

Partial Compositeness

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Partial Compositeness is an attractive paradigm
for flavor violation:

1. mass hierarchies and mixings arise dynamically
2. predictive pattern of FV beyond the Standard Model
3. especially motivated (necessary?) in Composite Higgs models



Why Composite Higgs in 2017?

- ▶ Still a challenging theoretical question
- ▶ Phenomenological question

Outline

* The Composite Higgs

- Yukawa couplings
- Partial Compositeness

* Partial Compositeness without fundamental scalars

- Key ingredients for a successful model
- A minimal candidate and its phenomenology

A strong dynamics at the TeV

Motivation:

The Hierarchy problem \iff the SM is an Effective Theory

$$\begin{aligned}\mathcal{L}_{\text{SM}} = & -\frac{1}{4}F^2 + q^\dagger iDq + |DH|^2 - yqqH - \lambda|H|^4 \\ & + c\Lambda_{\text{UV}}^2|H|^2 + \sum_{n=1}^{\infty} c_n \frac{O_n}{\Lambda_{\text{UV}}^n}\end{aligned}$$

Two options:

$$\Lambda_{\text{UV}} \gg \text{TeV}, \quad c_n \sim 1, \quad c \ll 1$$

FV, B, L, etc are OK, Higgs tuned

$$\Lambda_{\text{UV}} \sim \text{TeV}, \quad c_n \ll 1, \quad c \sim 1$$

Higgs is natural, but FV, B, L?

no known symmetry



protected by symmetries



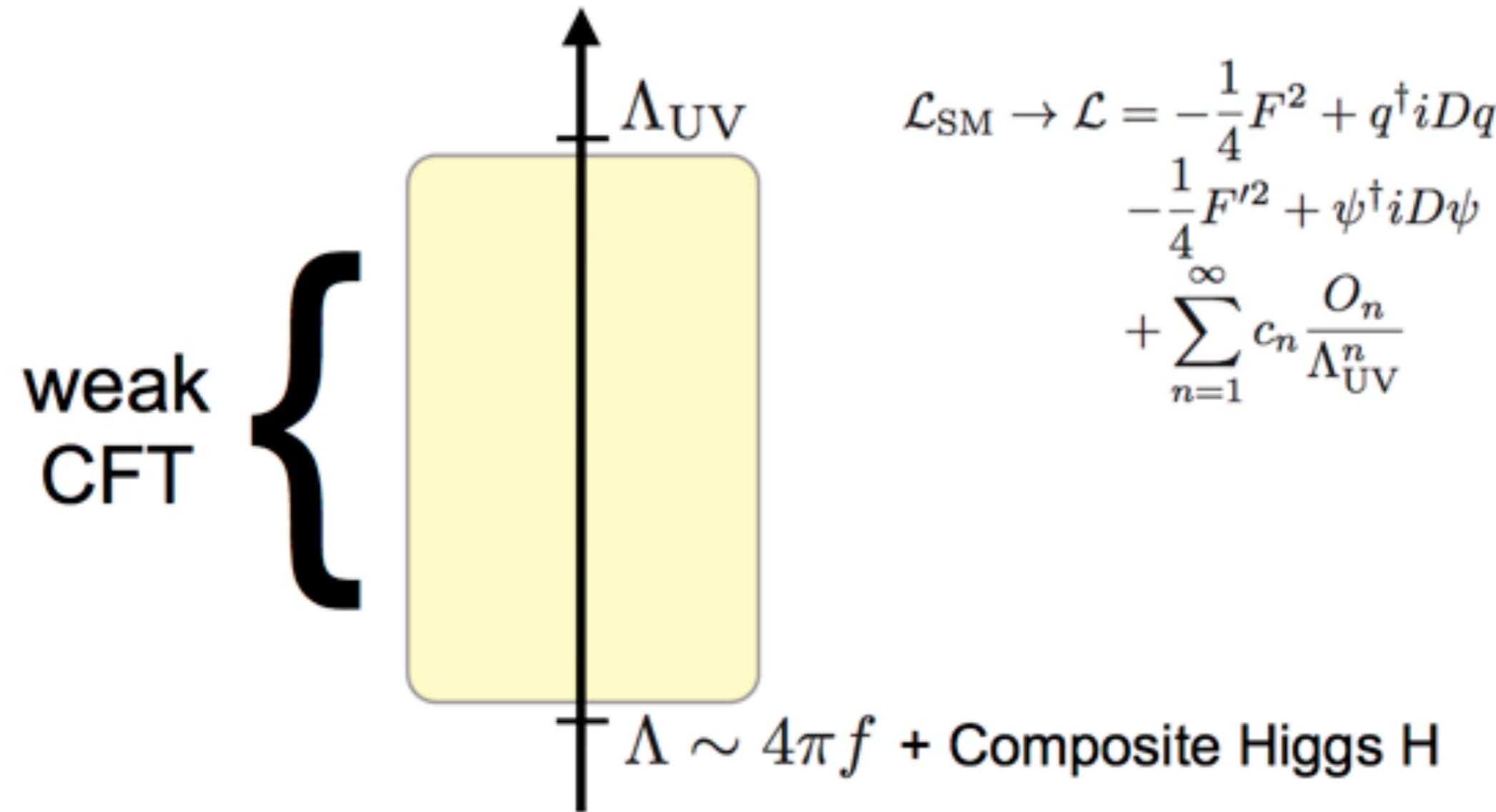
Composite Higgs (Technicolor)

$$\mathcal{L}_{\text{SM}} = -\frac{1}{4}F^2 + q^\dagger iDq + |DH|^2 - yqqH - \lambda|H|^4$$
$$+ c\Lambda_{\text{UV}}^2 |H|^2 + \sum_{n=1}^{\infty} c_n \frac{O_n}{\Lambda_{\text{UV}}^n}$$

$$\mathcal{L} = -\frac{1}{4}F^2 + q^\dagger iDq - \frac{1}{4}F'^2 + \psi^\dagger iD\psi$$
$$+ \sum_{n=1}^{\infty} c_n \frac{O_n}{\Lambda_{\text{UV}}^n}$$

Weinberg (1979)

Kaplan-Georgi (1984)



chiral sym. breaking with $\mathbf{G} \rightarrow \mathbf{H} \supset \mathbf{SM}$

$$\langle \bar{\Psi} \Psi \rangle \sim \Lambda f^2$$

Effective theory at Λ : coupling to the SM fermions?

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

$+yqqH$ **higher-dimensional operator !!!**

$$\frac{qq\psi\psi}{\Lambda_{\text{UV}}^2} + \frac{q\psi\psi\psi}{\Lambda_{\text{UV}}^2} + \dots$$

All irrelevant???

$+\mathcal{O}\left(\frac{1}{\Lambda_{\text{cutoff}}^2}\right)$ Very easy ✓

(EWPT, rare processes, etc.)

