An ambitious alternative: Partial Compositeness

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Why TeV-Compositeness in 2016?!

- **Still a challenging question theoretically**
  - top quark mass?

- **and phenomenologically**
  - What EFT (symmetries, spectrum)? New signatures?

The main challenge for models
of **Higgs compositeness**: the top mass

$$\mathcal{L} = -\frac{1}{4}F^2 + qiDq + |DH|^2 - V$$

$$+yqqH \quad \textbf{???}$$

$$+\mathcal{O}\left(\frac{1}{\Lambda^2_{\mathrm{cutoff}}}\right)$$

2 options:

coupling between the SM fermions
and Higgs dynamics

IRRELEVANT

$$\Lambda_\chi \sim \Lambda_{\rm UV}$$

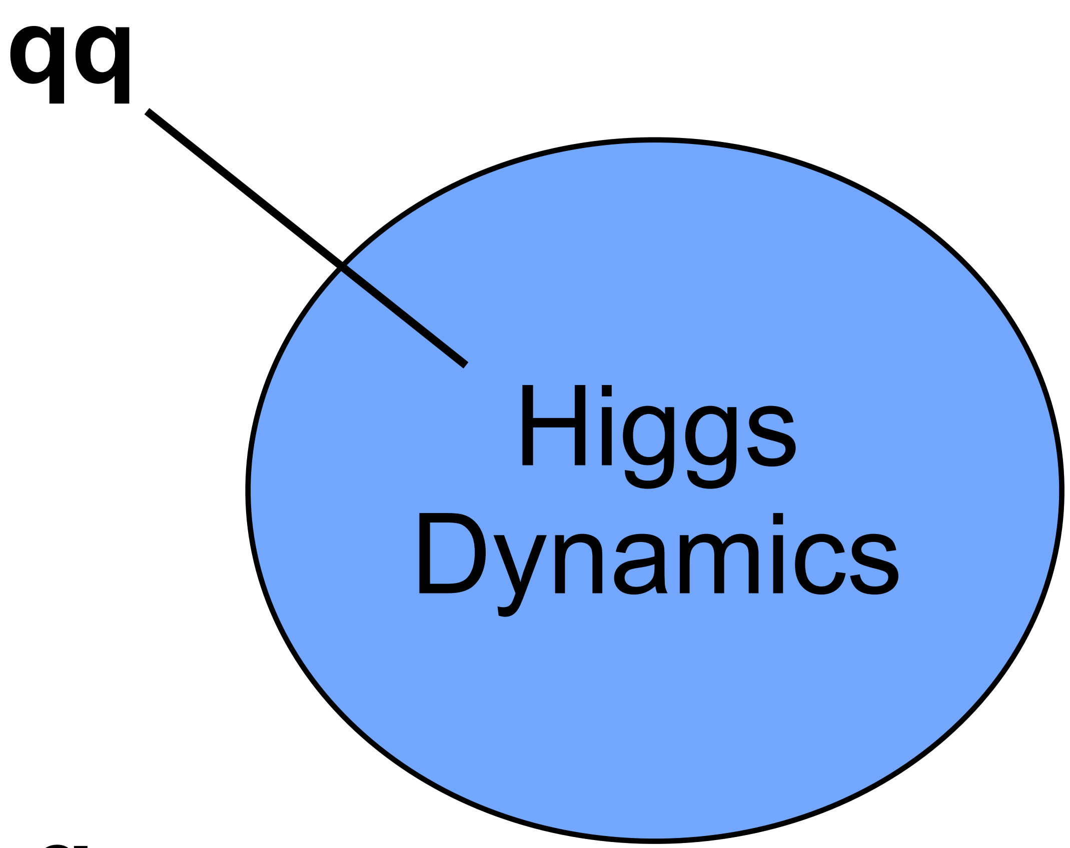
Actual operator not important
No EFT: what UV? why the same scale?

RELEVANT

$$\Lambda_\chi < \Lambda_{\rm UV}$$

We can decouple the UV!
What coupling can achieve this?!

