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The Flavor of the Composite Higgs: $\not{A}$narchy

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Motivations

SM

the only sources of flavor transitions are V_{CKM} and V_{PMNS} in CC with W

Only one phase of CP Violation in quark sector

CKM at work: meson mixing & decays

$$\begin{cases} \text{Flavor}-\text{changing transitions (ex}: \Delta m/m \text{ in K, D, } B_d, B_s \text{ } - \text{systems)} \\ \text{CP Violation (ex}: \epsilon_K, \text{ EDM)} \end{cases}$$

New Physics

generate new sources of flavor violation

ex: $\mathcal{L} = \frac{c_L^{ij}}{\Lambda_{NP}^2}(\bar{q}_L^i \gamma_\mu q_L^j)^2 + \frac{c_{LR}^{ij}}{\Lambda_{NP}^2}(\bar{q}_L^i \gamma_\mu q_L^j)(\bar{q}_R^i \gamma_\mu q_R^j) + \frac{\tilde{c}_L^{ij}}{\Lambda_{NP}^2}(\bar{q}_L^i T^a \gamma_\mu q_L^j)^2 + \frac{\tilde{c}_{LR}^{ij}}{\Lambda_{NP}^2}(\bar{q}_L^i T^a \gamma_\mu q_L^j)(\bar{q}_R^i T^a \gamma_\mu q_R^j)$

for generic coefficients $c \sim \mathcal{O}(1)$: $\Lambda_{NP} \gtrsim 10^{1 \div 5}$ **TeV** $\Rightarrow$ conflict with naturalness

Solution: $\Lambda_{NP} \sim few \times$TeV if NP is not generic

ex: symmetries, MFV, etc.

This talk: $\mathcal{A}$narchy (no flavor structure of the NP) in CHM

Outline of the talk

1) Flavor from bilinear operators: *a la* Technicolor

2) Flavor from linear operators: partial compositeness

3) Full $\mathscr{A}$narchy: linear and bilinear operators

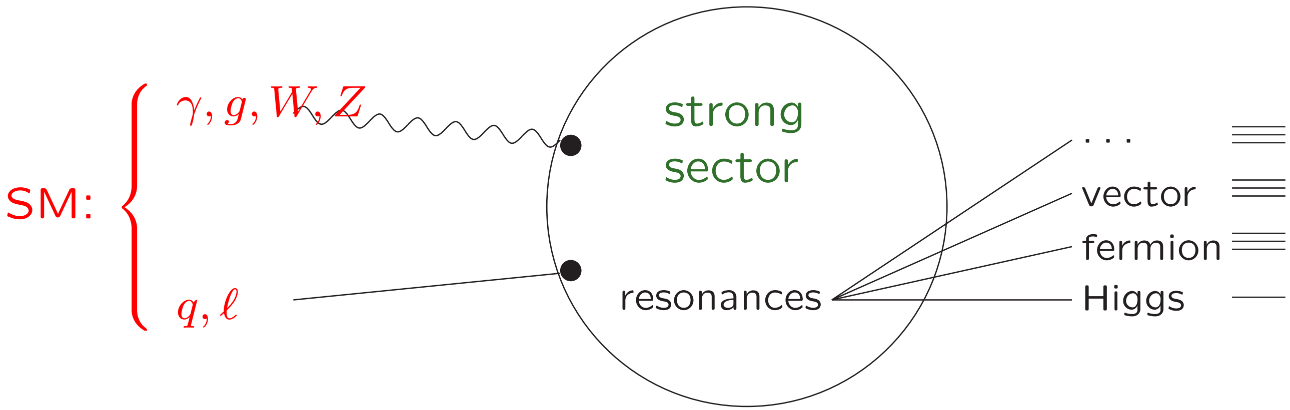
4) Bounds: $K^0\bar{K}^0$-mixing and dipole transitions

5) LHC phenomenology

6) Conclusions

Composite Higgs model

SM + a new sector with a composite Higgs



Hierarchy problem

(Luty Okui '04, Rattazi et al '08)

