125 GeV Higgs and the Scale of New Physics

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1208.6013 with A. Strumia

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1970-2012

Everything in agreement with $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ gauge theory

$$\mathcal{L}_{kinetic} = -\frac{1}{4\,g_1^2} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4\,g_2^2} W^i_{\mu\nu} W^{i\mu\nu} - \frac{1}{4\,g_3^2} G^a_{\mu\nu} W^{a\mu\nu} + i \sum_{j=1}^{3} (\bar{\Psi}^j \bar{\sigma}^\mu \partial_\mu \Psi^j + h.c.)$$

$$\Psi = (3,2)_{\frac{1}{6}} \oplus (\bar{3},1)_{-\frac{2}{3}} \oplus (\bar{3},1)_{\frac{1}{3}} \oplus (1,2)_{\frac{1}{2}} \oplus (1,1)_1$$ (3 parameters)

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(3 parameters)

Unbroken gauge symmetry forbids mass terms: vacuum must respect a smaller symmetry

$$SU(3)_c \otimes U(1)_Q$$

Mass terms can be written,

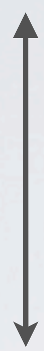
$$\mathcal{L}_{mass} = \sum_{i,j=1}^{3} \left[\bar{u}^i_L M^u_{i,j} u_R + \bar{d}^i_L M^d_{i,j} d_R + \bar{e}^i_L M^e_{i,j} e_R\right] + h.c.$$

$$+ m_W^2 W^2 + \frac{1}{2} m_Z^2 Z^2$$

O(20) parameters

Mass for gauge bosons implies new degrees of freedom

$m_1 = 0$



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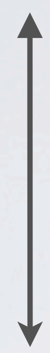

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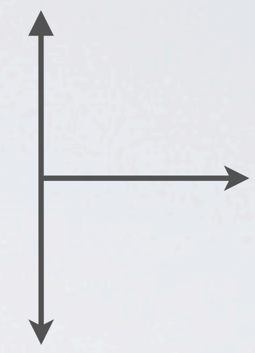

The extra degrees of freedom are Goldstone Bosons

$$SU(2)_L \otimes U(1)_Y \to U(1)_Q$$

They become longitudinal polarizations of W & Z

Conceptually identical to superconductivity.

In the SM the spontaneous breaking is due a doublet scalar

$$V(H) = \lambda \left(|H|^2 - v^2\right)^2$$

$$H(x) = U(x) \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}, \qquad v = 174\, GeV$$

VEV breaks symmetry spontaneously.
The Goldstone Bosons in $U(x)$ are eaten giving mass to W & Z.
Scalar h(x) is what we call the "Higgs".

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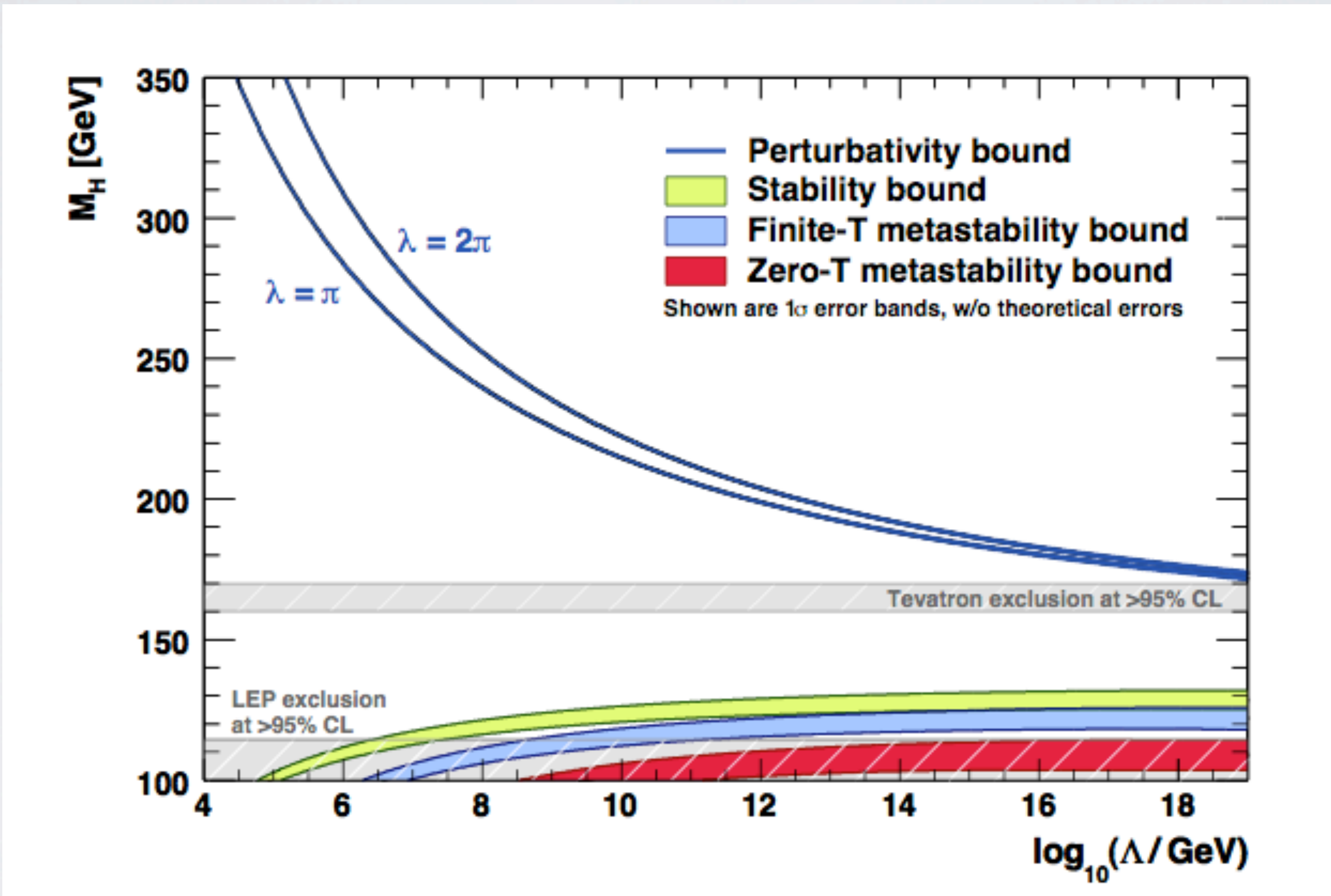
If SM is correct only unknown is the quartic/mass