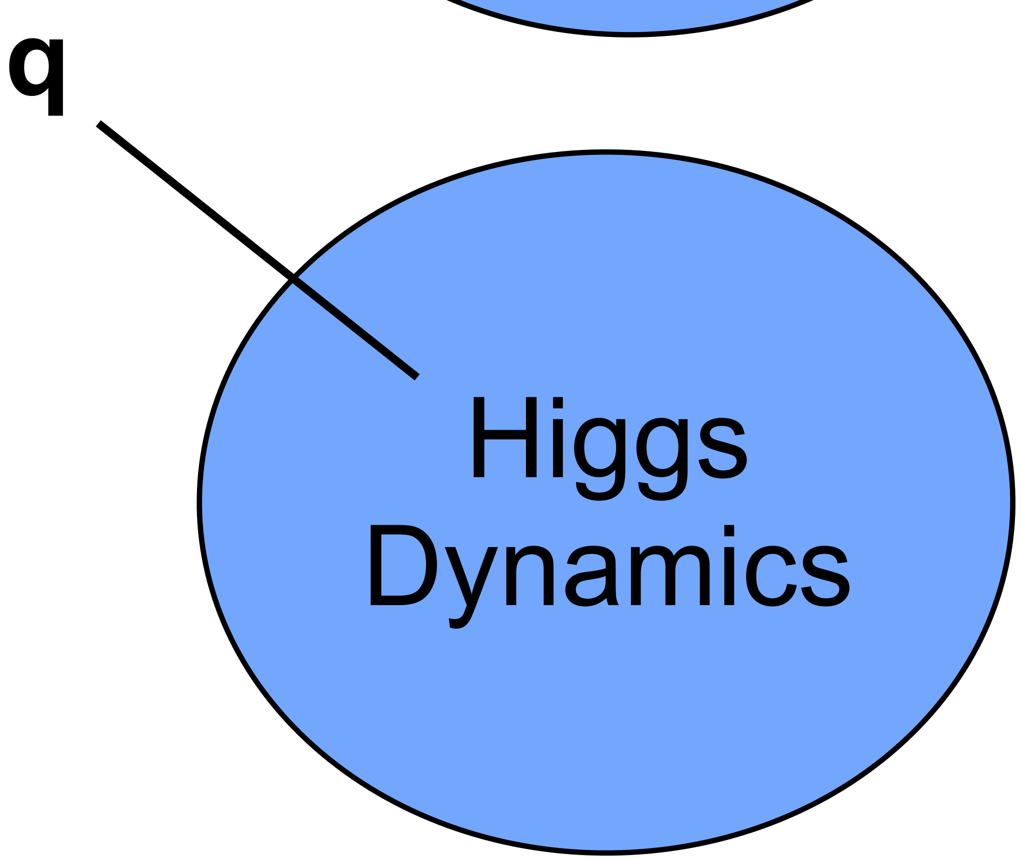
2 options (from a more concrete perspective):



$\lambda q q O_B$

IRRELEVANT
(ETC)

$$y_t \sim y_{t,\mathrm{UV}} \left(\frac{\Lambda}{\Lambda_{\mathrm{UV}}}\right)^{d[O_B]-1}$$



$\lambda q O_F$

RELEVANT?!
(Partial Compositeness)

$$y_t \propto \lambda_L \lambda_R$$

$$\mathcal{L}_{\mathrm{SM-Higgs}} + \mathcal{L}_{\mathrm{CFT}} + qO_F + qqO_B + qqqq \quad \Lambda_{\mathrm{UV}} \ (M_{\mathrm{Pl}}?!)$$

CFT with d[O_F]<2.5

$$\mathcal{L}_{\mathrm{SM-Higgs}} + \mathcal{L}_{\mathrm{CFT}} + qO_F + \cancel{qqO_B} + \cancel{qqqq} \quad \Lambda$$

small deformation of the CFT
if marginally relevant

5D Randall-Sundrum scenarios
are an effective realization

An ambitious possibility:

d[O_F]<2.5

What is qO_F?

$q\sigma^{\mu\nu}\Psi^a F^a_{\mu\nu}$

no asymptotic freedom...

$q\Psi_1\Psi_2\Psi_3$

seems the best option...

$-3<\gamma<-2$

must be non-perturbative: lattice.

...