Separation of scales: $\Lambda_{UV} \gg \Lambda_{IR}$

Let's assume that E-scaling of operators of strong sector is driven by their dimension Δ

$$\mathcal{L} = c\ \Lambda_{UV}^{4-\Delta}\ \mathcal{O} \Rightarrow \text{ an } IR \text{ scale is generated: } \Lambda_{IR} = c^{1/(4-\Delta)}\Lambda_{UV}$$

ex: **Higgs mass** $\longrightarrow \mathcal{O} = H^\dagger H$**, for Composite Higgs** Δ **can be** > 2

hierarchy if
- c hierarchically small $\Rightarrow$ fine tuning (or symmetry)
- $(4-\Delta)$ algebraically small $\Rightarrow$ spans $(4-\Delta)$ orders of magn., ex : 0.1 spans 10 oom

If the Higgs mass term has $\Delta_{H^\dagger H} \sim 4$ the hierarchy problem can be solved.

Bilinear interactions: *a la* Technicolor

Yukawa interactions

SM elementary fermions interacting with a composite operator $\langle 0|\mathcal{O}_H|h\rangle \neq 0$

$$\mathcal{L} = \frac{\omega_y}{\Lambda_{UV}^{\Delta_H - 1}} \; \bar{q}_L \; \mathcal{O}_H \; q_R \Rightarrow \text{ at low energies: } y = \omega_y \left(\frac{\Lambda_{IR}}{\Lambda_{UV}}\right)^{\Delta_H - 1}$$

- **small masses for** $\Delta_H > 1$
- **top mass requires** $y \sim \mathcal{O}(1)$**:**
  - $\Lambda_{UV} \sim \Lambda_{IR} \simeq$ TeV $\Rightarrow$ no separation of scales
  - $\Delta_H \simeq 1$ $\Rightarrow$ hierarchy problem recovered for Higgs mass

4-fermion operators

We expect higher dimensional operators suppressed by the same scale

$$\mathcal{L} = \frac{c_{ijk\ell}}{\Lambda_{UV}^2} \; (\bar{q}^i q^j)(\bar{q}^k q^\ell)$$

if: $\Lambda_{UV} \sim \Lambda_{IR} \simeq$ TeV $\Rightarrow$ **TC incompatible with flavor bounds**

Linear int.: Partial Compositeness

Linear interaction of fermions

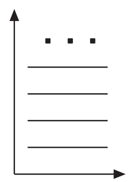
(Kaplan '91, Contino et al '04 '06)

SM elementary fermions ψ interacting linearly with NP operators $\mathcal{O}$

$$\mathcal{L} = \frac{\omega_L}{\Lambda_{UV}^{\Delta_R-5/2}} \bar{\psi}_L \mathcal{O}_R \quad \Rightarrow \quad \lambda_L \sim \omega_L \left(\frac{\Lambda_{IR}}{\Lambda_{UV}}\right)^{\Delta_R-5/2}$$

Δ_R determines the size of λ_L

Partial Compositeness



resonances

At low energies the NP-sector generates bound states: $|n\rangle$

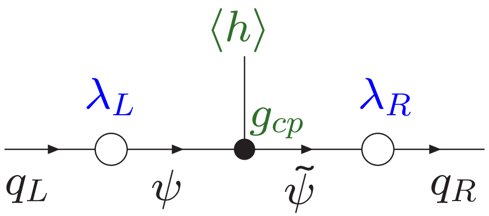
mass eigenstates are superpositions of elementary and composite states

$$|\psi_j^{\text{phys}}\rangle = \alpha_{j0}|\psi\rangle + \sum_n \alpha_{jn}|n\rangle$$

Δ_R determines the size of the mixing

Partial comp.: fermion masses and CKM

Fermion masses



$$m_{jk}^{\text{SM}} \sim C_{jk}\ \lambda_L \lambda_R$$

$\hookrightarrow C_{jk} \sim \mathcal{O}(1)$ **set flavor structure**

- **light fermions** $\Rightarrow$ **small mixing:** $\lambda \ll 1$
- **top mass** $\Rightarrow$ **large mixing:** $\lambda_{t_{L,R}} \sim \mathcal{O}(1)$