$$m_h = \sqrt{\lambda}\, v$$

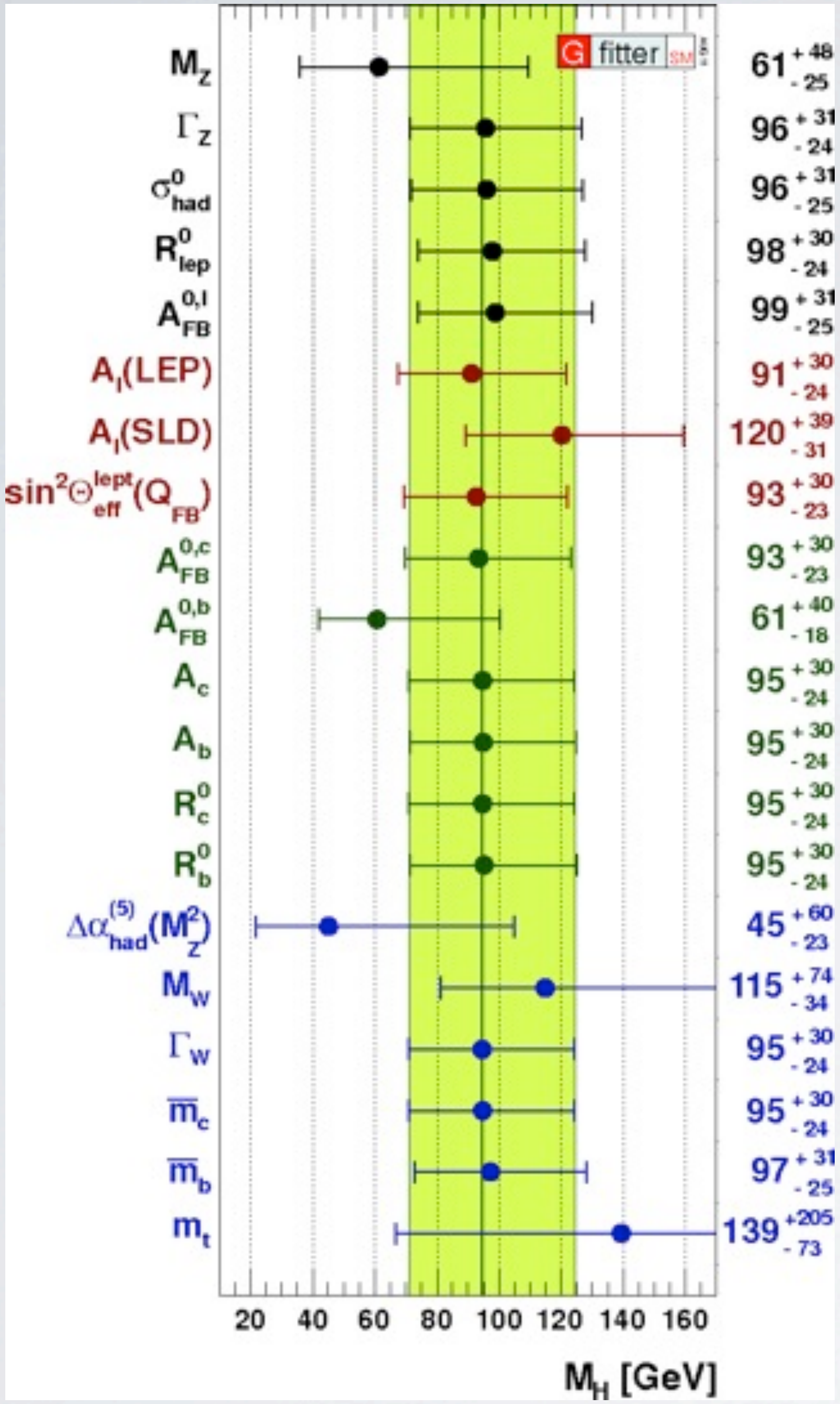
Can SM be the whole story?

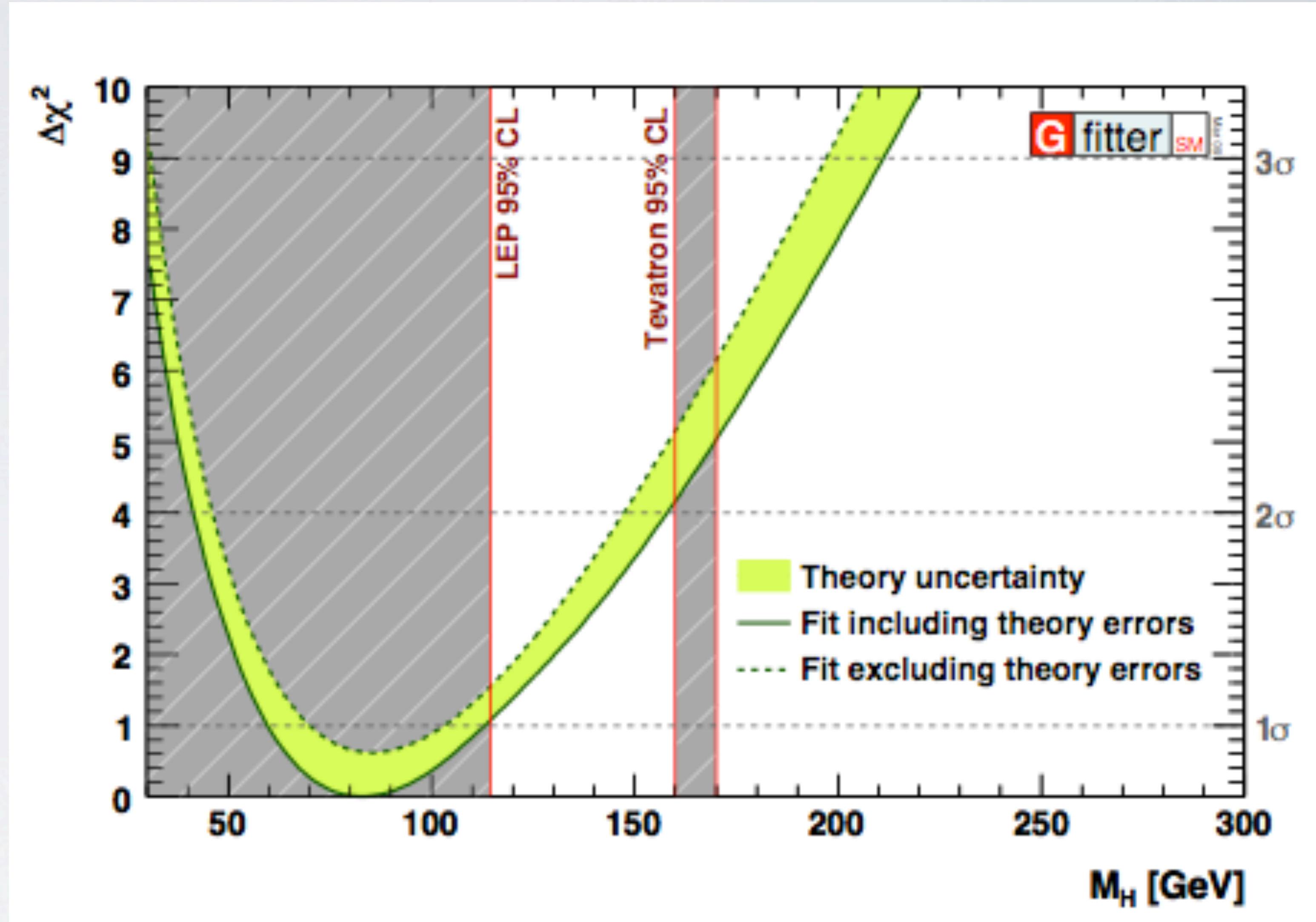
$$\mu \frac{d\lambda}{d\mu} = \frac{1}{16\pi^2}(24\lambda^2 - 6y_t^4 + \dots)$$



