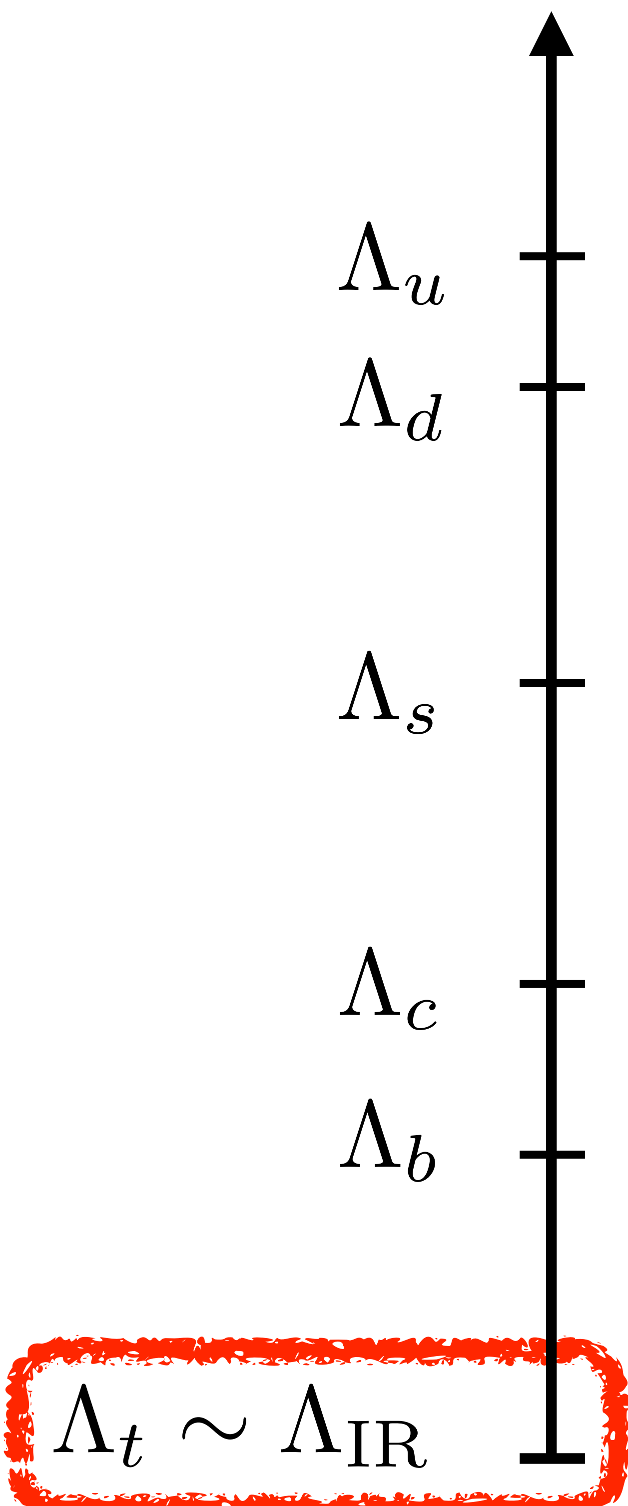
$$\sim \frac{g_* Y_t}{\Lambda_{\rm IR}^2}\ \bar{Q}_{L3}\gamma^\mu Q_{L3} i H^\dagger \overleftrightarrow{D}_\mu H$$

physical basis rotation $\sim V_{CKM}$

K→μμ, ϵ'/ϵ, B→Xll, Z→bb

correlated and all close to the experimental value for $\Lambda_{\rm IR}$~4-5 TeV

Different effects at different scales:



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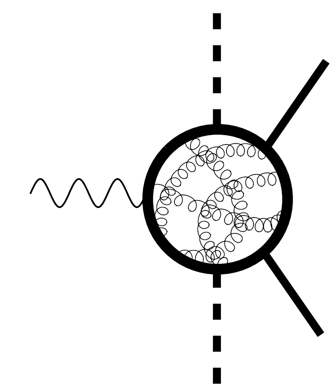


$\Delta F = 1$ transitions

$$\sim \frac{g_* Y_t}{\Lambda_{\rm IR}^2}\ \bar{Q}_{L3}\gamma^\mu Q_{L3} i H^\dagger \overleftrightarrow{D}_\mu H$$

ph...