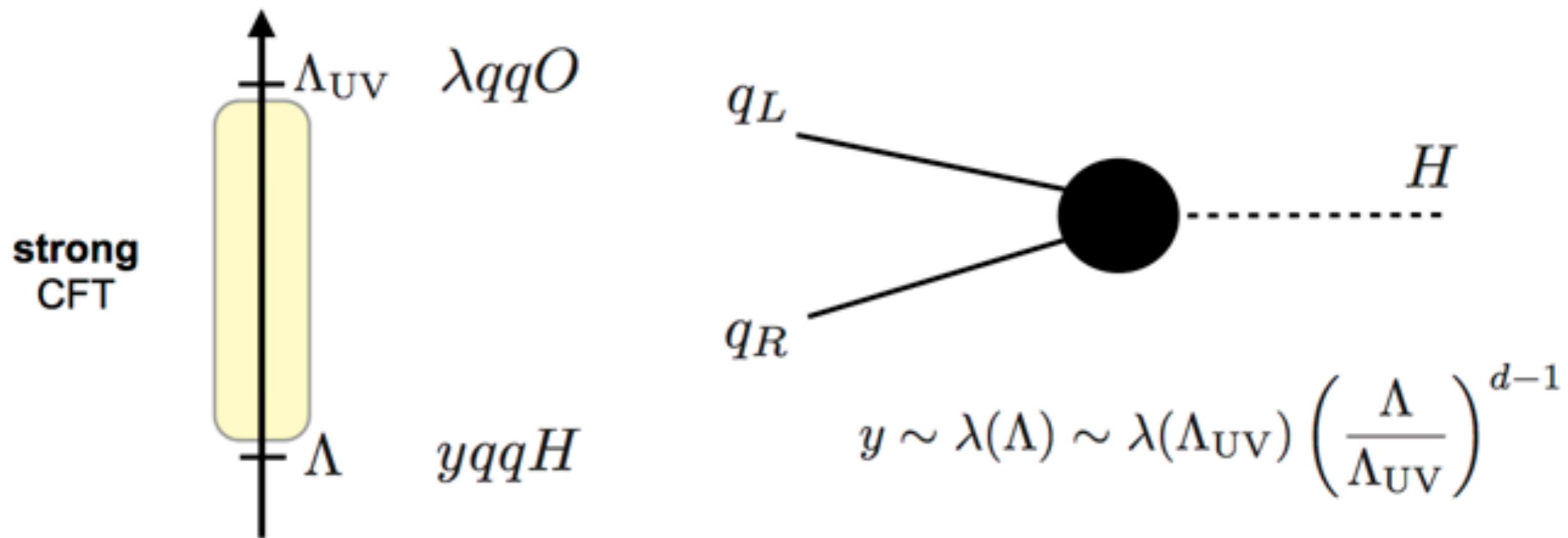
Coupling SM fermions to the Composite Higgs

TWO PATHS:



O = an operator of the strong dynamics (yet to be specified)

“Extended Technicolor”

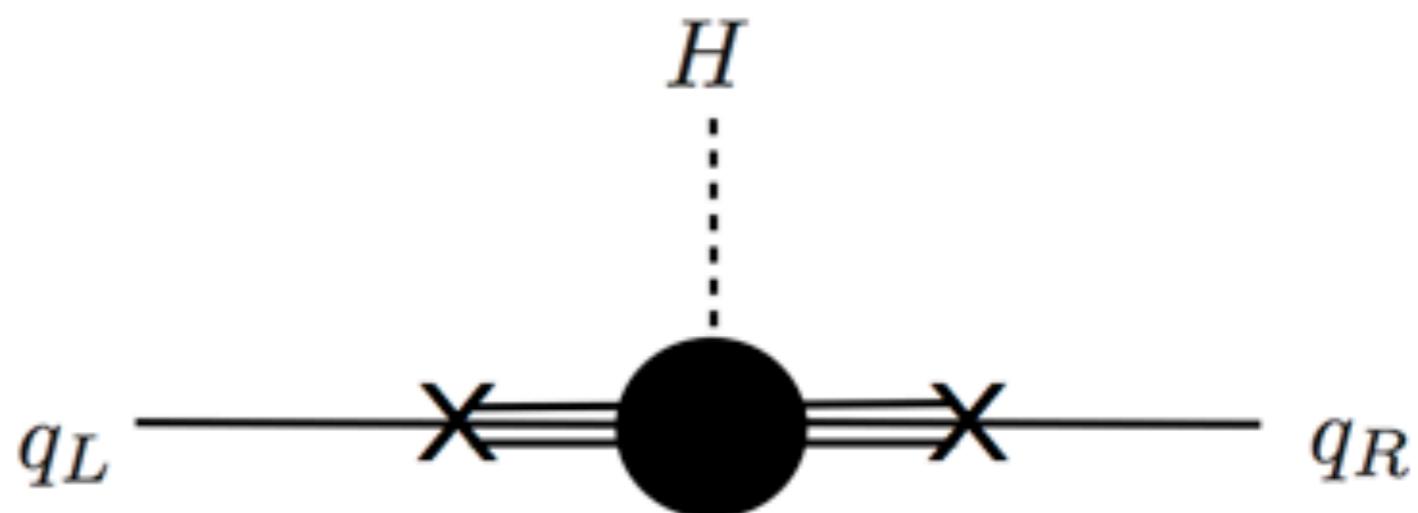
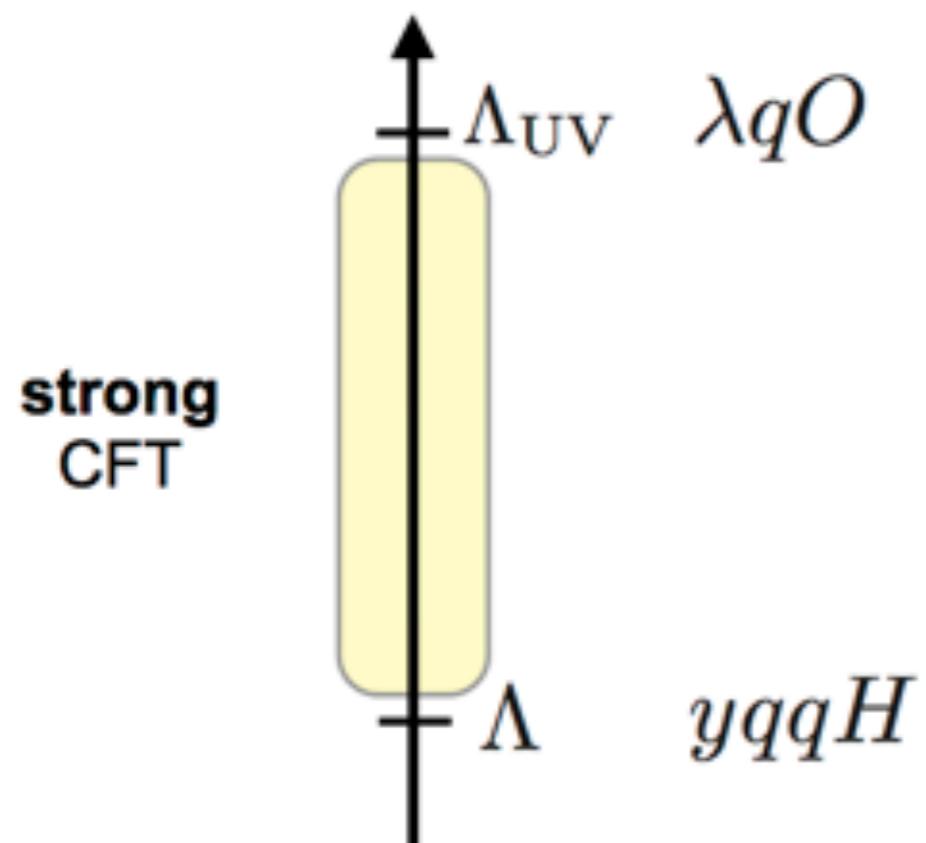


Theorem: O (scalar) has $d > 1$
→ y is always IRRELEVANT

$\Lambda \sim$ cutoff is necessary:
no room for an Effective Field Theory!



“Partial Compositeness”



