UV Completions of the PNGB Higgs

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Why should we care?

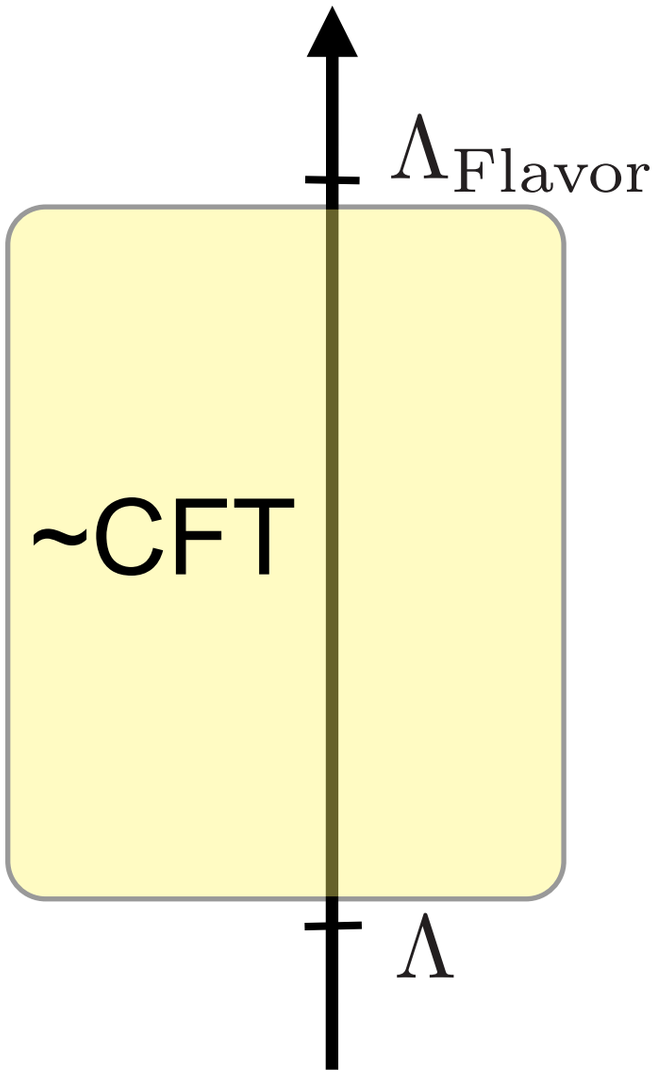
- **Plausibility of the PNGB Higgs framework:**
  - Do 4D realizations without fund. scalars exist?
  - Do we need SUSY?
  - Only a 5D construction?
  - ...

- **Phenomenological question:**
  - UV is constrained: What cosets? What spectrum? What EFT?
  - Are current searches covering generic signatures?
  - ...

Outline:

- UV theories without fundamental scalars
  - Key ingredients for a successful model
- The “simplest” candidate and its phenomenological implications
  - PNGB Higgs in “minimal” SU(4)xSU(4)/SU(4)
  - Novel collider signatures

The PNGB Higgs



$$\frac{v}{\Lambda} \to 0 \quad \text{OK (dim>4 operators)}$$

$$y_{\rm Yukawa} \sim \left(\frac{\Lambda}{\Lambda_{\rm Flavor}}\right)^{d-4} \quad \text{!!!}$$

UV-completion? $\Longleftrightarrow$ What is $\lambda q O$ with d=d[O]+3/2?!

$\lambda q O$ with d[O]<5/2 in tractable* UV-completions?

fund. scalars

SUSY

new particles & symmetries in IR

Serone et al.

NO fund. scalars

lattice $\Longleftrightarrow$ UV-free non-abelian

* we do not learn much if the UV is yet another strong dynamics...

$\lambda q O$ ($d[O] = d_{\rm cl} + \gamma \sim 5/2$) in non-abelian theories:

1. $\lambda \overline{q} \left(\sigma_{\mu\nu} \Psi^a G^a_{\mu\nu} \right) \Rightarrow$ no asymptotic freedom
2. $\lambda q \Psi_1 \Psi_2 \Psi_3$ **best option**
3. **...**

UV-completion without fundamental scalars $\Longleftrightarrow$ $\gamma \simeq -2$

lattice?