$\mathcal{A}$narchy: all entries of C_{jk} of the same order: $C_{jk} \sim \mathcal{O}(1)\ \forall j, k$, **no structure**

⋆ **ratios of Left-mixing give CKM angles:** $\lambda_L^1/\lambda_L^2 \sim \lambda_C$, $\lambda_L^2/\lambda_L^3 \sim \lambda_C^2$

⋆ **Right-mixing give the masses:** $\lambda_u^2 \sim \lambda_u^3 \frac{m_c}{m_t \lambda_C^2}$, $\lambda_d^2 \sim \lambda_d^3 \frac{m_s}{m_b \lambda_C^2}$

$$\lambda_u^1 \sim \lambda_u^3 \frac{m_u}{m_t \lambda_C^3}\ , \qquad \lambda_d^1 \sim \lambda_d^3 \frac{m_d}{m_b \lambda_C^3}$$

rationale for hierarchy of masses and V_{CKM} $\Rightarrow$ first success of $\mathcal{A}$narchy!

(Gherghetta Pomarol '00, Agashe et al '04)

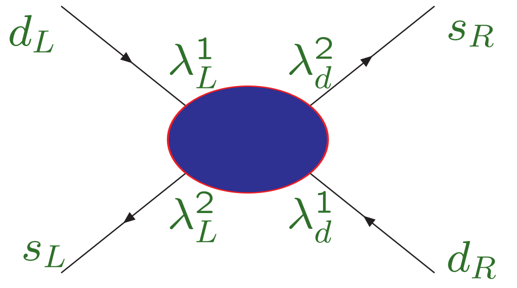
Flavor constraints in $\mathcal{A}$narchy

$\mathcal{A}$narchy succeeds in all flavor constraints for $\Lambda_{IR} \gtrsim 3$ TeV, except:

- ϵ_K **in Kaon system**

FCNC at tree level: $\mathcal{O}_4^{sd} = (\bar{d}_L s_R)(\bar{d}_R s_L)$

$$(C_4^{sd})_{pc} \sim \frac{2 m_d m_s}{v^2} \frac{1}{\Lambda_{IR}^2}$$

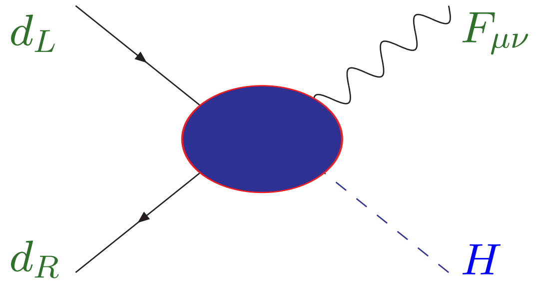


$\hookrightarrow$ highly non-generic, $\Lambda_{IR} \gtrsim 10 \div 30$ TeV (Panico-Wulzer '15)

- **Dipole Moments of the neutron**

CP Violation $\mathcal{O}_d = \bar{q}_L H \sigma_{\mu\nu} F^{\mu\nu} q_R$

$$(C_d^{\text{neutron}})_{pc} \sim \frac{e}{(4\pi)^2} \frac{m_d}{v} \frac{1}{\Lambda_{IR}^2}$$



$\hookrightarrow$ highly non-generic, $\Lambda_{IR} \gtrsim 10 \div 20$ TeV (Neubert '13)

Full $\mathscr{A}$narchy

Most general scenario: linear + bilinear interactions

$$\mathcal{L} = \frac{\omega_y}{\Lambda_{UV}^{\Delta_H - 1}}\ \bar{q}_L\ \mathcal{O}_H\ q_R + \frac{\omega_L}{\Lambda_{UV}^{\Delta_R - 5/2}} \bar{q}_L \mathcal{O}_R + \frac{\omega_R}{\Lambda_{UV}^{\Delta_L - 5/2}} \bar{q}_R \mathcal{O}_L$$

Two contributions to masses: $Y_{jk} \sim y\ C^y_{jk}\ +\ \lambda^j_L\ \lambda^k_R\ C^\lambda_{jk}$