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

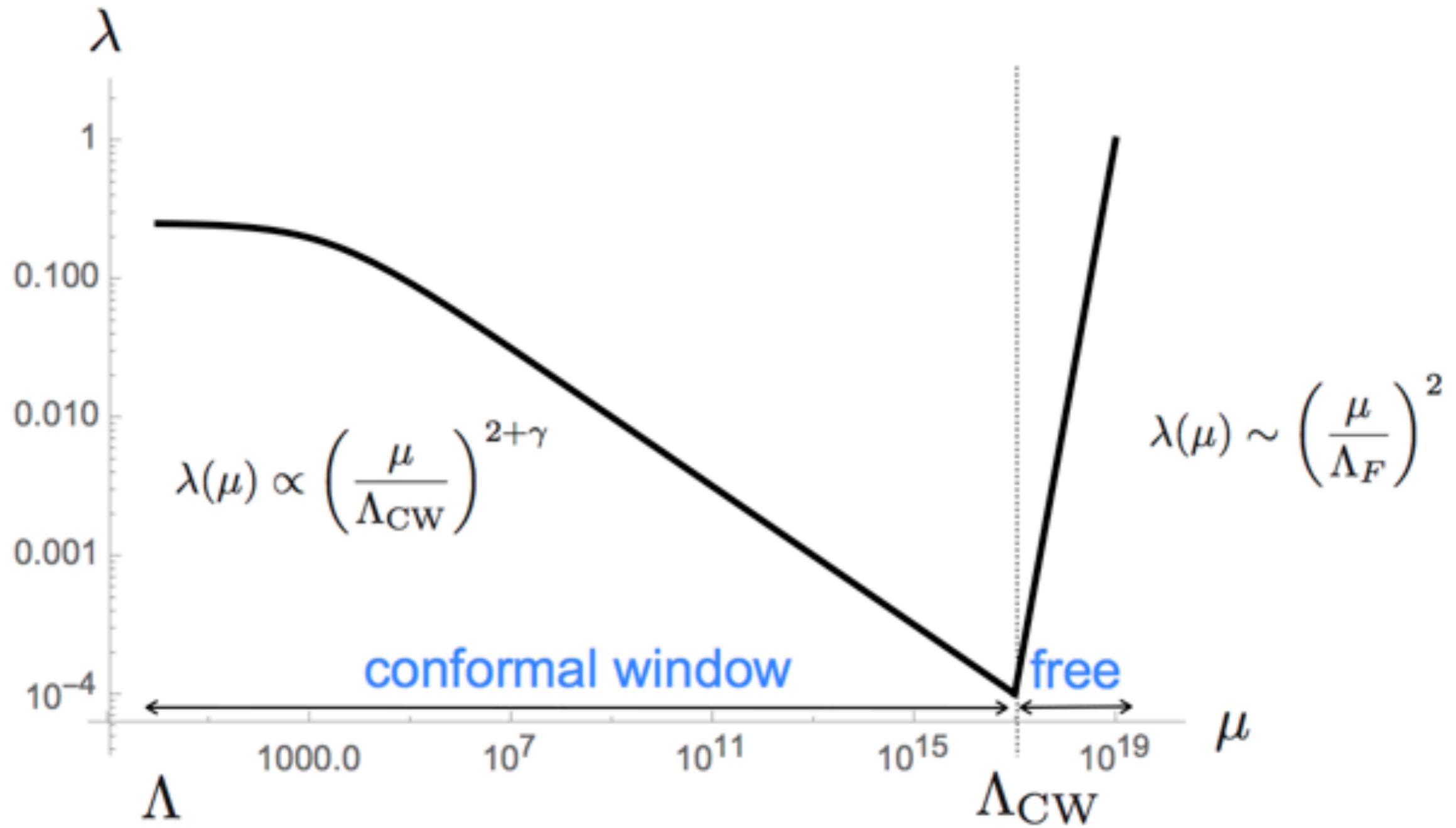
need RG evolution of λ ...

Theorem: O (fermion) has $d > 1.5$
 $\rightarrow y$ is RELEVANT IF $d < 2.5$

When $d < 2.5$ the cutoff may be large!



$$\lambda qO = \frac{q\Psi\Psi\Psi}{M_{Pl}^2}$$



$$\mathcal{L}_{\text{SM-Higgs}} + \mathcal{L}_{\text{CFT}} + qO_F + qqO_B + qqqq$$

Λ_{UV} ($M_{\text{Pl}}?$!)



strong CFT
with $d[O_F] < 2.5$

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

Dangerous
irrelevant ?!

A theory of flavor?!

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

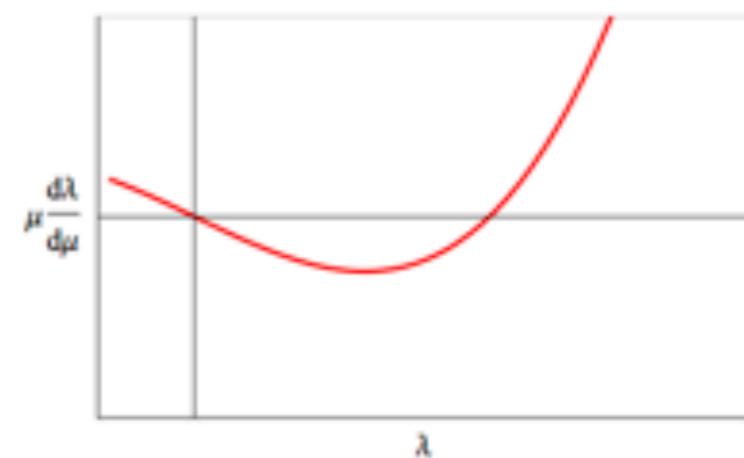
positive by unitarity

Lighter fermions $d[O] \geq 5/2$

do not reach the IR fixed point $\lambda(\Lambda) \sim \lambda(\Lambda_{UV}) \left(\frac{\Lambda}{\Lambda_{UV}} \right)^{d-2.5}$

Top quark $d[O] < 5/2$

the coupling reaches the IR fixed point with $y \sim 1$!



mass hierarchy?!

A predictive paradigm for flavor-violation

Operator $\Delta F = 2$	$\text{Re}(c) \times (4\pi/g_\rho)^2$	$\text{Im}(c) \times (4\pi/g_\rho)^2$	Observables
$(\bar{s}_L \gamma^\mu d_L)^2$	$6 \times 10^2 \left(\frac{\epsilon_3^u}{\epsilon_3^d}\right)^2$	$2 \left(\frac{\epsilon_3^u}{\epsilon_3^d}\right)^2$	$\Delta m_K; \epsilon_K$
$(\bar{s}_R d_L)^2$	500	2	"
$(\bar{s}_R d_L)(\bar{s}_L d_R)$	2×10^2	0.6	"
$(\bar{c}_L \gamma^\mu u_L)^2$	$4 \times 10^2 \left(\frac{\epsilon_3^u}{\epsilon_3^d}\right)^2$	$70 \left(\frac{\epsilon_3^u}{\epsilon_3^d}\right)^2$	$\Delta m_D; q/p , \phi_D$
$(\bar{c}_L u_R)^2$	30	6	"
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	3×10^2	50	"
$(\bar{b}_L \gamma^\mu d_L)^2$	$5 \left(\frac{\epsilon_3^u}{\epsilon_3^d}\right)^2$	$2 \left(\frac{\epsilon_3^u}{\epsilon_3^d}\right)^2$	$\Delta m_{B_d}; S_{\psi K_S}$
$(\bar{b}_R d_L)^2$	80	30	"
$(\bar{b}_R d_L)(\bar{b}_L d_R)$	3×10^2	80	"
$(\bar{b}_L \gamma^\mu s_L)^2$		$6 \left(\frac{\epsilon_3^u}{\epsilon_3^d}\right)^2$	Δm_{B_s}
$(\bar{b}_R s_L)^2$		1×10^2	"
$(\bar{b}_R s_L)(\bar{b}_L s_R)$		3×10^2	"
Operator $\Delta F = 1$	Re(c)	Im(c)	Observables
$\bar{s}_R \sigma^{\mu\nu} e F_{\mu\nu} b_L$		1	$B \rightarrow X_s$
$\bar{s}_L \sigma^{\mu\nu} e F_{\mu\nu} b_R$	2	0	"
$\bar{s}_R \sigma^{\mu\nu} g_s G_{\mu\nu} d_L$	-	0.4	$K \rightarrow 2\pi; \epsilon'/\epsilon$
$\bar{s}_L \sigma^{\mu\nu} g_s G_{\mu\nu} d_R$	-	0.4	"
$\bar{s}_L \gamma^\mu b_L H^\dagger i \overleftrightarrow{D}_\mu H$		$30 \left(\frac{g_e}{4\pi}\right)^2 (\epsilon_3^u)^2$	$B_s \rightarrow \mu^+ \mu^-$
$\bar{s}_L \gamma^\mu b_L H^\dagger i \overleftrightarrow{D}_\mu H$	$6 \left(\frac{g_e}{4\pi}\right)^2 (\epsilon_3^u)^2$	$10 \left(\frac{g_e}{4\pi}\right)^2 (\epsilon_3^u)^2$	$B \rightarrow X_s \ell^+ \ell^-$
Operator $\Delta F = 0$	Re(c)	Im(c)	Observables
$\bar{d} \sigma^{\mu\nu} e F_{\mu\nu} d_{L,R}$	-	3×10^{-2}	neutron EDM
$\bar{u} \sigma^{\mu\nu} e F_{\mu\nu} u_{L,R}$	-	0.3	"
$\bar{d} \sigma^{\mu\nu} g_s G_{\mu\nu} d_{L,R}$	-	4×10^{-2}	"
$\bar{u} \sigma^{\mu\nu} g_s G_{\mu\nu} u_{L,R}$	-	0.2	"
$\bar{b}_L \gamma^\mu b_L H^\dagger i \overleftrightarrow{D}_\mu H$		$5 \left(\frac{g_e}{4\pi}\right)^2 (\epsilon_3^u)^2$	$Z \rightarrow b\bar{b}$
Leptonic Operator	Re(c)	Im(c)	Observables
$\bar{e} \sigma^{\mu\nu} e F_{\mu\nu} e_{L,R}$	-	5×10^{-2}	electron EDM
$\bar{\mu} \sigma^{\mu\nu} e F_{\mu\nu} e_{L,R}$		4×10^{-3}	$\mu \rightarrow e\gamma$
$\bar{e} \gamma^\mu \mu_{L,R} H^\dagger i \overleftrightarrow{D}_\mu H$		$1.5 \left(\frac{g_e}{4\pi}\right) \frac{\epsilon_3^e}{\epsilon_3^u}$	$\mu(Au) \rightarrow e(Au)$