Giudice et al.
1112.3022

$$115\,\mathrm{GeV} < m_h < 160\,\mathrm{GeV}$$

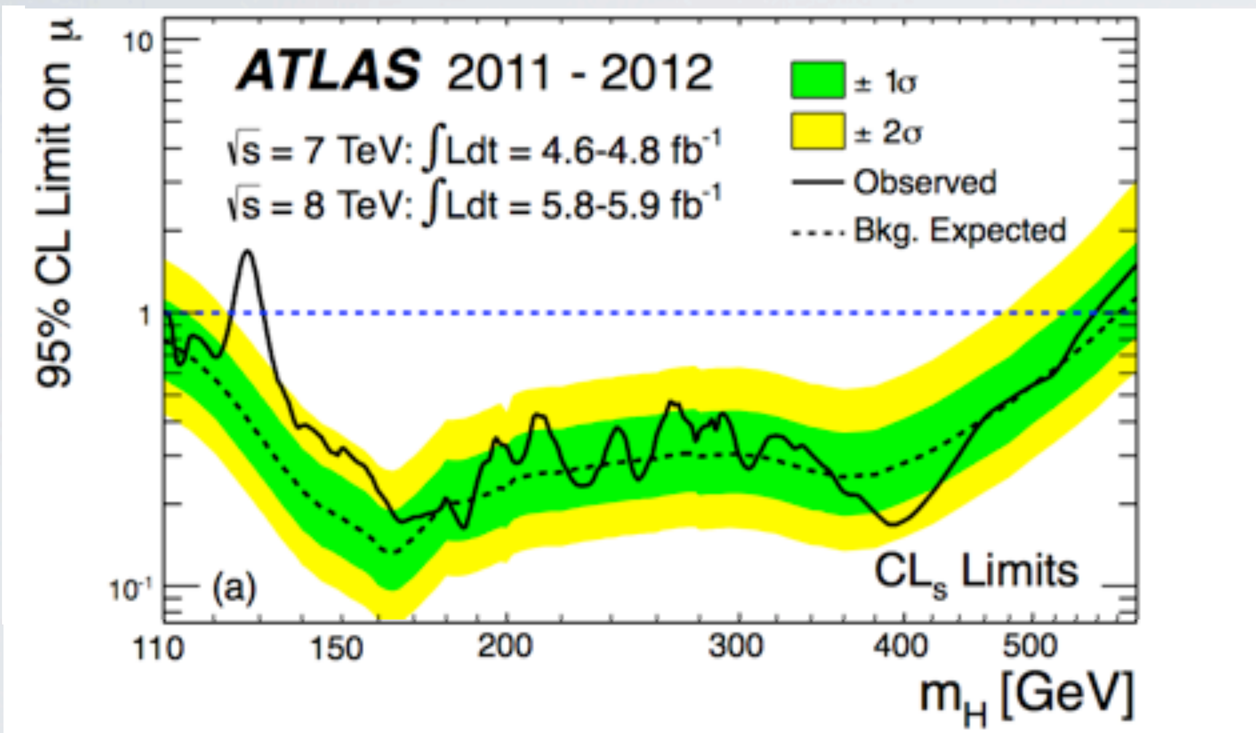


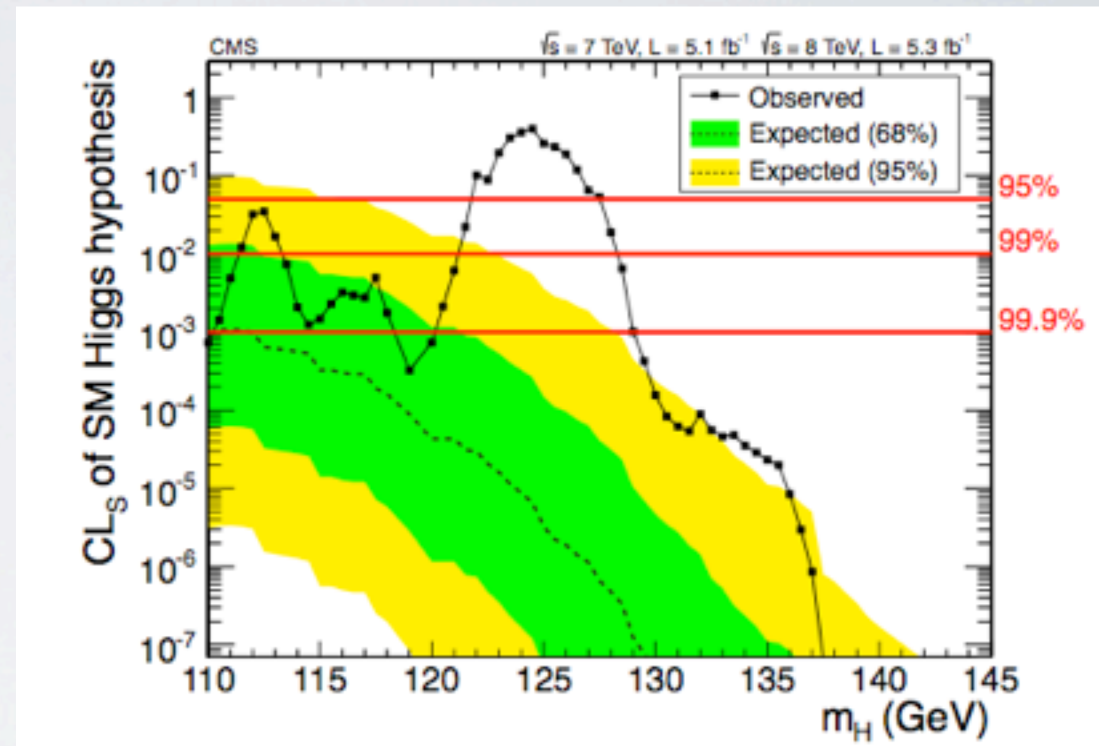


Indirect tests: $m_h < 150$ GeV

Direct search: $m_h > 114$ GeV

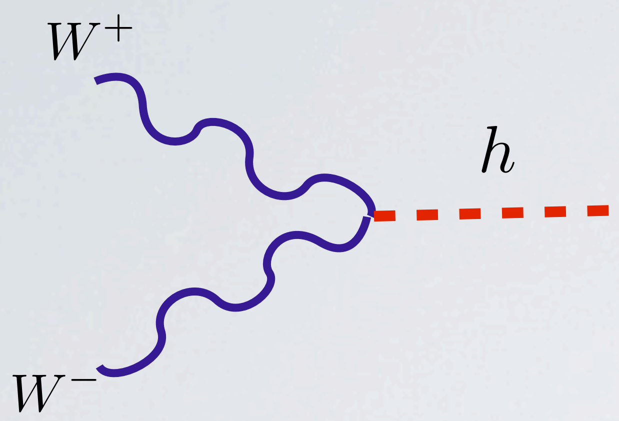
July 31, 2012   Phys. Lett. B716



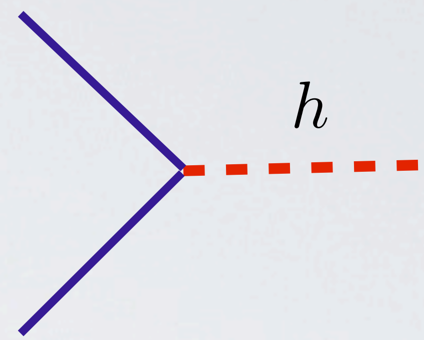


$$m_h \approx 125\,\mathrm{GeV}$$

SM HIGGS?