In partial compositeness:

- ⋆ C_d^{neutron} and C_4^{sd} are controlled by: $\lambda_L^1 \times \lambda_d^1$
- ⋆ Suppressing one of them can lower bound on Λ_{IR} to TeV
- ⋆ However $m_d \propto \lambda_L^1 \times \lambda_d^1 \Rightarrow$ supress m_d also

Full $\mathscr{A}$narchy with elementary d_R and u_R: $\lambda^1_{d,u} \to 0 \Rightarrow C_d^{\text{neutron}},\ C_4^{sd} \to 0$

- Bilinear interactions give masses to 1st generation if: $y \sim m_{u,d}/v$
- Left-handed couplings generate V_{CKM} as in partial comp.
- Partial compositeness give masses to 2nd and 3rd generation

$\Rightarrow$ quark masses and CKM reproduced

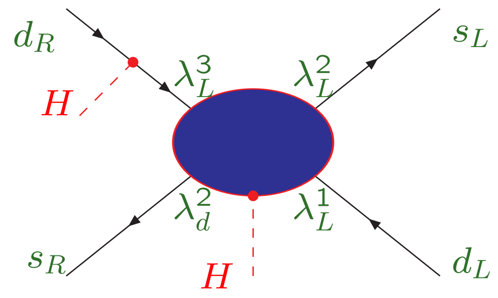
Flavor constraints in full $\mathcal{A}$narchy

$\star$ **Interactions between u_R or d_R and NP require insertions of $y \sim m_d/v$**

- **ϵ_K in Kaon system**

$C_4^{sd} \sim (C_4^{sd})_{pc}\ \lambda_C^3\ \left(\frac{\lambda_L^3}{g_{cp}}\right)^2\ \left(\frac{v}{\Lambda_{IR}}\right)^2$

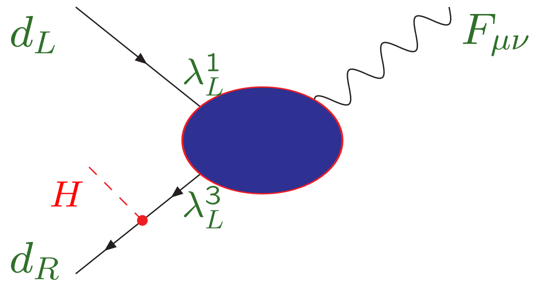
$\hookrightarrow$ $\Lambda_{IR} \gtrsim 0.5 \div 0.9$ **TeV**



- **Dipole Moments of the neutron**

$C_d^{\text{neutron}} \sim (C_d^{\text{neutron}})_{pc}\ \lambda_C^3\ \left(\frac{\lambda_L^3}{g_{cp}}\right)^2$

$\hookrightarrow$ $\Lambda_{IR} \gtrsim \frac{\lambda_L^3}{g_{cp}} \times 1 \div 2$ **TeV**



LHC phenomenology: dijets

⋆ In partial compositeness flavor symmetries required to lower bounds

↪ they usually lead to composite u and d quarks

4-fermion operators for light fermions at the scale Λ_{IR}:

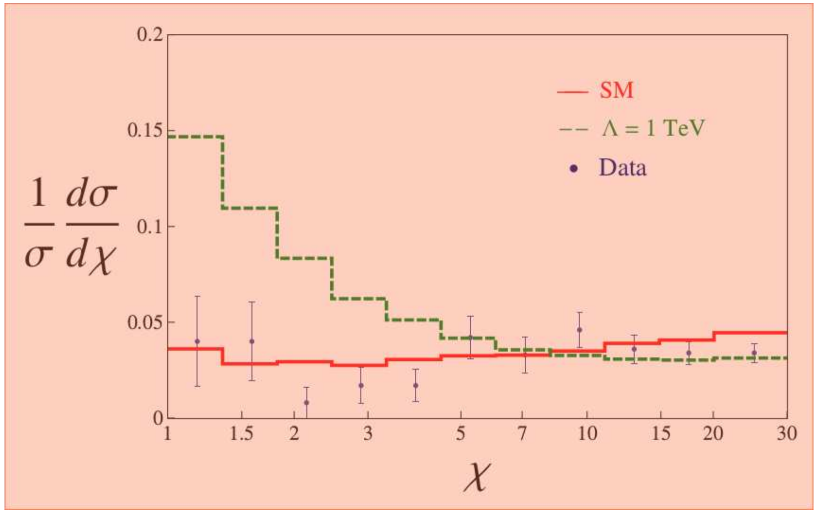
$$\mathcal{L}_{4f} = \sum_{\psi,\psi'=q_L,u_R,d_R} \frac{1}{\Lambda_{IR}^2} (\bar{\psi}\gamma_\mu T\psi)(\bar{\psi}'\gamma_\mu T\psi')$$