Keren-Zur et al (2012)

Any concrete (toy) model?

What is $\lambda q O$?



Serone et al. (2013)
Sannino et al. (2016)

$$\lambda \bar{q} \phi \Psi$$

$$\lambda \bar{q} (\sigma_{\mu\nu} \Psi^a G_{\mu\nu}^a)$$

$$\lambda q \Psi_1 \Psi_2 \Psi_3$$

Barnard et al. (2014)
Ferretti et al. (2014)
LV (2015)

...

What is λqO ?



fundamental
 $\lambda \bar{q} \phi \Psi$
scalars!



no asymptotic
 $\lambda \bar{q} (\sigma_{\mu\nu} \Psi^\nu G^a_{\mu\nu})$
freedom

$\lambda q \Psi_1 \Psi_2 \Psi_3$ best option

UV-completion without
fundamental scalars

$$\iff \gamma \simeq -2$$

Wish-list

- G/H \supset Higgs doublet [Georgi-Kaplan \('80s\)](#)
- H \supset custodial SU(2) [Sikivie et al. \(1980\)](#)
- Realistic phenomenology (ex: Higgs potential)
- Partners O for the top quark
- Partners O for all SM quarks (to decouple the flavor scale)
- Proton is stable
- Anomalies cancel
- No Landau poles at low energy
- A strong IR fixed point (conformal window)
- $d[O] < 5/2$ within the CFT?

Wish-list

Ferretti-Karateev (2013): SU(N)/SO(N), SU(N)/Sp(N)

- G/H \supset Higgs doublet
- H \supset custodial SU(2)
- Realistic phenomenology (ex: Higgs potential)
- Partners O for the top quark
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- $d[O] < 5/2$ within the CFT?

Wish-list: **SU(3)** and **Nf** Dirac flavors

LV (2015): $SU(N) \times SU(N) / SU(N)$

- $G/H \supset Higgs$ doublet
- $H \supset$ custodial $SU(2)$
- Realistic phenomenology (ex: Higgs potential)
- Partners O for the top quark
- Partners O for all SM quarks (to decouple the flavor scale)
- Proton is stable
- Anomalies cancel
- No Landau poles at low energy
- A strong IR fixed point (conformal window)
- $d[O] < 5/2$ within the CFT? **Non-perturbative!**

The only known model
with all these features...

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

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

Plus the right handed components, and flavor indices:
 $N_f = 3 NT + 2 ND + NS + NS' \geq 7$

IR fixed point for $N_f^*(8-12) \leq N_f \leq 16.5$ (non-perturbative at $N_f < 13$)

5-loop β -function:
Baikov et al. (2016)

$(O_q)_I$	(O_u)	$(O'_u)_I$	$(O_d)_{IJ}$
$\overline{T}(DS_I)$	$D(TD)$	$T(S_IS')$	$T(S_IS_J)$
$\overline{D}(TS_I)$		$S_I(TS')$	$S_I(TS_J)$
$\overline{T}(DS_I)^\dagger$	$D(\overline{TD})^\dagger$	$T(S_IS')^\dagger$	$T(S_IS_J)^\dagger$
$\overline{D}(TS_I)^\dagger$		$S_I(\overline{TS'})^\dagger$	$S_I(\overline{TS_J})^\dagger$
$\overline{S_I}(TD)^\dagger$		$S'(\overline{TS_I})^\dagger$	

PC: dangerous irrelevant?!

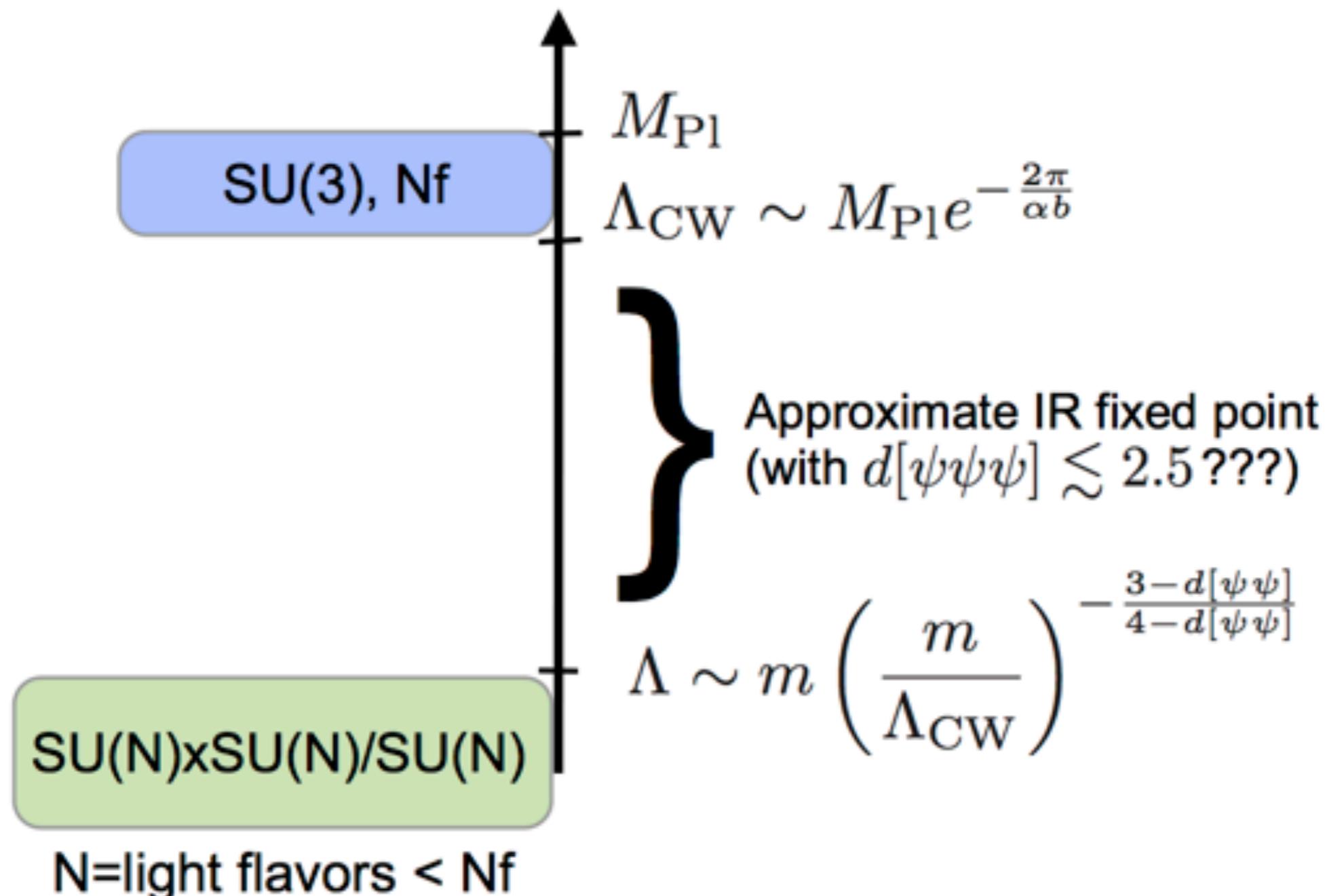
$$\mathcal{L}_{\text{PC}} = qO_u + u(O_u + O'_u) + dO_d$$

ETC: irrelevant

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

Mass: relevant \rightarrow Exit CFT

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



Phenomenology

- ▶ non-minimal $SU(N) \times SU(N) / SU(N)$ \Rightarrow Collider (exotic EW-NGBs)
- ▶ color not factorized \Rightarrow Collider (direct production of colored NGBs)
- ▶ accidental symmetries \Rightarrow Collider (new collider signatures)

Exotic NGBs: general structure

anomalous couplings to $G\tilde{G}$

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

**collider stable
(T-hadrons)** 

**color singlets \supset Higgs
(must be light)** 

Anomalous couplings to EW gauge...