$$= \sqrt{2} i \frac{m_W^2}{v} \kappa_V$$



$$= -\frac{m_f}{\sqrt{2} v} \kappa_F$$

$$\mathrm{SM}: \quad \kappa_F = \kappa_V = 1$$

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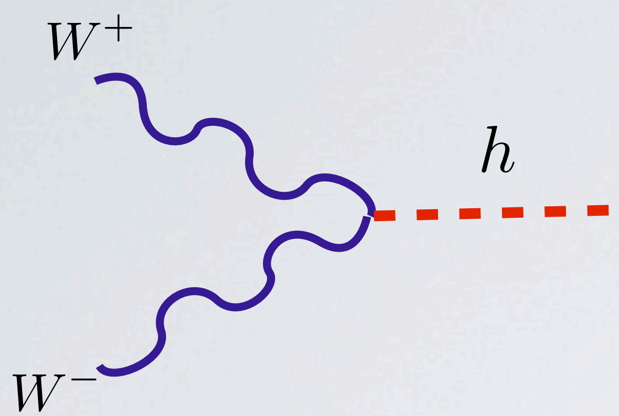

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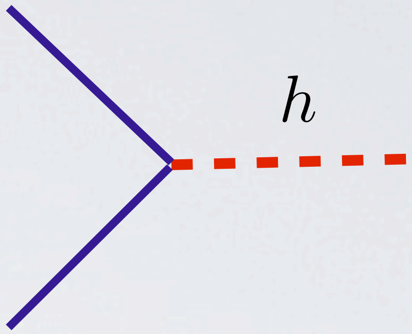

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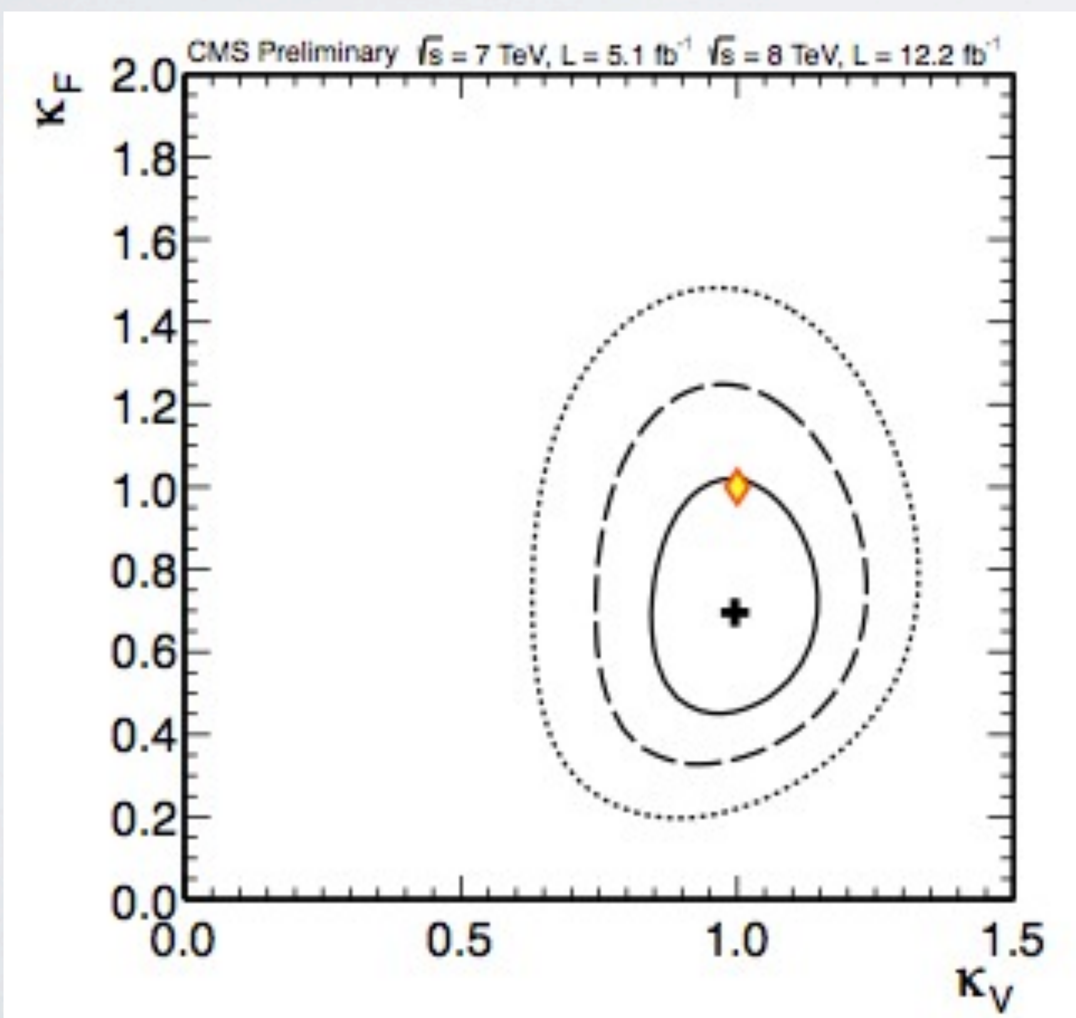

HIERARCHY PROBLEM

SM is an effective theory valid up to Λ

$$\mathcal{L} = \mathcal{L}_{kin} + g\, A_\mu \bar{\psi}\gamma^\mu \psi + y\, \bar{\psi} H \psi - \lambda\, |H|^4 \qquad D = 4$$

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Irrelevant interactions:

$$\frac{1}{\Lambda}(l H^c)^2 \qquad \frac{1}{\Lambda^2}(\bar{\psi}\psi)^2 \qquad \frac{1}{\Lambda}\bar{\psi}\,\sigma^{\mu\nu}\psi F_{\mu\nu} \qquad D > 4$$

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One relevant operator

$$[H^2] \approx 2$$

Without tuning:

$$m_h \sim \Lambda$$

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No obvious experimentalist:

New physics will be seen at the LHC

FLAVOR HAS FOUND NOTHING

$$\Lambda > 10^5\,\mathrm{TeV}$$

LEP HAS FOUND NOTHING

$$\Lambda > 5 - 10\,\mathrm{TeV}$$

LHC HAS FOUND THE HIGGS + NOTHING

$$\Lambda > \text{few} \times \text{TeV}$$

$$\Lambda \gg \mathrm{TeV}?$$

- Explains why we have not seen anything

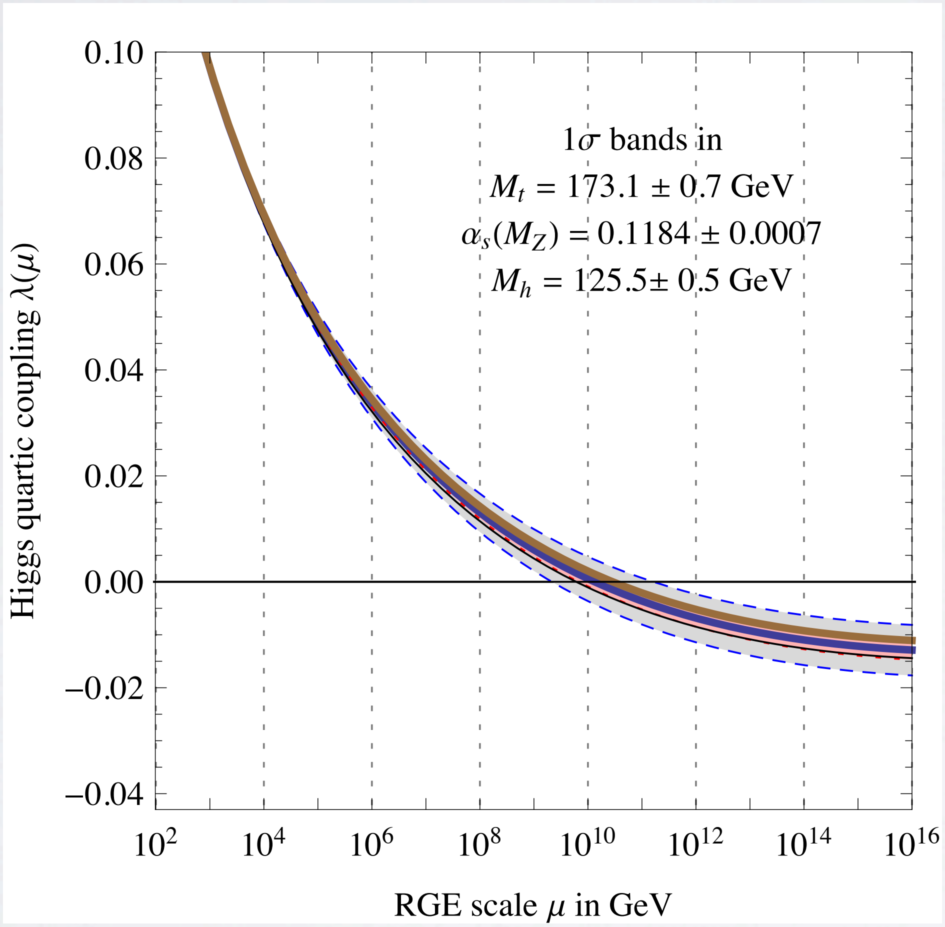
$$\Lambda \gg \text{TeV}?$$

- Explains why we have not seen anything

- Higgs could be tuned anthropically

HINTS

- Running:



$$V(h) = m^2h^2/2 + \lambda h^4/4$$

De Grassi et al. '12

Quartic almost zero at high scale for 125 GeV Higgs

- Strong CP problem:

$$\frac{\theta}{32\pi^2}\int d^4x\,\epsilon^{\mu\nu\rho\sigma}\,Tr[G_{\mu\nu}G_{\rho\sigma}] \qquad\qquad \theta < 10^{-9}$$

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Elegantly solved by axions

$$\theta \to \frac{a(x)}{f}$$

Axions are Goldstones of a symmetry anomalous under QCD

$$m_a \sim \frac{\Lambda^2_{QCD}}{f}$$

Star cooling:

$$f > 10^9\,\mathrm{GeV}$$

Axions can be dark matter

$$\frac{\rho_a}{\rho_{\mathrm{DM}}} \approx \theta_i^2 \left(\frac{f}{2-3\times 10^{11}\,\mathrm{GeV}} \right) \longrightarrow \qquad f \approx 10^{11}\,\mathrm{GeV}$$

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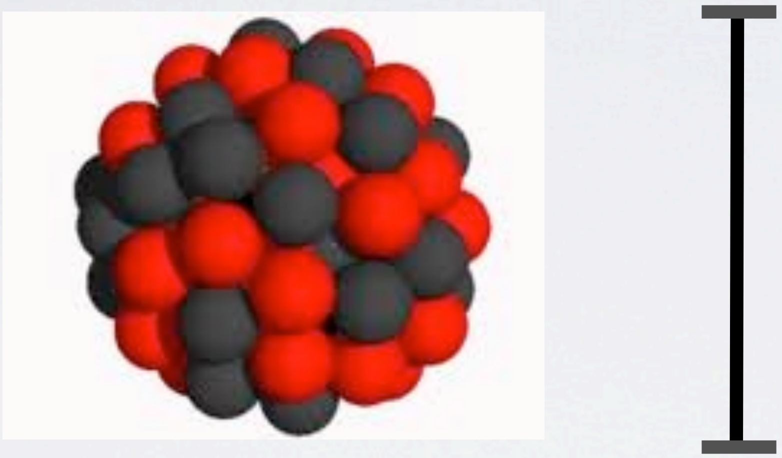
- Neutrino masses

$$\frac{1}{\Lambda}(lH^c)^2 \qquad\qquad m_\nu \propto \frac{v^2}{\Lambda}$$

- Unification

COMPOSITE HIGGS

Higgs could a be a remnant of strong dynamics



$$\sim \frac{1}{m_\rho}$$

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$$\sim \frac{1}{m_\rho}$$

If $m_\rho = \Lambda \sim \mathrm{TeV}$ theory natural

$$\delta m_h^2 = \frac{g_{SM}^2}{16\pi^2}\Lambda^2$$

Most compelling scenario Higgs is Goldstone boson

Georgi, Kaplan '80

$$\frac{G}{H} \xrightarrow{SM \in H} \mathcal{L} = f^2 D_\mu^{\hat{a}} D^{\mu \hat{a}}$$

$$m_\rho \sim g_\rho f$$

Ex: $$\frac{SO(5)}{SU(2)_L \otimes SU(2)_R} \longrightarrow GB = (2,2)$$

Agashe , Contino, Pomarol, '04

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Main difference from technicolor is that f is not linked to v.

Deviation from SM:

$$\mathcal{O}\left(\frac{v^2}{f^2}\right)$$

Despite smart theorists difficulties remain:

- flavor

$$m_\rho > 10\,\mathrm{TeV}$$

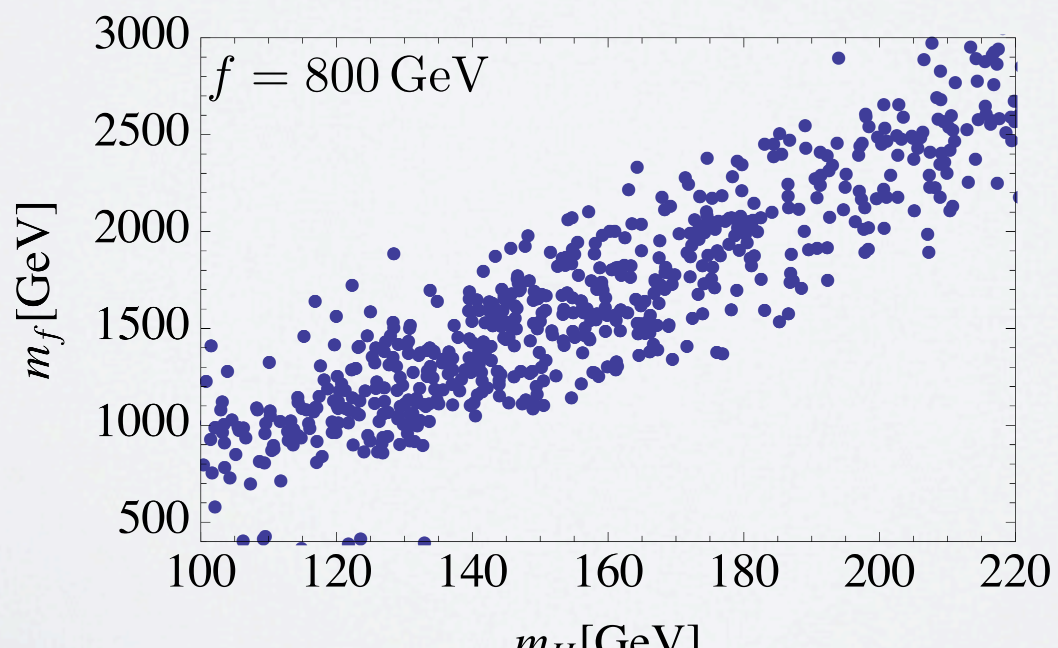
- precision tests

$$m_\rho > 3\,\mathrm{TeV}$$

- direct exclusion

$$m_f > 0.7\,\mathrm{TeV} \qquad m_\rho > 1.5\,\mathrm{TeV}$$

- Higgs mass



Redi, Tesi '12

$$\Lambda \sim 10^{11}\,\mathrm{GeV}$$

AXION-HIGGS

Basic idea:
Axion and Higgs are GBs from common dynamics.
f is fixed by dark matter and the electro-weak scale is tuned.