⋆ $\mathcal{L}_{4f}$ contributes to $pp \to jj$

for large m_{jj} mostly: $uu, dd \to jj$

give bounds: $\Lambda_{IR} \gtrsim \mathcal{O}(10)$ TeV

(Domenech et al '12)



⋆ In the present scenario light fermions are mostly elementary

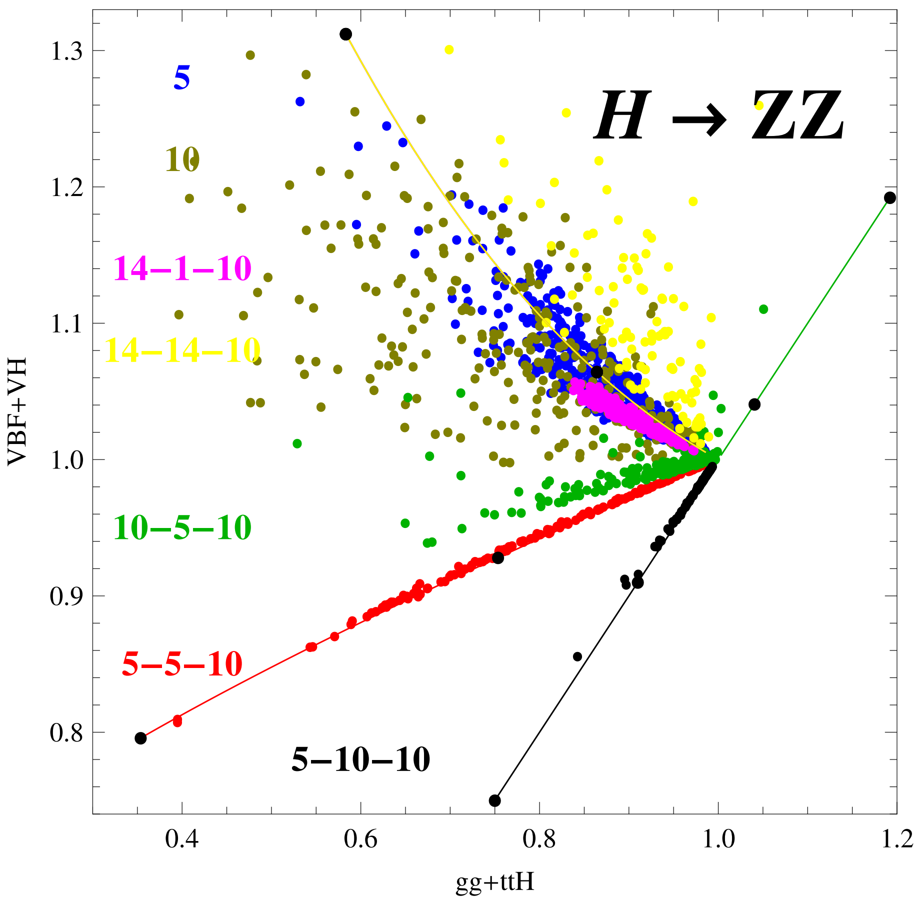
⇒ dijets of 1st generation quarks are not an issue ($\Lambda_{IR}/\sqrt{c} \gtrsim 10^4$ TeV)