Vacuum alignment: minimal $SU(4) \times SU(4)/SU(4)$

* Assume all constituents are heavy except $D+S+S'$.

→ 15 Goldstones: $SU(2)_w \times SU(2)_{\text{cust}} \subset SU(4)_V$

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

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

[Cacciapaglia and Ma \(2015\)](#)
[LV \(2015\)](#)

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

* Vacuum alignment

[Mrazek et al. \(2011\)](#)

Problem: Exotic EW-NGBs → Generically EW T parameter is too large

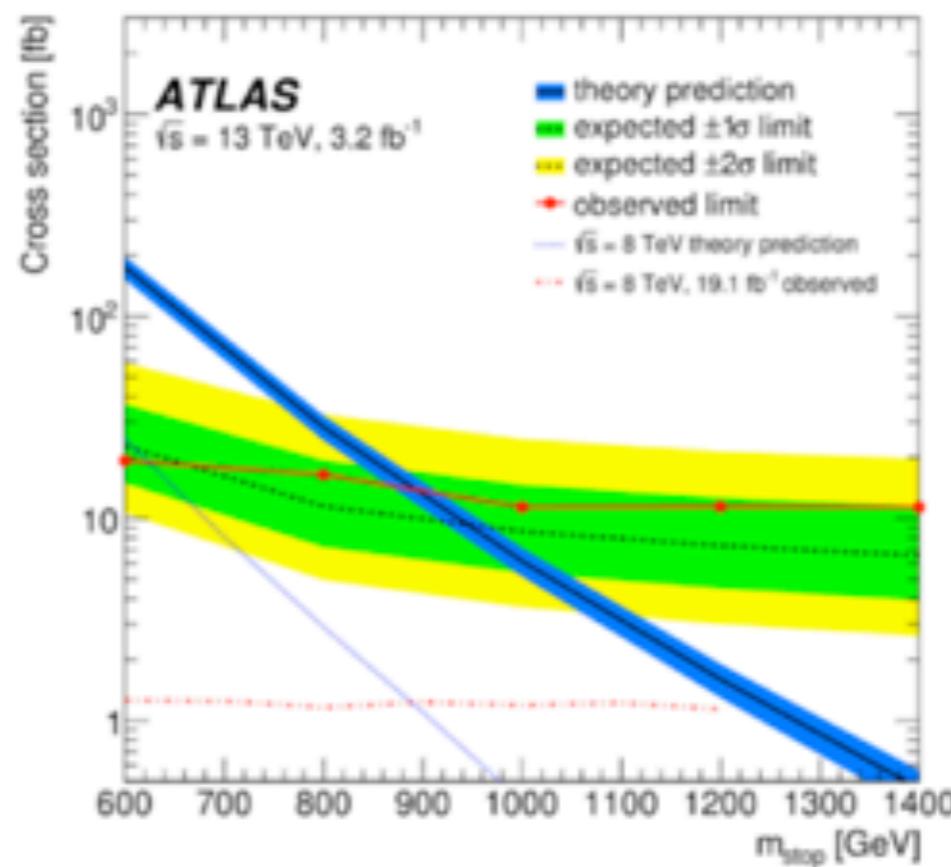
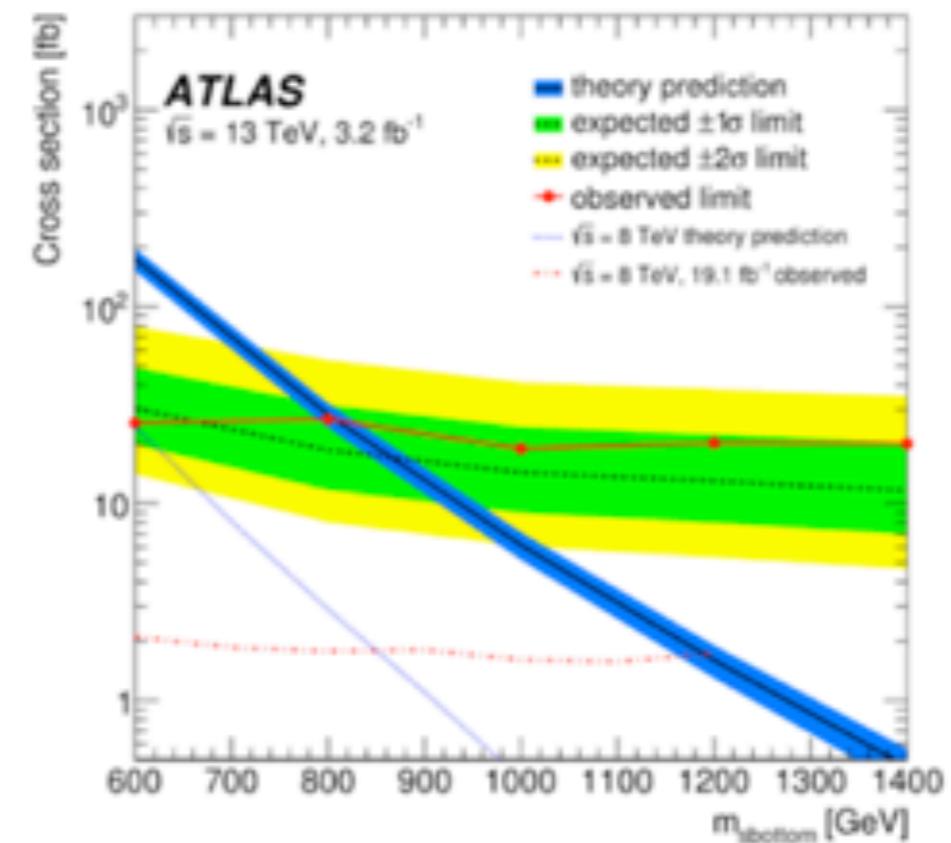
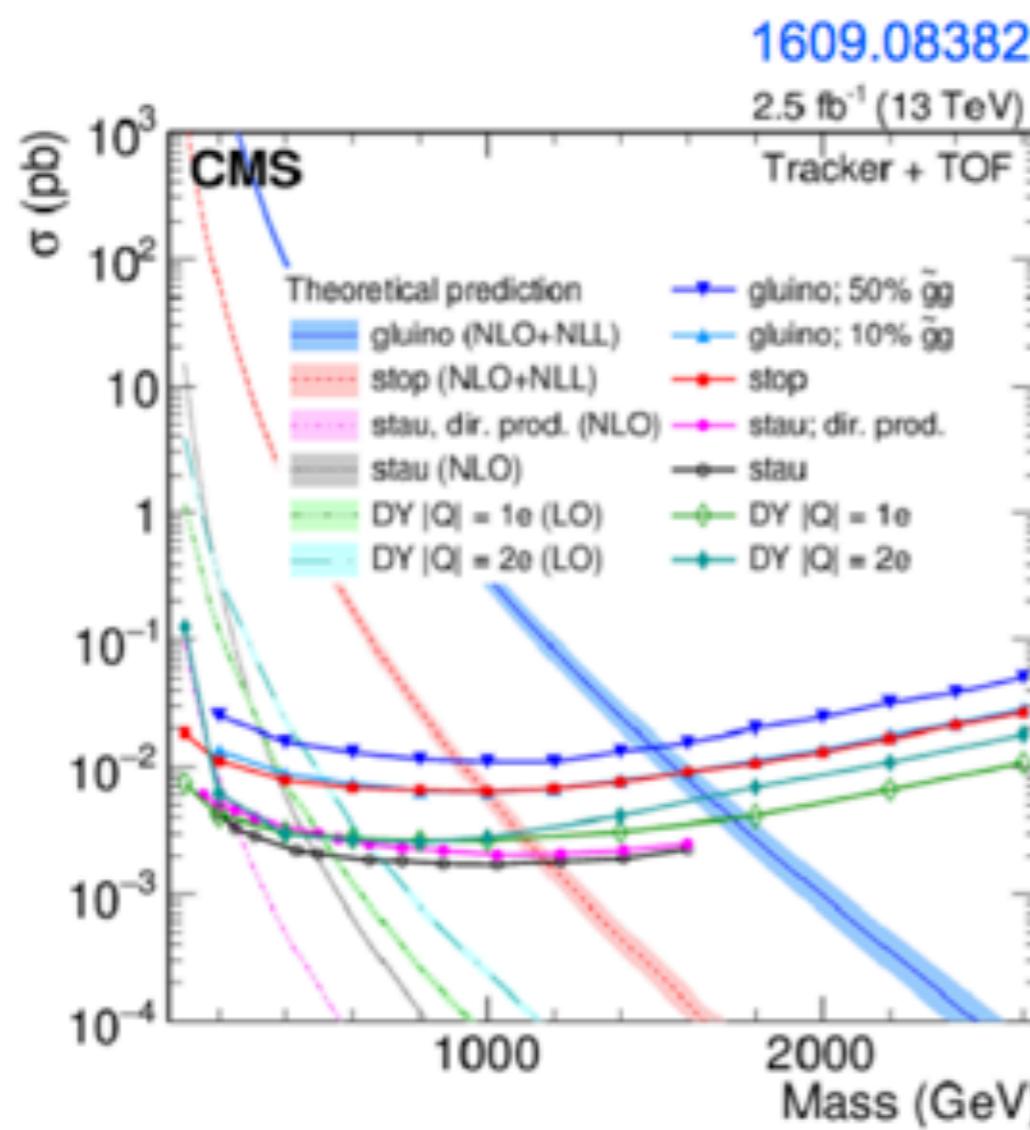
Solution: natural choice of top partners couplings → heavy Exotic EW-NGBs
→ the coset is effectively $SU(4)/Sp(4)$