Need toy models to test on the lattice

Wish-list

- ☐ Partners for top-quark (<u>all quarks</u> if we want decouple the flavor scale)
- ☐ A strong approximate IR fixed point (or walking)
- ☐ A baryon with dimension <2.5 within the conformal window?
- ☐ Realistic phenomenology

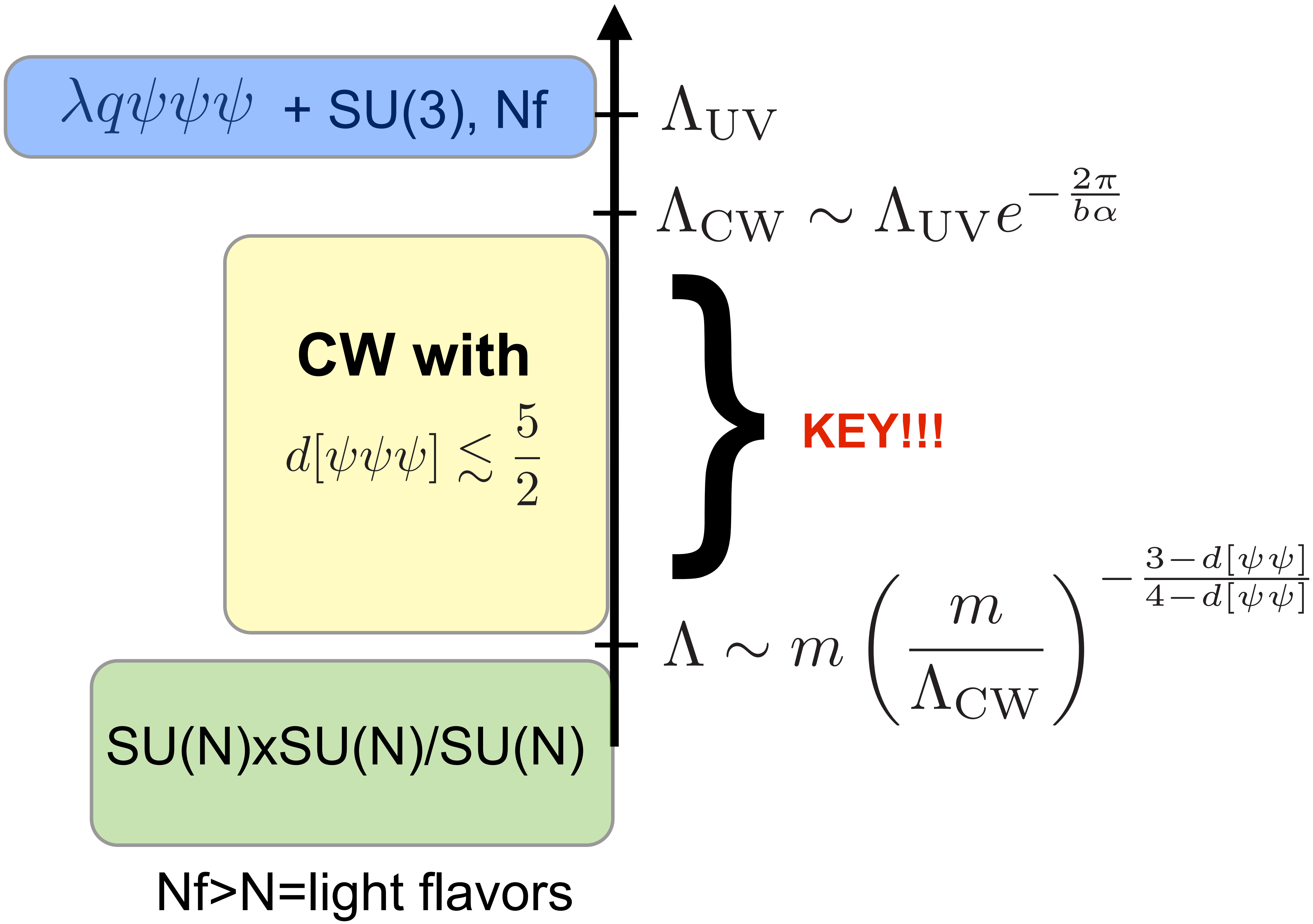
An example with NGB Higgs (more by G. Ferretti)

An QCD-like SU(3) candidate with Nf Dirac flavors

$$N_f = 3N_T + 2N_D + N_S + N_{S'} \geq 7$$

	$SU(3)$	$SU(3)_c$	$SU(2)_w$	$U(1)_Y$
T	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$	a
D	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{2}$	$\frac{1}{3} - \frac{1}{2}a$
S	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$-\frac{1}{6} - \frac{1}{2}a$
S'	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\frac{5}{6} - \frac{1}{2}a$

$$O_F = \psi_\alpha^{\{i}(\psi^{j\}}\psi^k) \quad \text{or} \quad \psi_\alpha^i(\overline{\psi}^{\bar{j}}\overline{\psi}^{\bar{k}})^*$$