Wish-list

- ☐ G/H ⊃ Higgs doublet Georgi-Kaplan (‘80s)
- ☐ H ⊃ 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)

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Most obvious theory: SU(3) and Nf Dirac flavors

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- ☑ A strong IR fixed point (conformal window)
- ☐ **d[O]<5/2 within the CFT?** **Lattice!** work in progress

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

	$SU(3)$	$SU(3)_c$	$SU(2)_w$	$U(1)_Y$
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'	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\frac{5}{6} - \frac{1}{2}a$

Plus the right handed components

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

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

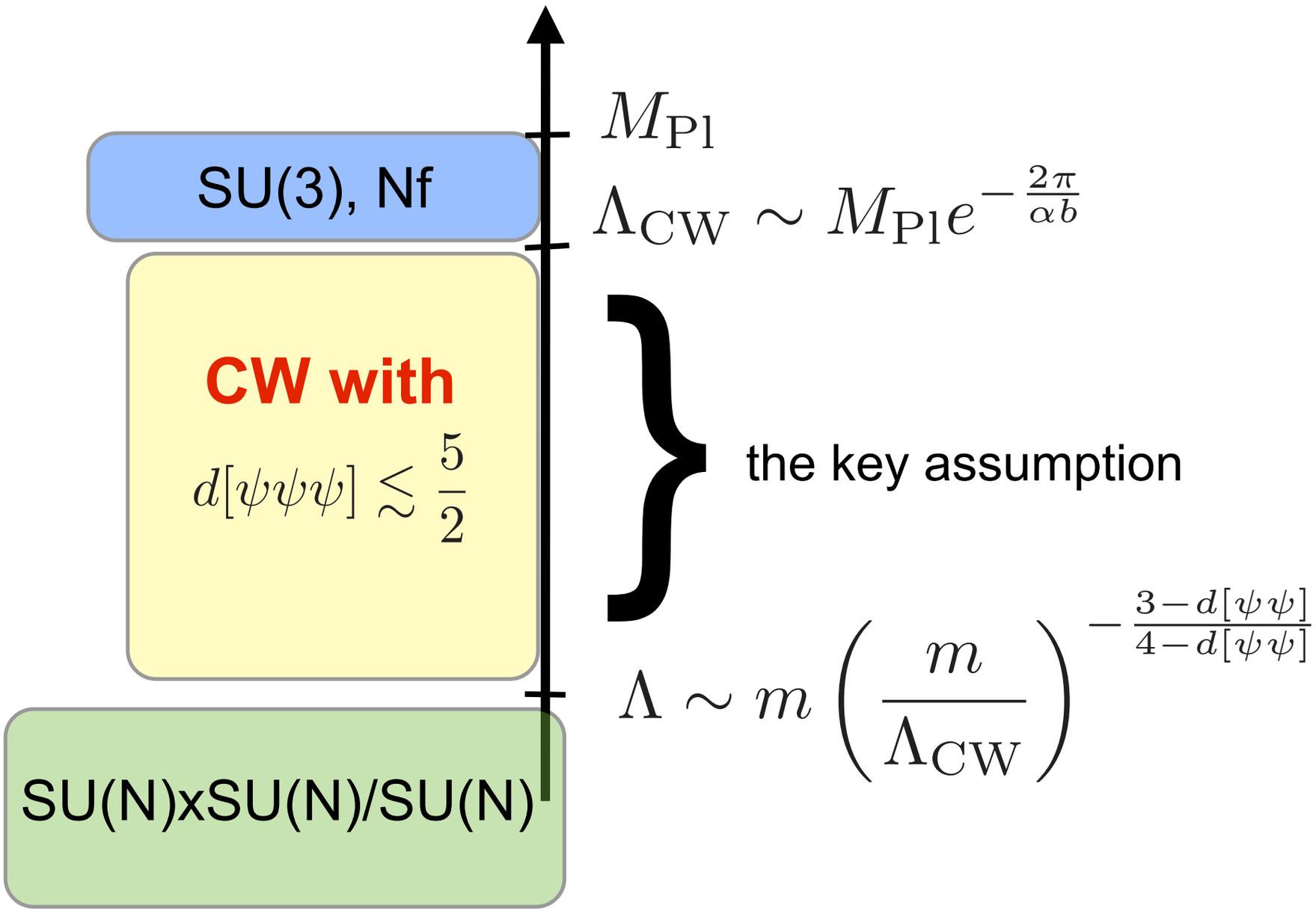
$$\mathcal{L}_{\rm ETC} = quD\overline{S} + qu\overline{D}S' + qd\overline{D}S + qdD\overline{S'}$$

$$+\ell e\overline{D}S + \ell eD\overline{S'} + Q^\dagger\overline{\sigma}^\mu Q\psi^\dagger\overline{\sigma}_\mu\psi + \text{hc}$$

Exit CFT:

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

...