[LV \(2015\)](#)

Accidental symmetries

1606.05129

baryon & lepton & $U(1)_T$ family
⇒ T-hadrons ($f > \text{TeV}$)



d[O]<2.5?!

All we need to have a complete theory!

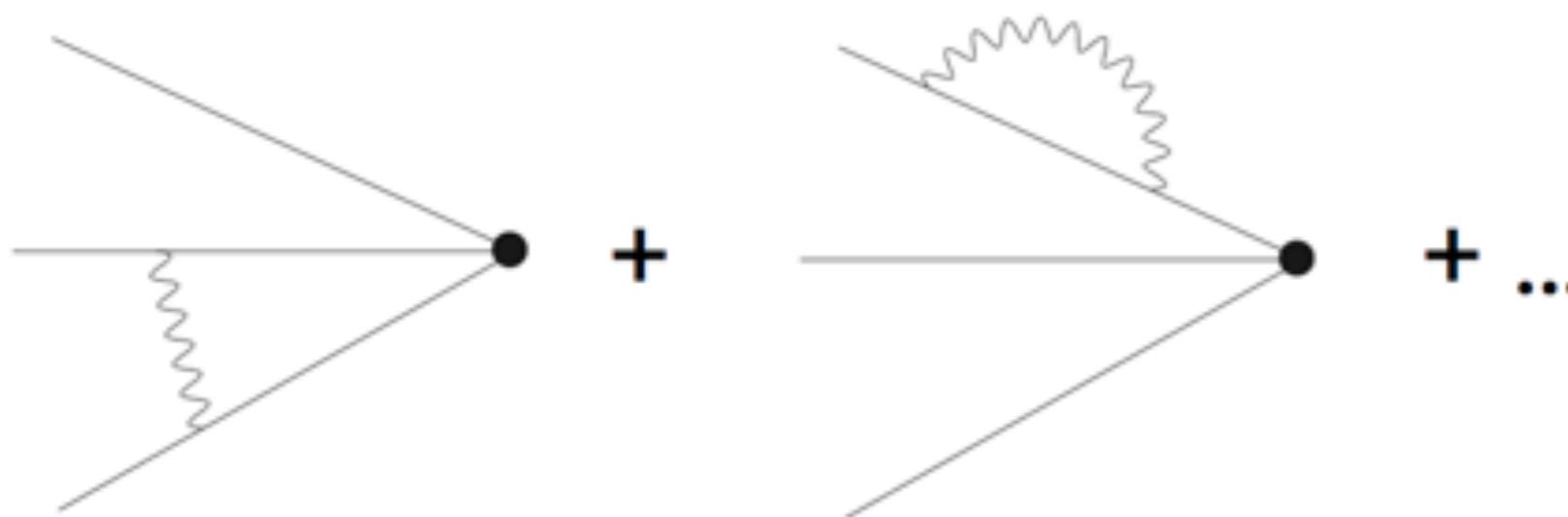
In d=4 dimensions:

$$\left\{ \begin{array}{ll} [B_+]_{\alpha}^{ijk} = \psi_{\alpha}^{\{i} (\psi^j} \psi^{k\}} & \sim \left(\frac{1}{3} \mathbf{N_f} (\mathbf{N_f}^2 - 1), 1 \right) \in SU(N_f) \times SU(N_f) \\ [B_-]_{\alpha}^{i\tilde{j}\tilde{k}} = \psi_{\alpha}^i (\tilde{\psi}^j \tilde{\psi}^{\tilde{k}})^* & \sim (\mathbf{N_f}, [\mathbf{N_f} \otimes \mathbf{N_f}]_{\text{antisym}}) \in SU(N_f) \times SU(N_f) \end{array} \right.$$

$$\mu \frac{d}{d\mu} \begin{pmatrix} B_+^r \\ B_-^r \end{pmatrix} = - \begin{pmatrix} \gamma_+ & \\ & \gamma_- \end{pmatrix} \begin{pmatrix} B_+^r \\ B_-^r \end{pmatrix}$$