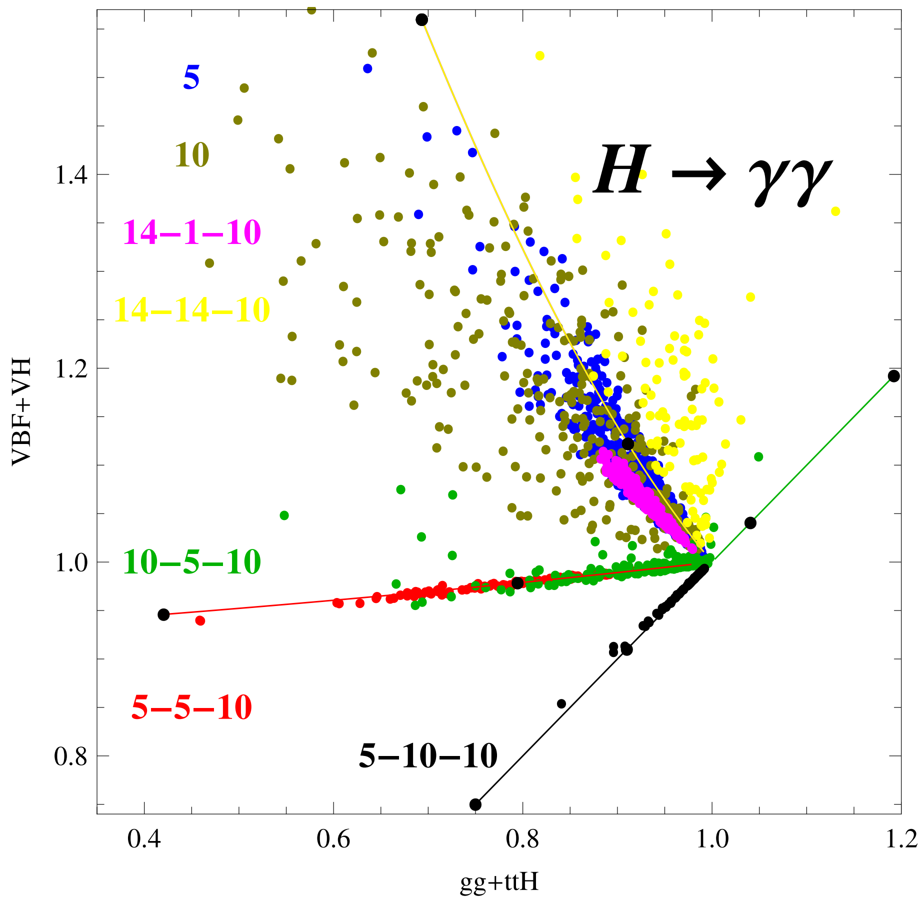
LHC phenomenology: Higgs

- ⋆ **Little hierarchy problem ($\Lambda_{IR} \sim 10 \times v$) alleviated if the Higgs is a pNGB**

  linear and bilinear interactions explicitly break sym. ⇒ radiative potential and dynamical EWSB

- ⋆ **Predictions for single Higgs production in the MCHM** (Carena DR Ponton '13)





Conclusions

⋆ Partial compositeness and Anarchy almost solve the flavor problem of CHM, however $\Lambda_{NP} \sim 10 \div 30$ TeV.

⋆ Assuming the most general scenario: bilinear couplings and pc, the flavor problem can be solved if:

- u_R and d_R are elementary, while the other fermions are partially composite,
- bilinear Yukawa are of the size of masses of the first generation: $y \sim m_{u,d}/v$.

⋆ The hardest flavor bounds come from C_1 in B-systems: $\Lambda_{IR} \sim 2 \div 4$ TeV.

⋆ Leptons: $\mu \to e\gamma$ and electron EDM give $\Lambda_{NP} \sim 50 \div 100$ TeV for Dirac ν and pc

$\hookrightarrow$ however the picture can change dramatically if Majorana masses are allowed and generate V_{PMNS}.

⋆ Most promising CHM: Higgs = pNGB, compatible with present flavor scenario.