$\lambda q\psi\psi\psi$ + SU(3), Nf
$\Lambda_{\rm UV}$
$\Lambda_{\rm CW} \sim \Lambda_{\rm UV} e^{-\frac{2\pi}{b\alpha}}$
CW with
$d[\psi\psi\psi] \lesssim \frac{5}{2}$
KEY!!!
$\Lambda \sim m \left(\frac{m}{\Lambda_{\rm CW}}\right)^{-\frac{3-d[\psi\psi]}{4-d[\psi\psi]}}$
SU(N)xSU(N)/SU(N)
Nf>N=light flavors

Phenomenology

anomalous couplings to $G\widetilde{G}$

$$\mathrm{NGB} = \begin{pmatrix} \text{octet} + \text{singlet} & \text{triplet} \\ \text{triplet}^\dagger & \Pi - \text{singlet} \end{pmatrix}$$

collider stable
(T-hadrons)

color singlets ⊃ Higgs
(must be light)

Anomalous couplings...

$$(W\widetilde{W} - B\widetilde{B})\eta$$

$$W\widetilde{B}\phi \propto U(1)_B$$

$$B\widetilde{B}\phi' \propto U(1)_B$$

Minimal SU(4)xSU(4)/SU(4)

- All consitituents are heavy except D+S+S'.
- 15 Goldstones: $SU(2)_w \times SU(2)_{\rm cust} \subset SU(4)_V$

$$\text{NGB} = (2,2) + (2,2) + (3,1) + (1,3) + (1,1)$$

$$U = e^{i\Pi/f}$$

Cacciapaglia and Ma (2015)

$$\Pi = \begin{pmatrix} \phi_a \sigma_a + \frac{1}{\sqrt{2}}\eta\mathbf{1} & \mathcal{H}_1 + i\mathcal{H}_2 \\ \mathcal{H}_1^\dagger - i\mathcal{H}_2^\dagger & \phi'_a \sigma_a - \frac{1}{\sqrt{2}}\eta\mathbf{1} \end{pmatrix}$$

- **Problem?** Generically, couplings to fermions break custodial: T parameter too large when f<5 TeV!

Mrazek et al. (2011)

$$\delta\mathcal{L} = m_{1,2}^2 \; iH_1^\dagger H_2 + \text{hc}$$

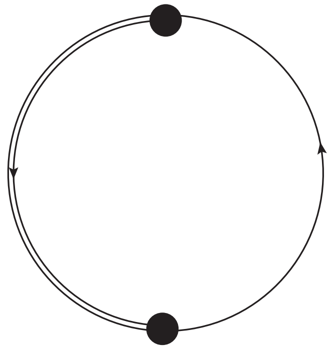
An interesting approach: "choose the right couplings to RH top"

$$\sum_a \lambda_q^{(a)} q O_q^{(a)} + \sum_b \lambda_u^{(b)} u O_u^{(b)} + \sum_c \lambda_d^{(c)} d O_d^{(c)}$$

Special combination $\Longrightarrow$ 1) respects custodial (no tadpole for H_2)

2) decouples the "dangerous" NGBs (rho is OK!)

$$\mathrm{NGB} = (2,2) + \cancel{(2,2)} + \cancel{(3,1)} + \cancel{(1,3)} + (1,1)$$



$$\delta V = C_u \ \mathrm{tr}\left[(\lambda_u U)(\lambda_u U)^*\right] + \mathcal{O}(\lambda_u^4)$$ positive masses

$$C_u = 4\int \frac{d^4 p_E}{(2\pi)^4} \int ds \frac{\rho(s)}{p_E^2 + s} > 0.$$

The coupling respects an **SU(4)**: technically natural

$$\begin{cases} U \to V U \Upsilon V^t \Upsilon^\dagger & \Upsilon = \begin{pmatrix} \epsilon & \mathbf{0} \\ \mathbf{0} & \epsilon \end{pmatrix} \\ U = \mathbf{1} \implies \delta V = -C_u \end{cases}$$

Sp(4) symmetric!