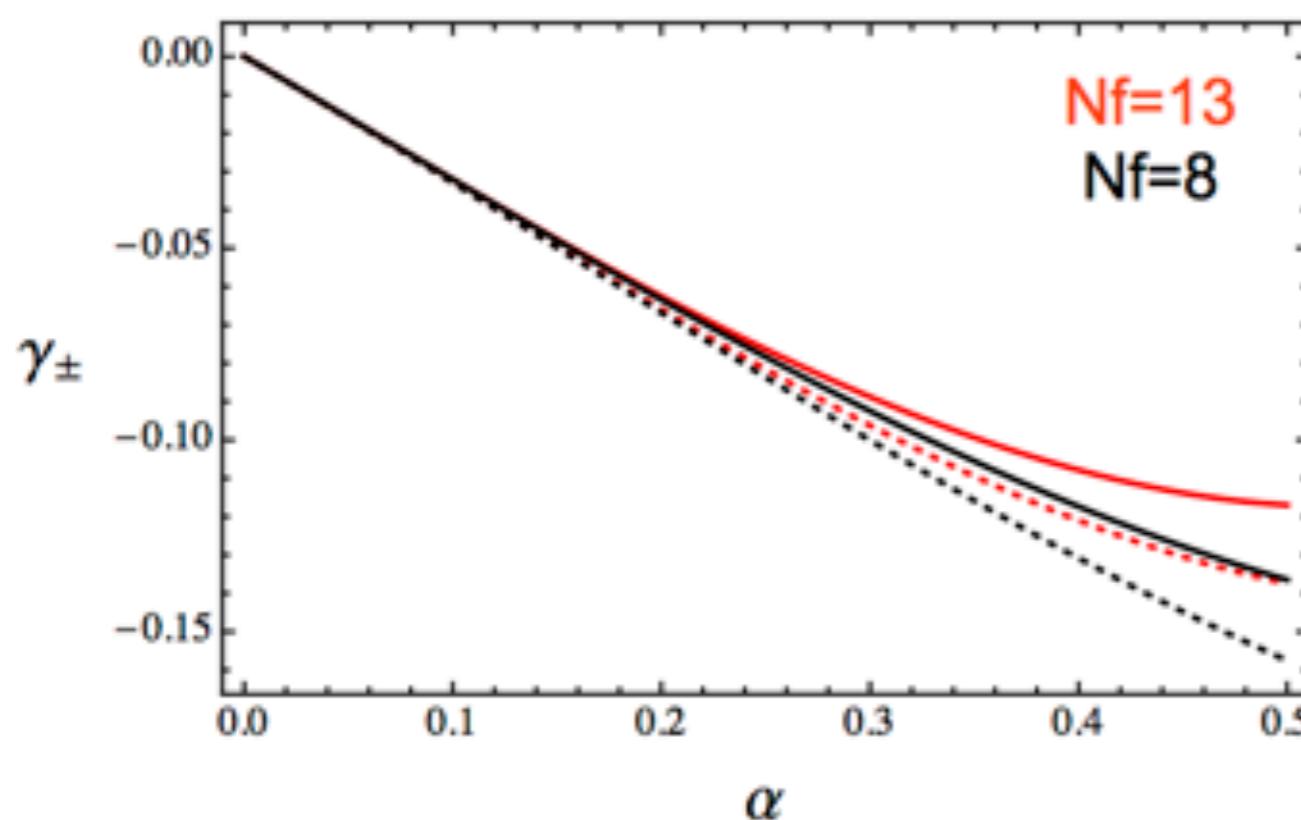
In d=4- ϵ dimensions:

evanescent operators starting at 2-loop $\psi \gamma^{\mu_1 \dots \mu_n} (\psi \gamma_{\mu_1 \dots \mu_n} \psi)$



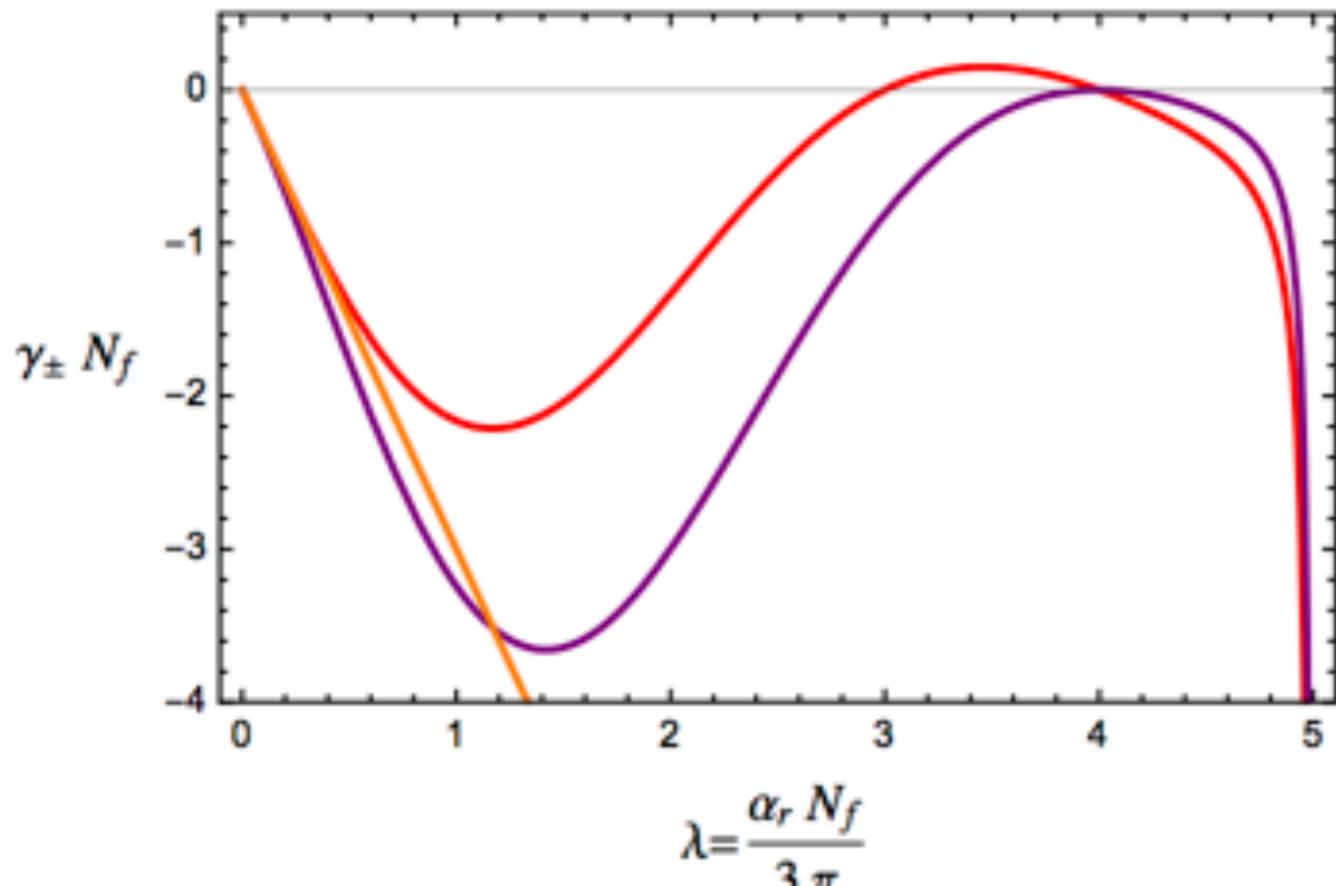
The overall sign is unaffected
by higher orders!

$$\gamma_{\pm} = -\frac{\alpha}{\pi} [1 + \mathcal{O}(\alpha)]$$



1-loop in Peskin (1979)
3-loop in Gracey (2012)