⋆ Deviations of $\sim 10 \div 30\%$ in single Higgs production, signs of corrections depend on the global symmetries of the composite sector and on the fermionic representations.

⋆ Enhancement in double Higgs production, up to a factor 3 (Gillioz et al '12).

A toy model

⋆ 2-site model with a set of fermionic resonances Q and D

$$\mathcal{L} \supset f \bar{q}_L \lambda_q Q + f \bar{d}_R \lambda_d D + \bar{q}_L y H d_R + \bar{Q}_L y_* H D_R + \bar{Q}_R \hat{y}_* H D_L + \text{h.c.}$$

if $\lambda_d^1 \to 0$:

$$Y \sim \begin{pmatrix} y & \lambda_q^1 \lambda_d^2 / g_* & \lambda_q^1 \lambda_d^3 / g_* \\ y & \lambda_q^2 \lambda_d^2 / g_* & \lambda_q^2 \lambda_d^3 / g_* \\ y & \lambda_q^3 \lambda_d^2 / g_* & \lambda_q^3 \lambda_d^3 / g_* \end{pmatrix}$$

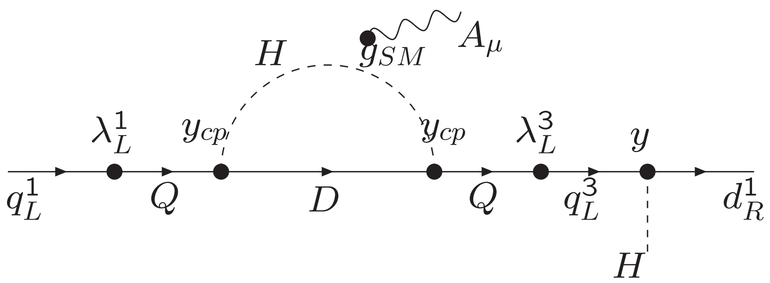
It is a simple algebraic excercise to show that it leads to the same Lef-mixing matrix as pc.

Also straightforward to see that spectrum and V_{CKM} can be obtained.

⋆ Composite massive gluons: $\mathcal{L} \supset g_* (\bar{Q} \not{G} Q + \bar{D} \not{G} D)$

- integrating-out heavy resonances and going to mass basis generates C_4^{sd}

- Dipole at 1-loop



Algebric manipulations

start with: $M_{jk} \sim \lambda_L^j C_{jk} \lambda_R^k$ **,** $C_{jk} \sim \mathcal{O}(1)$ **and** $\lambda^j \leq \lambda^k$ **for** $j < k$

diagonalize M **by bi-unitary rotation**

$$M_{jk} = (U_L^\dagger)_{jl} D_{ln} (U_R)_{nk} \quad , \quad D = \textbf{diagonal}(d_j)$$

results: $d_j \sim \lambda_L^j \lambda_R^j$

$$(U_L)_{jk} \sim \begin{cases} \lambda_L^j / \lambda_L^k \;, & j < k \\ 1 \;, & j = k \\ \lambda_L^k / \lambda_L^j \;, & j > k \end{cases}$$

$$(U_R)_{jk} \sim \begin{cases} \lambda_R^j / \lambda_R^k \;, & j < k \\ 1 \;, & j = k \\ \lambda_R^k / \lambda_R^j \;, & j > k \end{cases}$$

- **hierarchical** λ^j**:** • **hierarchy of fermionic masses**
  • **small rotation angles**
  $\Rightarrow$ **quarks**

- **same** λ^j**:** • **no-hierarchy of fermionic masses**
  • **large rotation angles**
  $\Rightarrow$ **leptons if** $\lambda_L^i \sim \lambda_L^j$ **&** $\lambda_R^i \ll \lambda_R^j$