SU(3), Nf
CW with
$d[\psi\psi\psi] \lesssim \frac{5}{2}$
SU(N)xSU(N)/SU(N)
$M_{\rm Pl}$
$\Lambda_{\rm CW} \sim M_{\rm Pl} e^{-\frac{2\pi}{\alpha b}}$
the key assumption
$\Lambda \sim m \left(\frac{m}{\Lambda_{\rm CW}}\right)^{-\frac{3-d[\psi\psi]}{4-d[\psi\psi]}}$

Phenomenology

- non-minimal SU(N)xSU(N)/SU(N) ⇒ Collider (exotic NGBs)
- color not factorized ⇒ Collider (direct production of colored NGBs)
- accidental symmetries ⇒ Collider (new collider signatures)
- ...

Vacuum Alignment in SU(4)xSU(4)/SU(4) $SU(2)_w \times SU(2)_{\rm cust} \subset SU(4)_V$

* 15 Goldstones:

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

* Fermions in (reducible) 2-index representations:

$$O \sim T\Psi_i\Psi_j$$

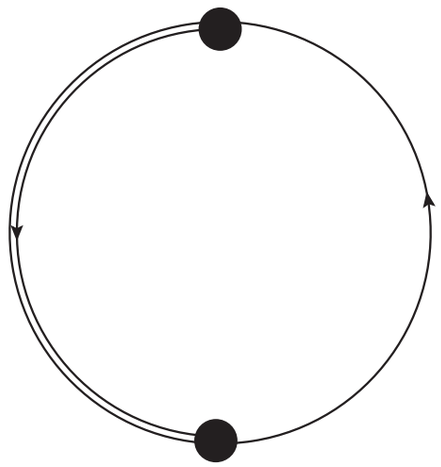
* Generically, couplings to fermions break custodial: problem with rho parameter

Gripaios et al. (2009)
Mrazek et al. (2011)

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

Robust solution: $\lambda_R \overline{t_R} O$

choose O in the $\mathbf{6} \in SU(4)_V$ of $(\mathbf{4},\mathbf{4}) \in SU(4)_L \times SU(4)_R$



$$\delta V = C_u \ \mathrm{tr}\left[(\lambda_R U)(\lambda_R U)^*\right]$$

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

$\Longrightarrow$ **no tadpole for H_2** (respects custodial)

& positive masses for the "dangerous" NGBs (rho is OK!)

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

technically natural:

effectively SU(4)/Sp(4)!

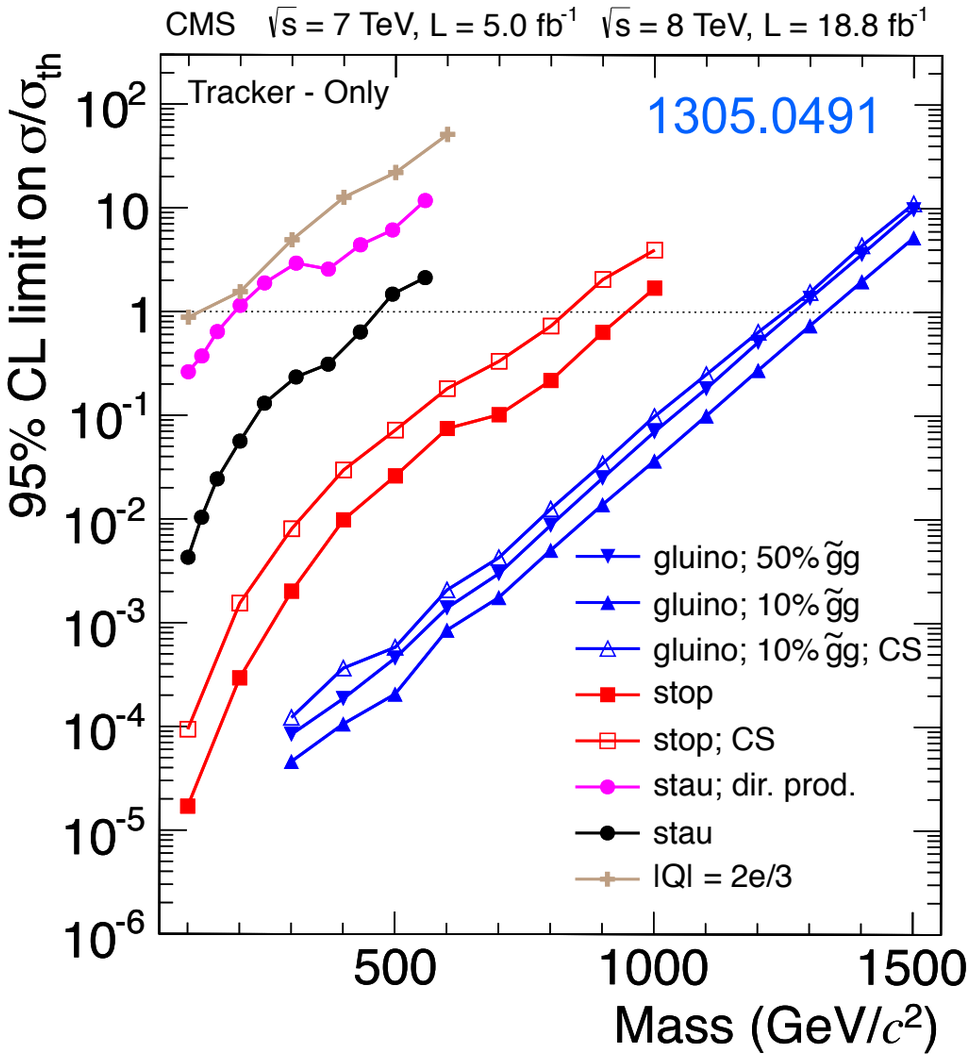
⁎ realistic Higgs potential .... Gripaios et al. (2009)