Below the heavy NGB:
Effectively SU(4)/Sp(4)

Conclusion

- **Partial Compositeness is a very attractive/ambitious option**
  -- UV-complete models without fundamental scalars
  -- may account for fermion mass hierarchy (see RS models)

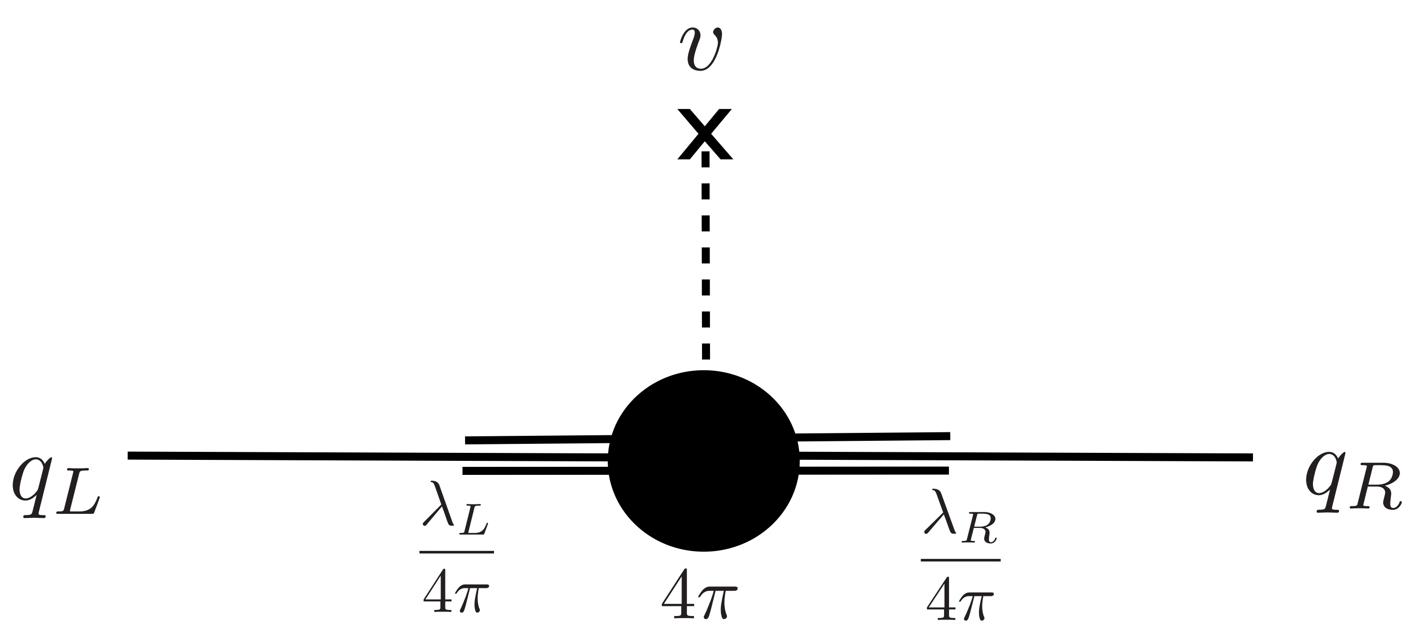
- **Toy models exist**
  -- satisfy all basic requirements under theoretical control
  -- have realistic vacuum alignment and Higgs potential
  -- very rich collider phenomenology (colored scalars, TC-hadrons, etc)