Partial comp.: quarks

- Assume that each SM quark interacts with one SCFT operator:

$$\mathcal{L} \supset \lambda_q^j\ \bar{q}_L^j\ \mathcal{O}_q^j\ +\ \lambda_u^j\ \bar{u}_R^j\ \mathcal{O}_u^j\ +\ \lambda_d^j\ \bar{d}_R^j\ \mathcal{O}_d^j\ +\ \text{h.c.}$$

the mass matrices for the up- and down-sectors

$$M_{jk}^u \sim \lambda_q^j C_{jk}^u \lambda_u^k \quad \text{and} \quad M_{jk}^d \sim \lambda_q^j C_{jk}^d \lambda_d^k$$

diagonalize by a bi-unitary rotation

$$M_{jk}^u = (U_L^{u\dagger})_{jl} D_{ln}^u (U_R^u)_{nk} \quad \text{and} \quad M_{jk}^d = (U_L^{d\dagger})_{jl} D_{ln}^d (U_R^d)_{nk}$$

- Assuming Ⓐnarchy: size of $(U_{L,R}^{u,d})_{jk}$ determined by $\lambda_{q,u,d}^j$ and $\lambda_{q,u,d}^k$

reproducing the SM spectrum gives relations: $d_j \sim \lambda_L^j \lambda_R^j \Rightarrow \begin{cases} m_u^j \sim \lambda_q^j \lambda_u^j \\ m_d^j \sim \lambda_q^j \lambda_d^j \end{cases}$

$$\frac{m_t}{m_c} \sim \frac{\lambda_q^3 \lambda_u^3}{\lambda_q^2 \lambda_u^2} \qquad \frac{m_b}{m_s} \sim \frac{\lambda_q^3 \lambda_d^3}{\lambda_q^2 \lambda_d^2}$$

$$\frac{m_c}{m_u} \sim \frac{\lambda_q^2 \lambda_u^2}{\lambda_q^1 \lambda_u^1} \qquad \frac{m_s}{m_d} \sim \frac{\lambda_q^2 \lambda_d^2}{\lambda_q^1 \lambda_d^1}$$

Partial comp.: quarks

- We also want the CKM matrix: $V_{\text{CKM}} = U_L^u U_L^{d\dagger}$

$$V_{\text{CKM}} \sim \begin{bmatrix} 1-\lambda_C^2/2 & \lambda_C & \lambda_C^3 \\ \lambda_C & 1-\lambda_C^2/2 & \lambda_C^2 \\ \lambda_C^3 & \lambda_C^2 & 1 \end{bmatrix}, \qquad \lambda_C \sim 0.2$$

using previous results

$$(U_L^u U_L^{d\dagger})_{jk} \sim \lambda_L^j/\lambda_L^k \,, \qquad j<k$$

determining the ratios of Left-mixing: $\lambda_L^1/\lambda_L^2 \sim \lambda_C$, $\lambda_L^2/\lambda_L^3 \sim \lambda_C^2$

- Using the relations from the masses determines almost all mixing:

$$\lambda_u^2 \sim \lambda_u^3 \frac{m_c}{m_t \lambda_C^2} \,, \qquad \lambda_d^2 \sim \lambda_d^3 \frac{m_s}{m_b \lambda_C^2}$$

$$\lambda_u^1 \sim \lambda_u^3 \frac{m_u}{m_t \lambda_C^3} \,, \qquad \lambda_d^1 \sim \lambda_d^3 \frac{m_d}{m_b \lambda_C^3}$$

ex.: if $\lambda_u^3 \sim g_{cp} \;\Rightarrow\; \lambda_3^q$ and λ_d^3 are fixed

rationale for hierarchy of masses and V_{CKM} $\Rightarrow$ first success of Anarchy!

Different basis

At the UV scale

$$\mathcal{L} = \frac{\omega_R^{ij}}{\Lambda_{UV}^{\Delta_L - 5/2}} \bar{u}_R^i \mathcal{O}_L^j$$

by RGE at low energies the couplings are

$$\lambda_R^{ij} \simeq \omega_R^{ij} \left(\frac{\Lambda_{IR}}{\Lambda_{UV}} \right)^{\Delta_L - 5/2}$$

in the UV the operators can be distinguished by their dimensions, and thus do not mix during the evolution

in the IR they are not distinguished anymore and we can rotate them to diagonalize λ_R^{ij}

we end up with hierarchical mixing if there are different Δ_L^j