...on ~V_{CKM}

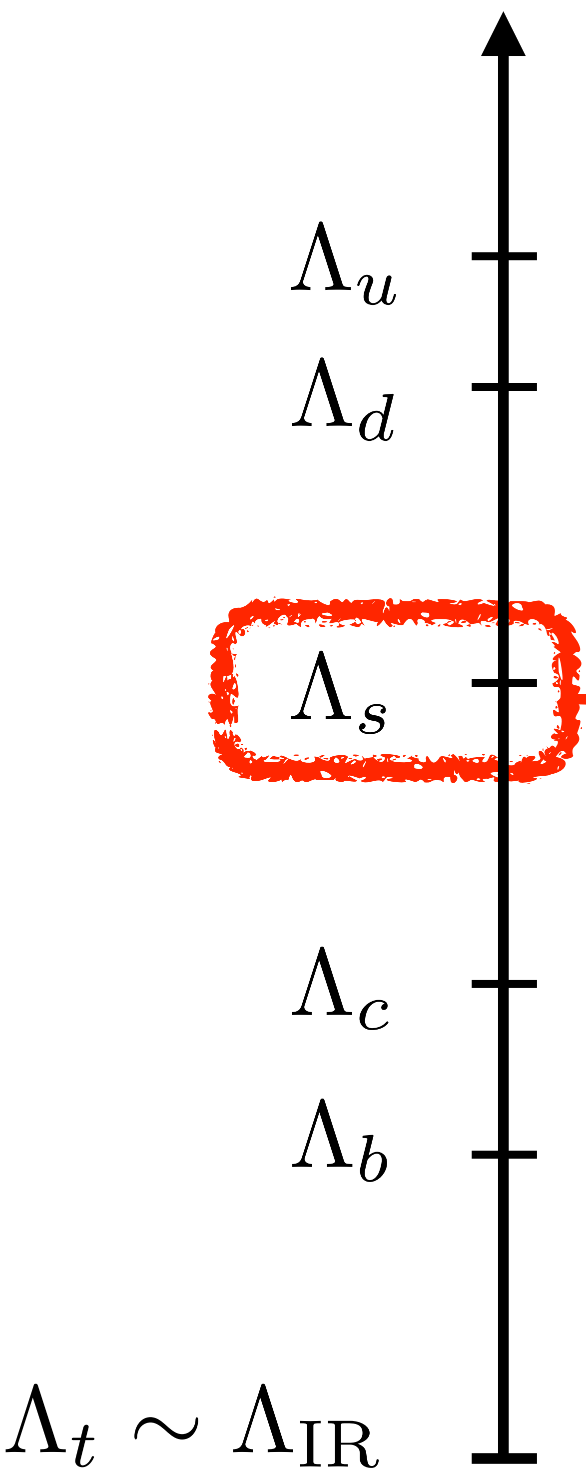
K... , B→Xll, Z→bb

...rrelated and all close

to ...e experimental value for Λ_{IR}~4-5 TeV

Suppressed if left↔right symmetry

Different effects at different scales:



Effects from the strange scale

$\Delta F = 2$ transitions

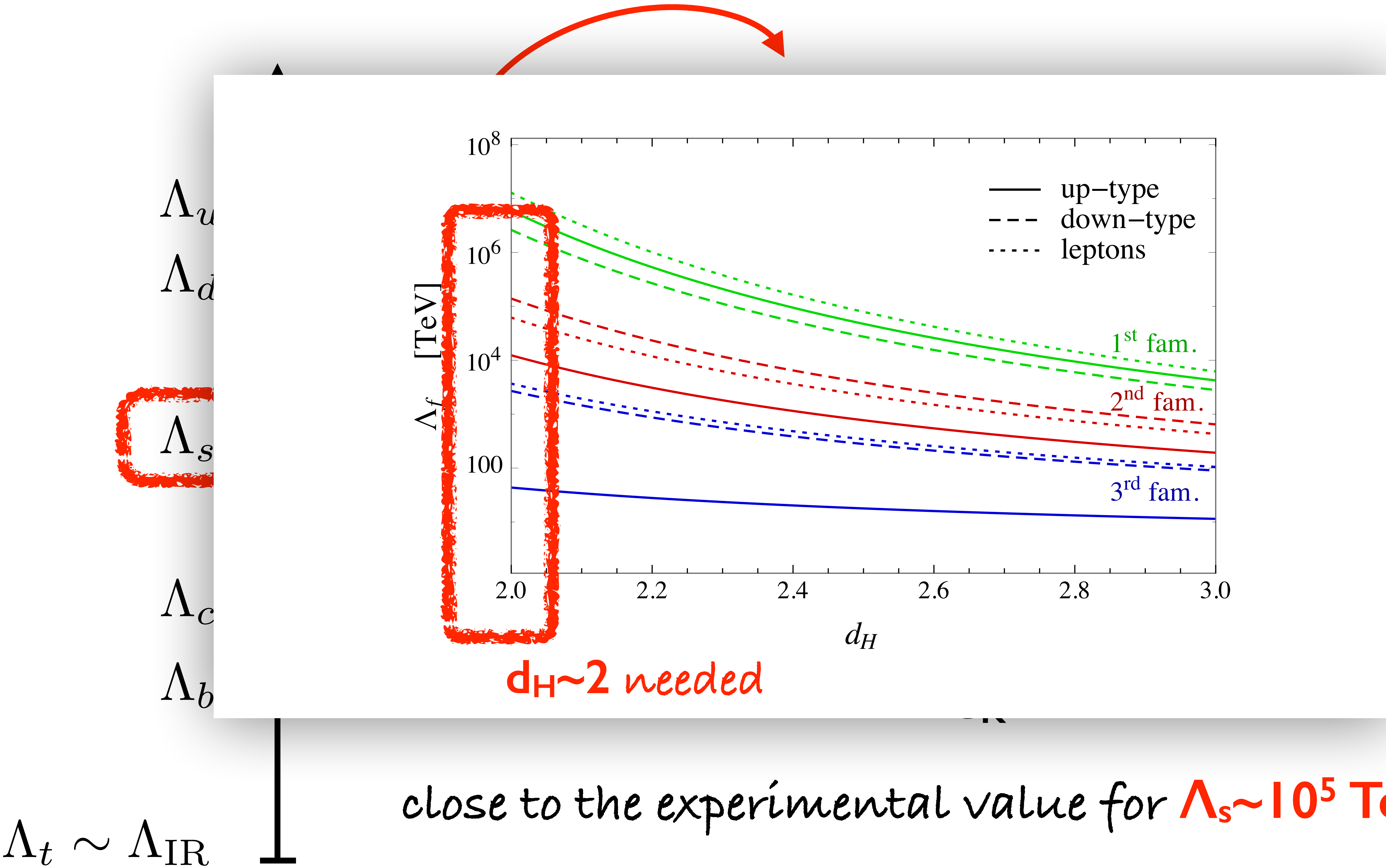
$$\sim \frac{g_*^2}{\Lambda_s^2} (\overline{Q}_{L2} s_R)(\overline{s}_R Q_{L2})$$

physical basis rotation $\sim V_{CKM}$

ϵ_K

close to the experimental value for $\Lambda_s \sim 10^5$ TeV

Different effects at different scales:



close to the experimental value for $\Lambda_s \sim 10^5$ TeV

Like in "walking" TC, we need large anomalous dimension for $\mathcal{O}_H$:

$$\mathcal{O}_H \sim \bar{\psi}\psi$$ $d_H \sim 2$ $(\gamma=1)$

If so, theory close to an unstable point in the CFT:

For $d_H<2$, relevant singlet in the theory: $|\mathcal{O}_H|^2$

$\dim[\,|\mathcal{O}_H|^2\,]<4$ (large N)

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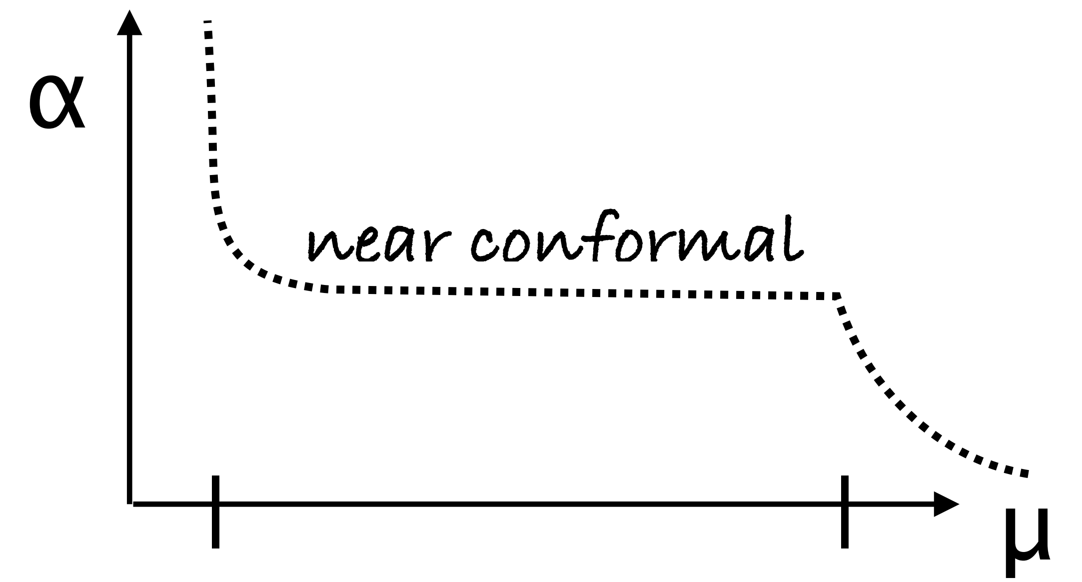
$\dim[|\mathcal{O}_H|^2] < 4$ (large N)

$d_H \sim 2$ ☛ $\dim[|\mathcal{O}_H|^2] \sim 4$ marginal deformation

useful to generate $\Lambda_{IR} \ll M_P$:



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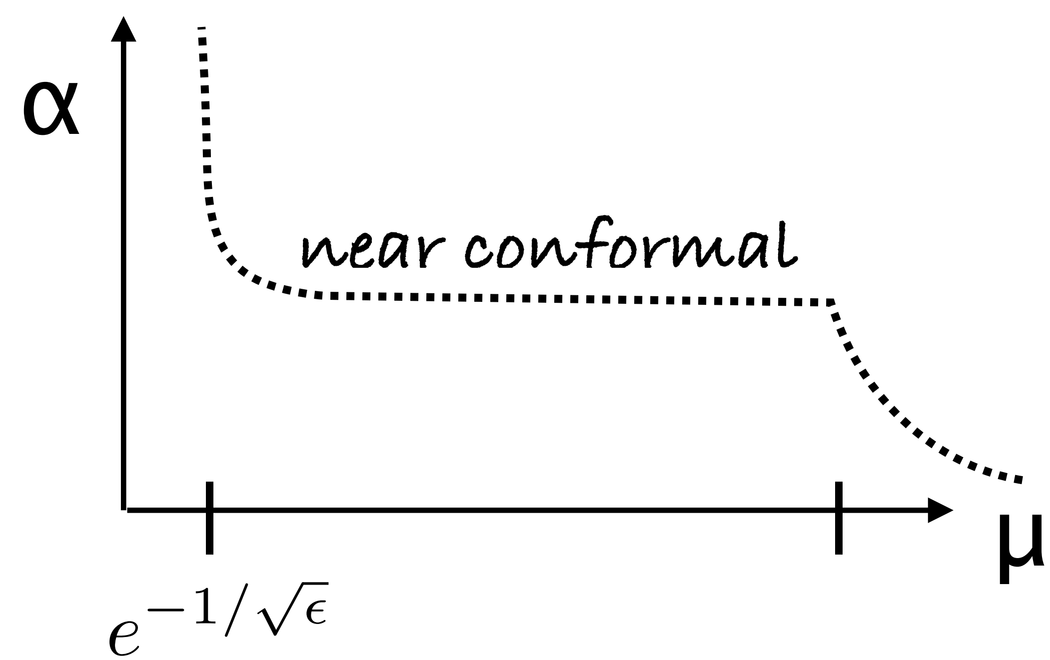