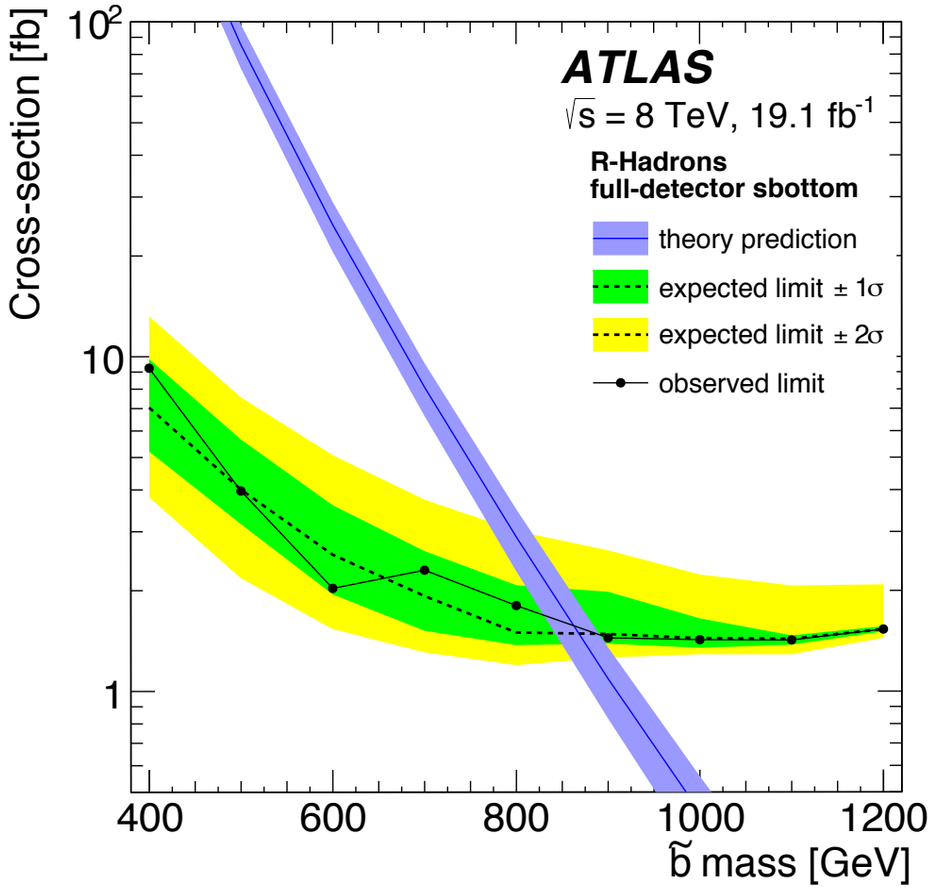
$$V_{\overline{\text{NDA}}} = \frac{(g_* f)^4}{16\pi^2}\left[a\left(\frac{y_t^2}{g_*^2}s_h^2\right) + b\left(\frac{y_t^2}{g_*^2}s_h^2\right)^2 + \cdots\right]$$