$$\frac{G}{H} \xrightarrow{f \approx 10^{11}\ \mathrm{GeV}} \mathrm{Higgs} + \mathrm{singlet}$$

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Ex:

$$\frac{SO(6)}{SO(5)} \longrightarrow GB = 5 = (2,2) + (1,1)$$

Singlet is axion candidate if SM interactions do not break its shift symmetry.

A SIMPLE MODEL

Kim-Shifman-Vainstein-Zakharov axion:

Add new colored fermions + complex scalar

$$\Psi_Q \to e^{i\alpha_Q\gamma_5}\Psi_Q, \qquad \sigma \to e^{-2i\alpha_Q}\sigma$$

$$L = L_{\rm SM} + \bar\Psi_Q \partial \Psi_Q + |\partial_\mu \sigma|^2 + (\lambda\,\sigma\,\bar\Psi_Q\Psi_Q + {\rm h.c.}) - V(\sigma)$$

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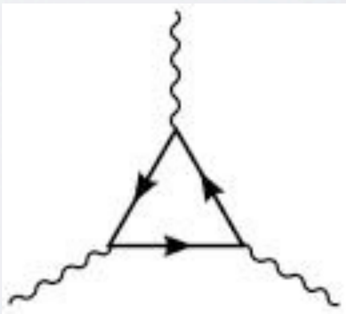
Spontaneous U(1) symmetry breaking

$$f \approx \langle \sigma \rangle \qquad\qquad a = \sqrt{2}\, {\rm Im}[\sigma]$$

U(1) symmetry anomalous under QCD



$$\frac{G}{H} = \frac{SU(6)_L \times SU(6)_R}{SU(6)_{L+R}}$$

Under $SU(5)_{SM}$

$$\mathbf{35} = \mathbf{24} \oplus \mathbf{5} \oplus \bar{\mathbf{5}} \oplus \mathbf{1}$$

One Higgs doublet.
Two massless singlets are axion candidates.

Under SM 33 charged scalars acquire mass.

$$m \approx \frac{g_{SM}}{4\pi}\Lambda$$

UV realization: SU(n) gauge theory with 6 flavors

Fermions	$\mathrm{U}(1)_Y$	$SU(2)_L$	$SU(3)_\mathrm{c}$	$SU(n)_\mathrm{TC}$
D	$\frac{1}{3}$	1	$\bar{3}$	n
L	$-\frac{1}{2}$	2	1	n
N	0	1	1	n
$\bar{D}$	$-\frac{1}{3}$	1	3	$\bar{n}$
$\bar{L}$	$\frac{1}{2}$	$\bar{2}$	1	$\bar{n}$
$\bar{N}$	0	1	1	$\bar{n}$

$$\langle D\bar{D}\rangle = \langle L\bar{L}\rangle = \langle N\bar{N}\rangle \approx \Lambda^3$$

$$H \sim (L\bar{N}) - (\bar{L}N)^*$$

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$\bar{L}$	$\frac{1}{2}$	$\bar{2}$	1	$\bar{n}$
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$$H \sim (L\bar{N}) - (\bar{L}N)^*$$

FLAVOR:

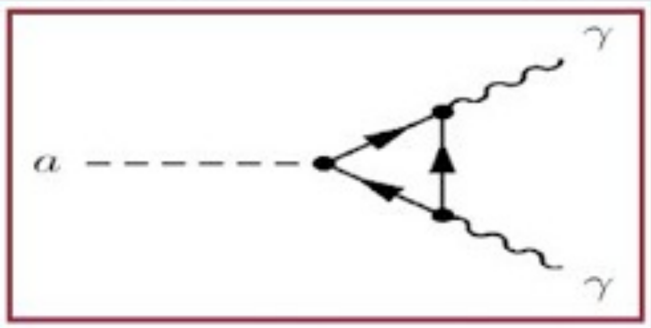
$(qu)(L\bar{N})$ $\qquad$ $(\bar{q}\bar{u})(\bar{L}N)$

Axions couple to photon and gluons through anomalies

$$\frac{a\,E}{32\pi^2 f}\epsilon^{\mu\nu\rho\sigma}F_{\mu\nu}F_{\rho\sigma} \qquad \frac{aN}{32\pi^2\,f}\epsilon^{\mu\nu\rho\sigma}Tr[G_{\mu\nu}G_{\rho\sigma}]$$