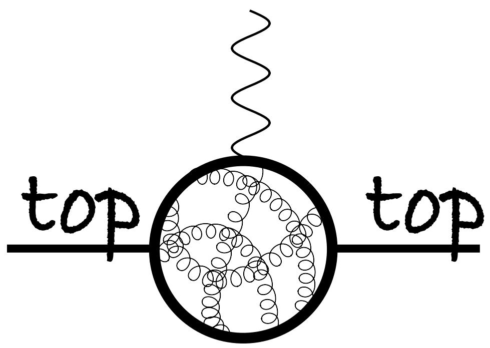
From AdS/CFT:

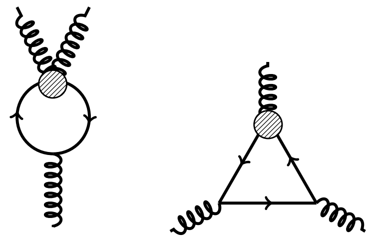
dim of CFT operator ↔ mass in AdS

5D Higgs mass slightly below the BF-bound: $m^2 = -4 - \epsilon$

EDMs

- EDM of u,d,e suppressed by $\Lambda_{d,u,e} > 10^9$ GeV
- Largest constraint from the top EDM:

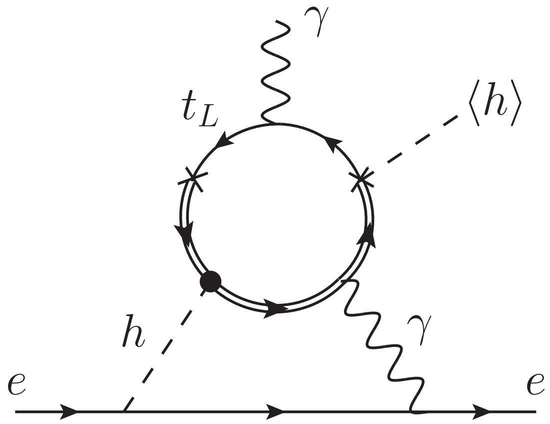




Weinberg operator

$\rightarrow$ d_N

- Two-loop Barr-Zee-like diagrams to d_e:



☛ d_N & d_e around the present bound for $\Lambda_{IR} \sim$ TeV

Always EDM!

If only one scale for each family:

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

Splittings within a given family must be explained by different mixings (ϵ_{fi}) at the respective scales

Only main difference: $\mu \to e\gamma$ gets close to the exp. bound

Other issues:

- Modifications to Higgs couplings:

  Similar effects as with linear mixing

- Neutrino masses:

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

for $d_H \sim 2$,
dimension-7 operator

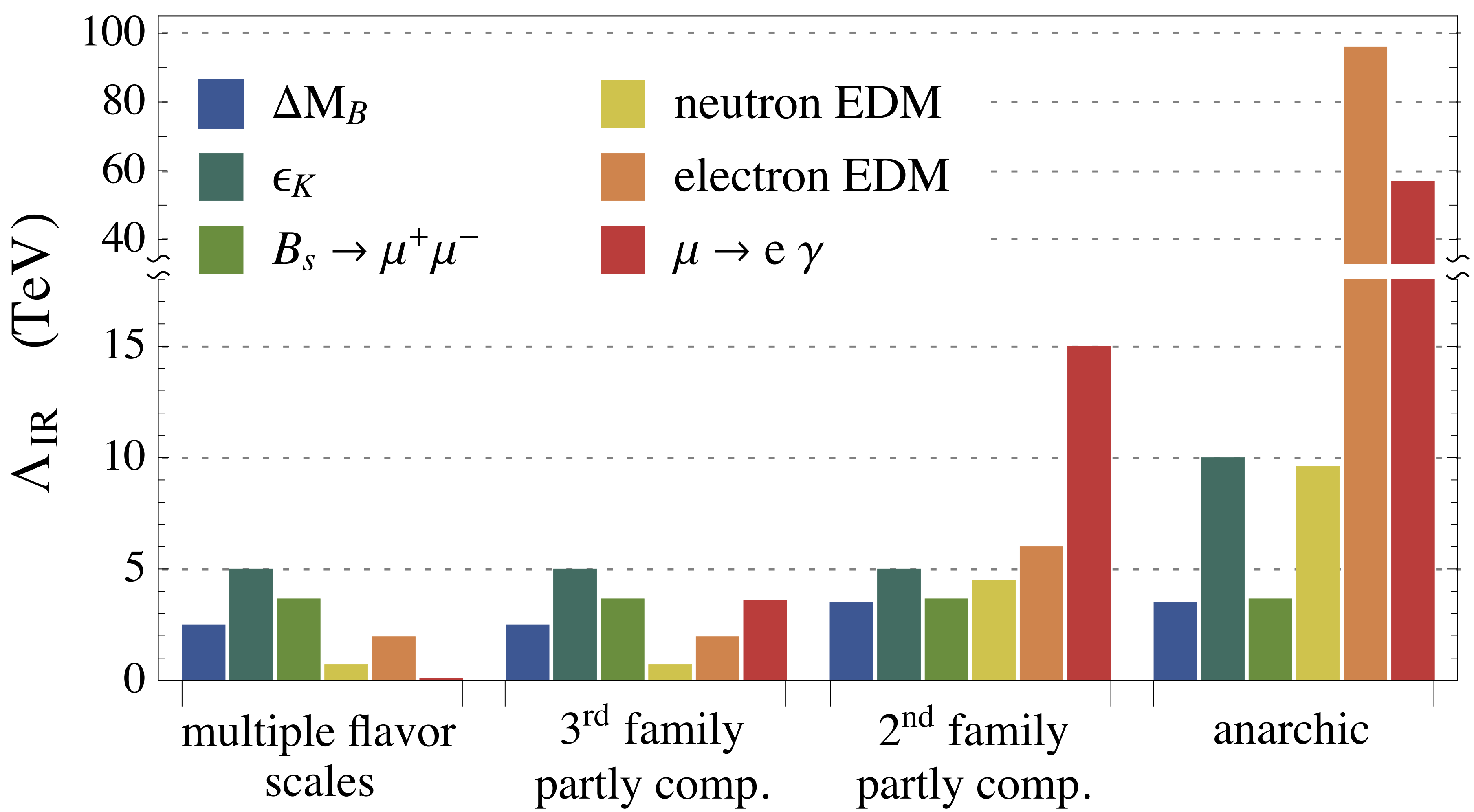
$$m_\nu \sim 0.1 - 0.01 \text{ eV} \quad \text{for} \quad \Lambda_\nu \sim 0.8 - 1.5\times 10^8 \text{ GeV}$$

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

for $d_H \sim 2$,
dimension-5 operator as in the SM

Summary

Flavor from dynamical scales (bilinear mixing)
consistent with BSM TeV physics



many observables around the corner!

Buys you more time to dream...