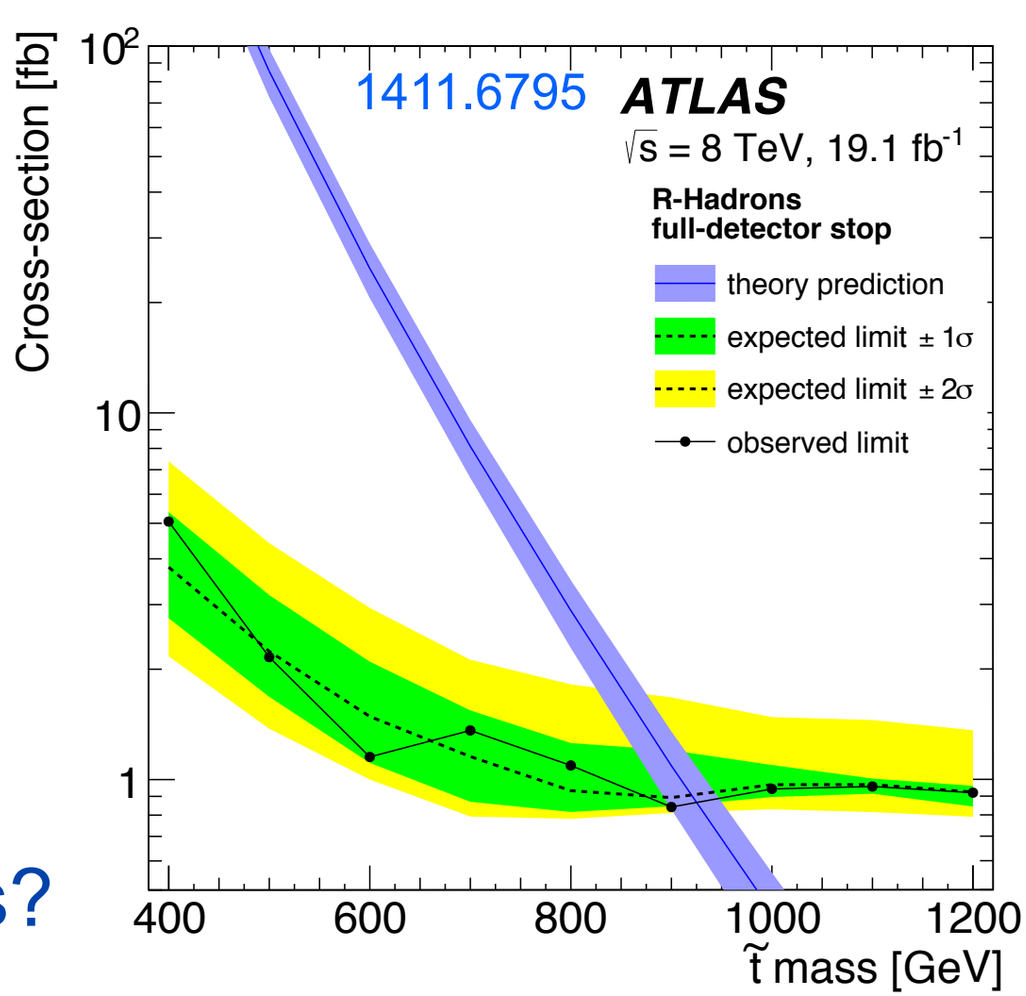
- To achieve v<<f ONE tuning (a<<b~1) of order $\sim (g_* f/m_t)^2$ "double-tuning" in Panico et al. (2013)
- The 126 GeV Higgs quartic is reproduced for b~4=O(1) and $g_* = 4\pi$

❋ Color-Triplet PNGBs with EW charges

- accidental baryon & lepton & U(1)_T family ⇒ **T-hadrons**







Fractional charge? Displaced vertices?

Conclusions

- Honest (pheno) question: **models without fund. scalars?**

- "Obvious" candidate: **SU(3) gauge with light flavors**
  - satisfies all basic requirements theoretically under control
  - has realistic vacuum alignment (v<f) and Higgs mass
  - use existing lattice data for baryon scaling dimension (in progress)

- **UV models $\Longrightarrow$ phenomenological work to do:**
  - extend studies to non-minimal cosets (SU(4)^2/SU(4) is fine)
  - collider pheno of colored scalars (generic from PC)
  - novel signatures? (T-hadrons, etc.)