$$E = \sum Q_{PQ}Q_{em}^2$$

$$N = \sum Q_{PQ}T_{SU(3)}^2$$



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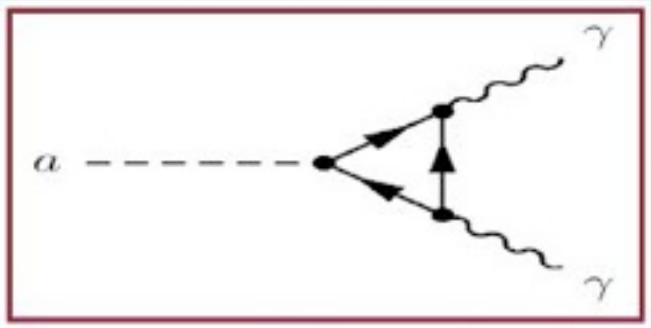
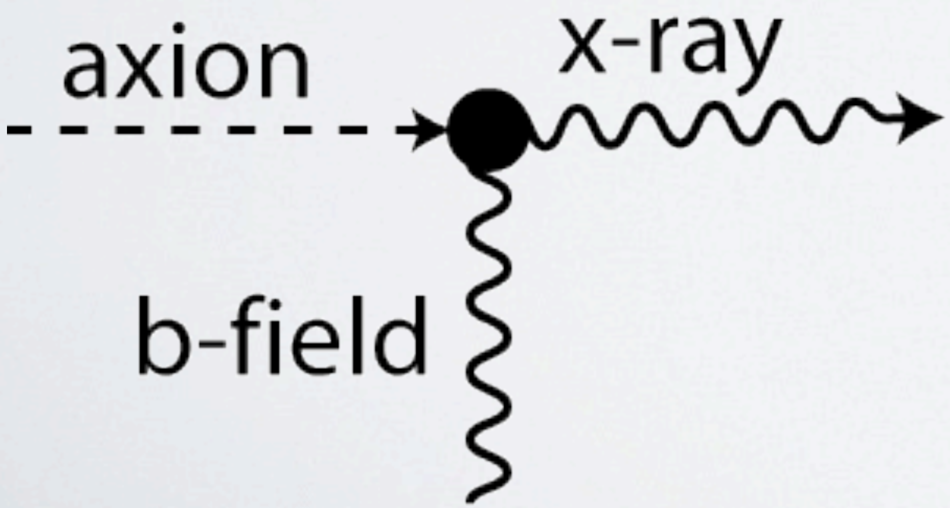
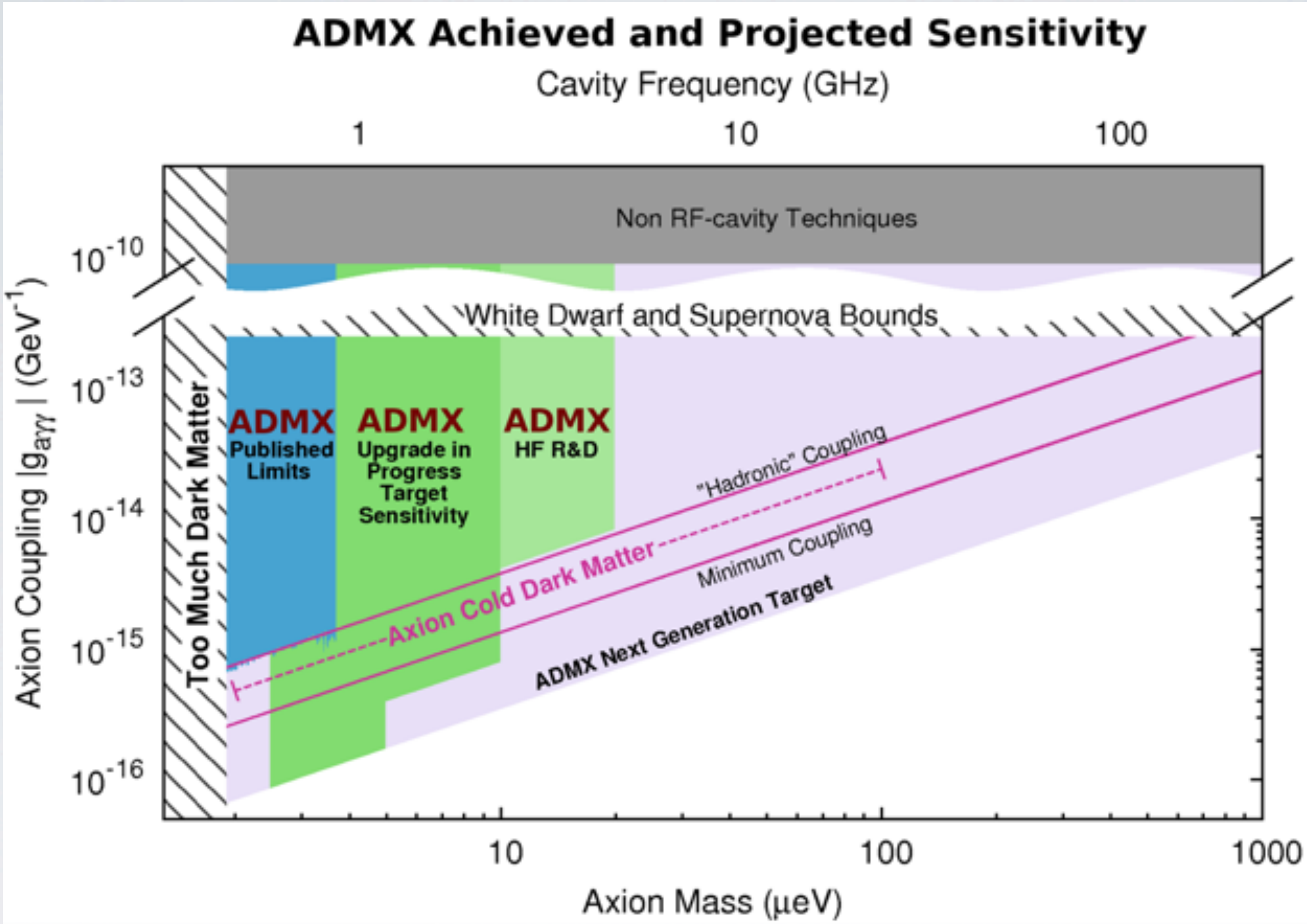


Experiments measure conversion of axion to photons



$$g_{a\gamma\gamma} = \frac{2(E/N - 1.92)}{10^{16}\,\mathrm{GeV}}\frac{m_a}{\mu\mathrm{eV}}$$

$$m_a \sim \frac{f_\pi m_\pi}{2f}\frac{\sqrt{m_u m_d}}{m_u + m_d}$$



$$\frac{E}{N} < 1.92 + 3.5\sqrt{\frac{0.3\,\mathrm{GeV/cm^3}}{\rho_{DM}}}$$

$$(m_a = 1.9 - 3.55 \times 10^{-6}\,\mathrm{ev})$$

a) If UV interactions respect singlets symmetry

$$\frac{4D - 3L - 6N}{\sqrt{102}}, \qquad \frac{L - 2N}{\sqrt{3}} \qquad\qquad \frac{E}{N} = -\frac{5}{6}$$

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b) If SU(5) is gauged

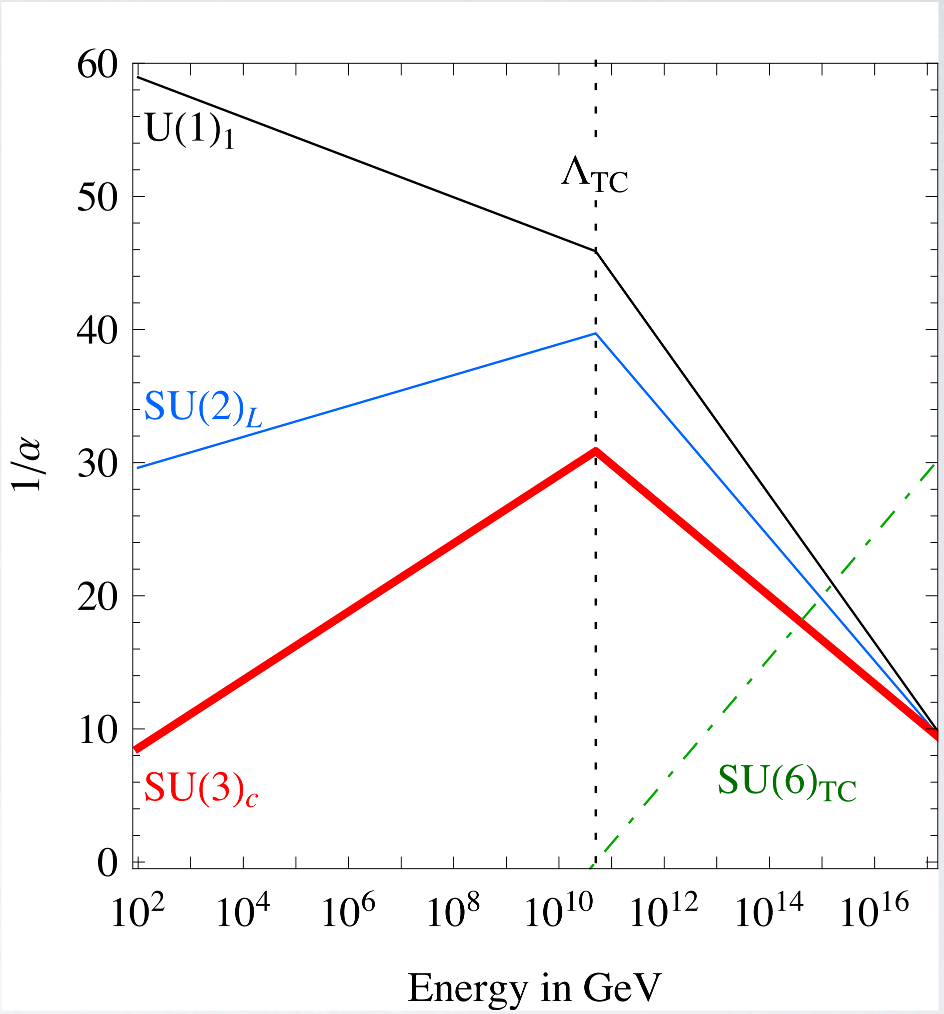
$$\frac{D + L - 5N}{\sqrt{30}} \qquad\qquad \frac{E}{N} = \frac{8}{3}$$