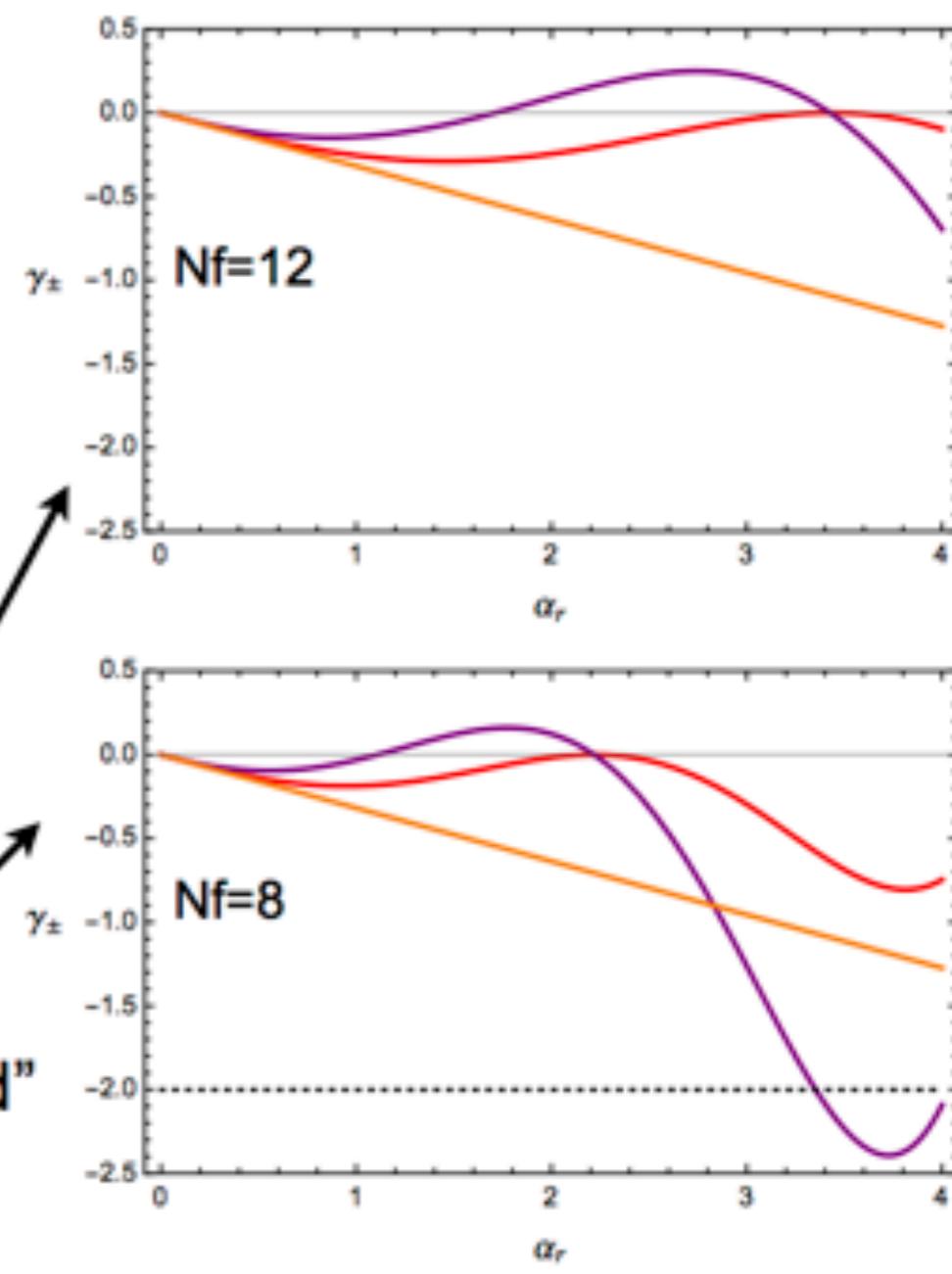
$$\gamma_{\pm}(\lambda) = -\frac{3}{N_f}\lambda \frac{(1-\lambda)\left(1-\frac{\lambda}{3}\right)^2 \Gamma(1-\lambda)}{\left(1-\frac{\lambda}{2}\right)^2 \left(1-\frac{\lambda}{4}\right) \Gamma\left(1+\frac{\lambda}{2}\right) \Gamma^3\left(1-\frac{\lambda}{2}\right)} \left(\frac{3}{4}\lambda + \frac{s_{\pm}(\lambda)}{1-\frac{\lambda}{3}} \right) + \mathcal{O}(1/N_f^2)$$



$$s_{\pm} = 1, (1 - \lambda/3)(1 - \lambda/4), \dots$$

scheme-dependence
(disappears at the IR fixed point)

Naively “non-abelianized”
 $N_f \rightarrow N_f - 33/2$
Broadhurst-Grozin (1995)



Conclusions

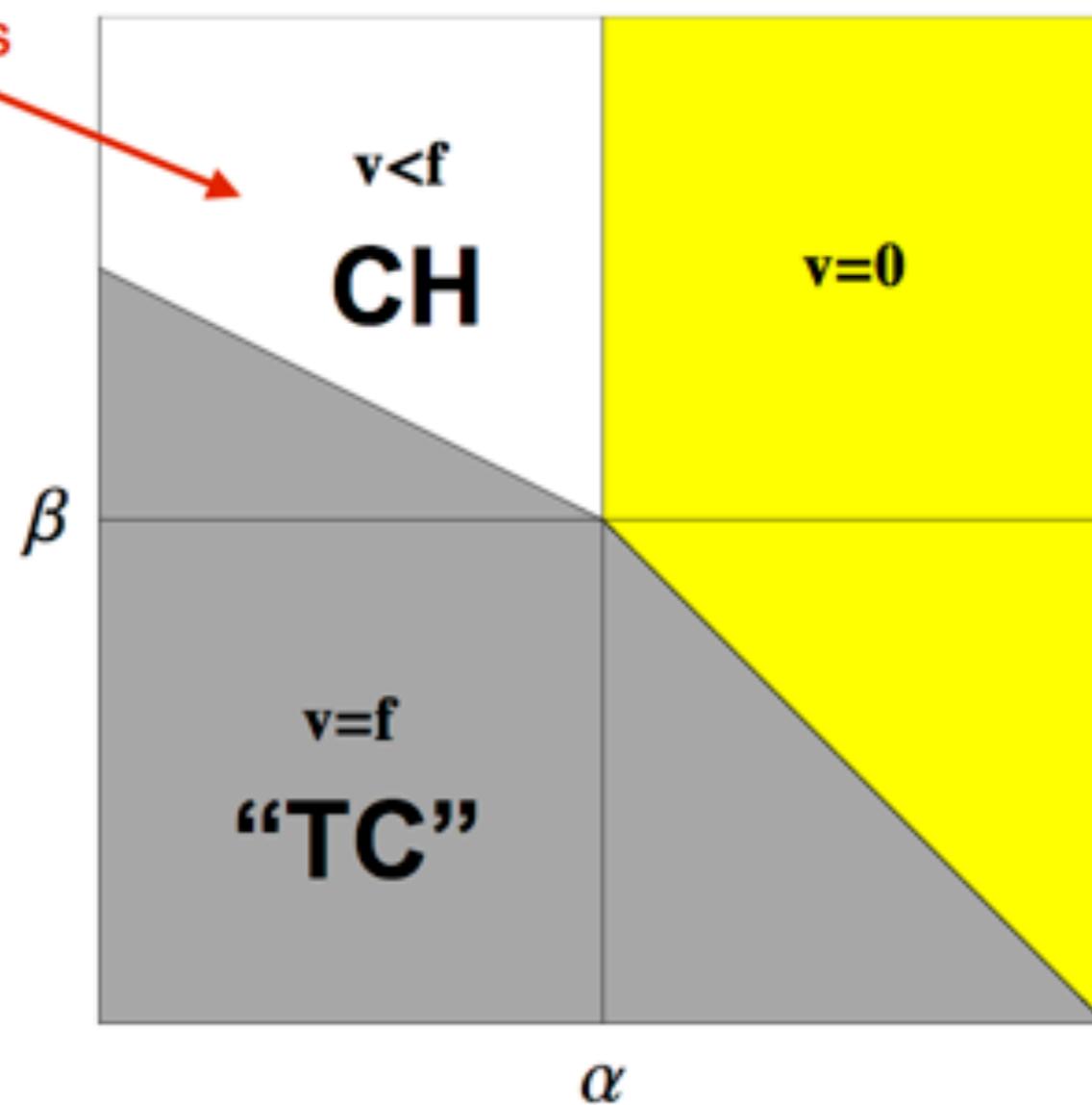
- * Complete models without fund. scalars exist provided the Partial Compositeness coupling λqO is **dangerous irrelevant** ($d[O] < 2.5$)
 - bonus: may account for fermion mass hierarchy
- * A toy candidate: **SU(3) gauge with light flavors**
 - only model that satisfies all basic requirements under th. control
 - has realistic vacuum alignment and Higgs mass
 - familiar to lattice community (baryon scaling dimension?)
- * **UV models → new phenomenology:**
 - non-minimal cosets ($SU(4)^2/SU(4)$, etc.)
 - novel signatures (colored scalars, T-hadrons, etc.?)

Backup slides...

TC or CH?

Vacuum alignment \Leftrightarrow NGB potential. Example: $V = \alpha \sin^2 \frac{h}{f} + \beta \sin^4 \frac{h}{f}$

SM-like Higgs
up to $v/f < 1$



$$v \equiv f \sin \frac{\langle h \rangle}{f}$$

$v < f$ generic when there exist ≥ 2 G-breaking parameters of comparable size

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 \Rightarrow 1) respects an $SU(4) \supset$ custodial (no tadpole for H_2)
2) decouples the “dangerous” NGBs (EW T is OK!)

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



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

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