- **Prove/Disprove d[O_F]<2.5 on the lattice!**

Back-up slides

SM Yukawas

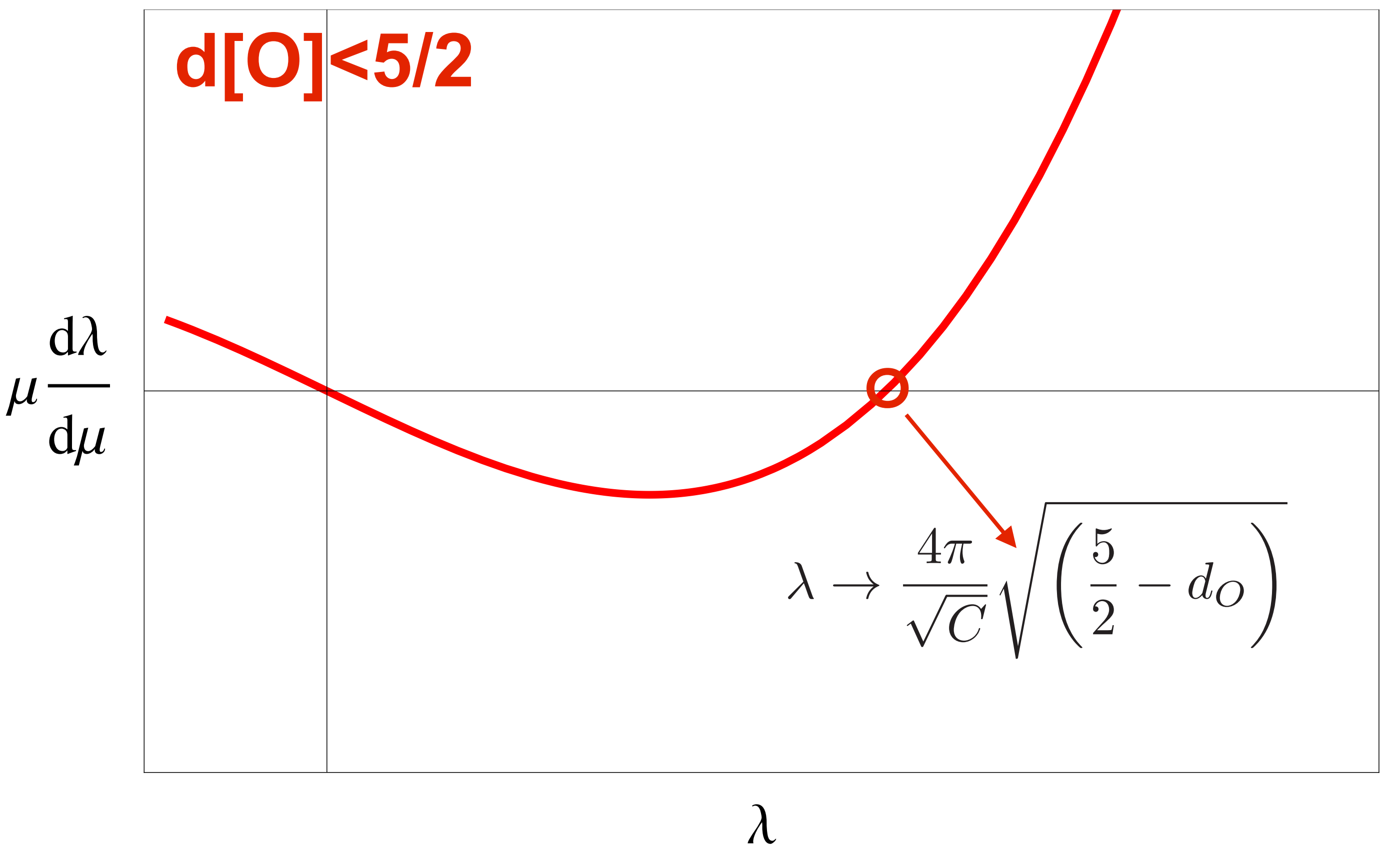
SM fermions are “partially composite”...



$$y \sim \frac{1}{4\pi}\lambda_L(\Lambda)\lambda_R(\Lambda)$$

need RG evolution of $\lambda q O$

A relevant coupling?



$$\frac{d\lambda}{d\ln\mu} = \left(d_O - \frac{5}{2}\right)\lambda + \frac{C}{16\pi^2}\lambda^3$$

positive by unitarity

If irrelevant: of course a perturbation
If slightly relevant: a perturbation

$$\psi_1\psi_2\psi_3 \equiv \Gamma\psi_1\left(\overline{\psi_2^c}\Gamma'\psi_3\right)$$

$$\mathcal{L}_{\rm PC} = q\overline{TDS} + uTDD + uTSS' + dTSS + \text{hc.}$$

$$\mathcal{L}_{\rm ETC} = quD\overline{S} + qu\overline{D}S' + qd\overline{D}S + qdD\overline{S'}$$
$$+\ell e\overline{D}S + \ell eD\overline{S'} + Q^\dagger\overline{\sigma}^\mu Q\psi^\dagger\overline{\sigma}_\mu\psi + \text{hc}$$

Exit CFT:

$$\mathcal{L}_{\rm mass} = -m_T T\overline{T} - m_D D\overline{D} - m_S S\overline{S} - m_{S'}S'\overline{S'} + \text{hc.}$$

...

Kaplan-Georgi (1984)

NGB from QCD-like models
Higgs is pseudo-scalar?!

As long as the EFT (Standard Model) is right nobody cares:

1 - CP/P are ambiguous because defined up to U(1) hypercharge

2 - If Higgs is odd: yqqh breaks it ‘explicitly’ while <h> ‘spontaneously’