c) If all Yukawas allowed

$$\frac{D - 3L + 3N}{\sqrt{30}} \qquad\qquad \frac{E}{N} = -\frac{16}{3}$$

Incomplete SU(5) multiplets can improve unification

Ex: D, L, Q, U, N



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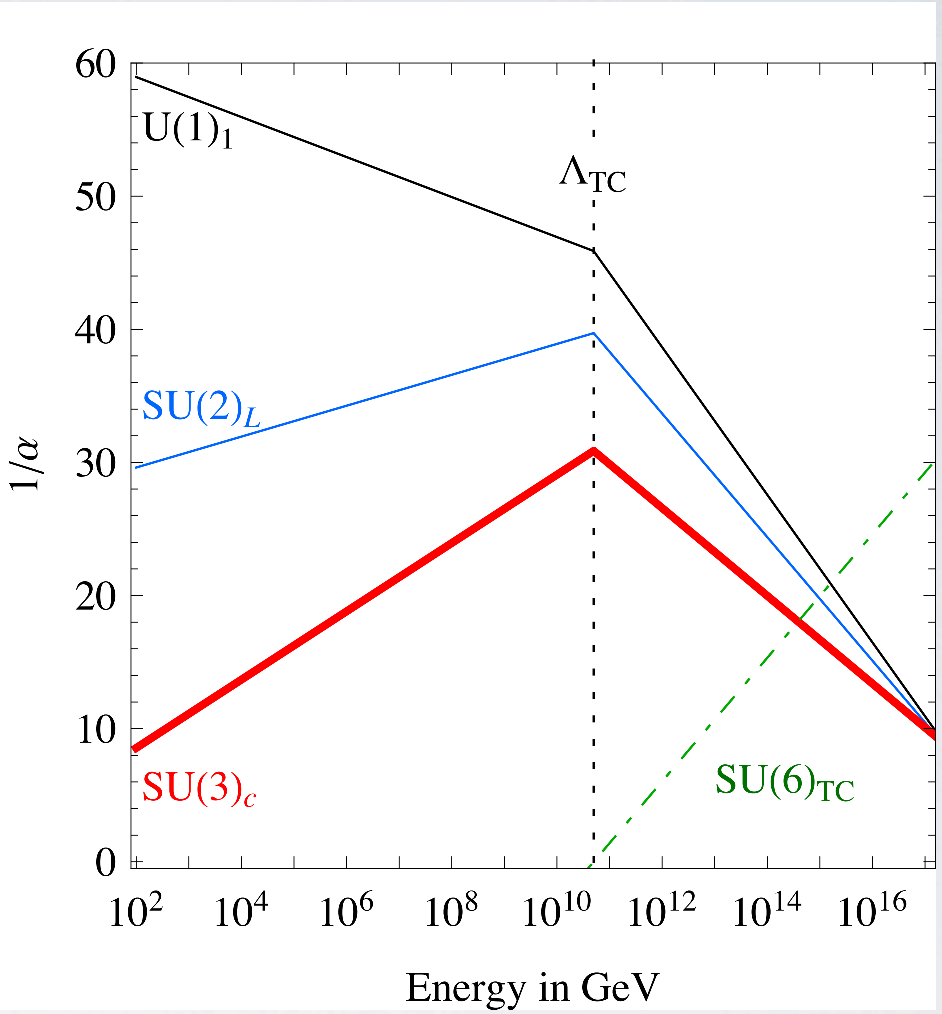


Neutrino masses obtained from see-saw

$$\frac{1}{\Lambda^2}(l\nu_R^c)(LN) + \Lambda(\nu_R^c)^2$$

HIGGS MASS

Higgs potential is generated by the couplings that break the global symmetry. Minimally gauge and Yukawa couplings.

$$V(h) = \sum_i a_i \sin^{2i}\left(\frac{h}{f}\right)$$

Electro-weak scale:

$$v \ll f \quad \longrightarrow \quad a_i \text{ must be tuned}$$

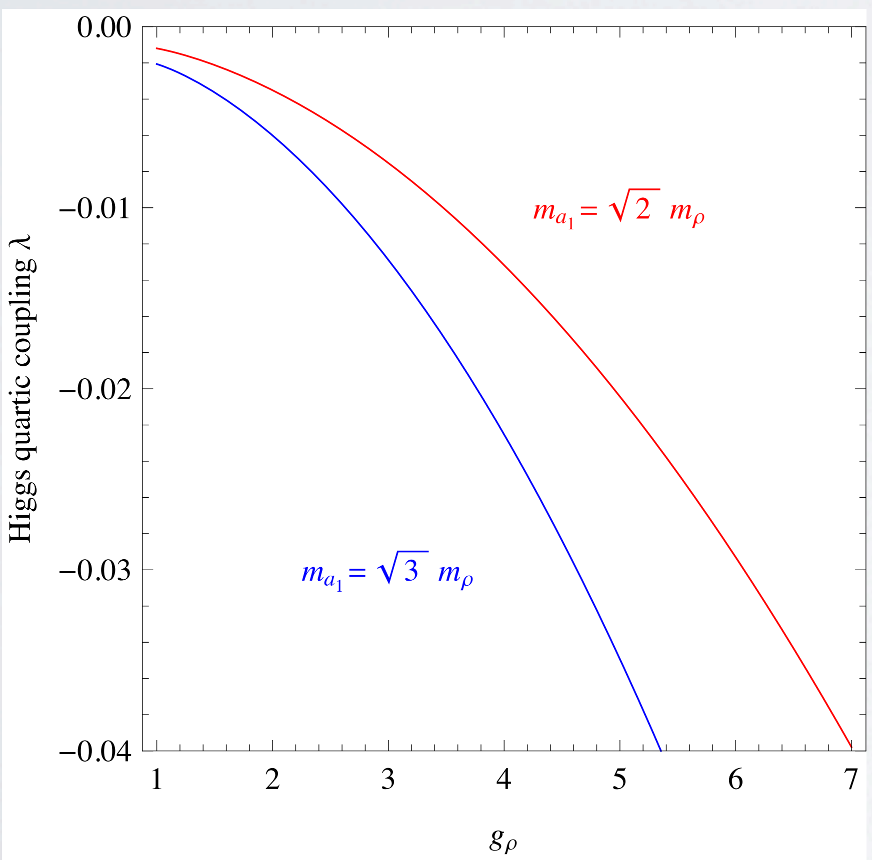
Higgs mass is then "predicted".

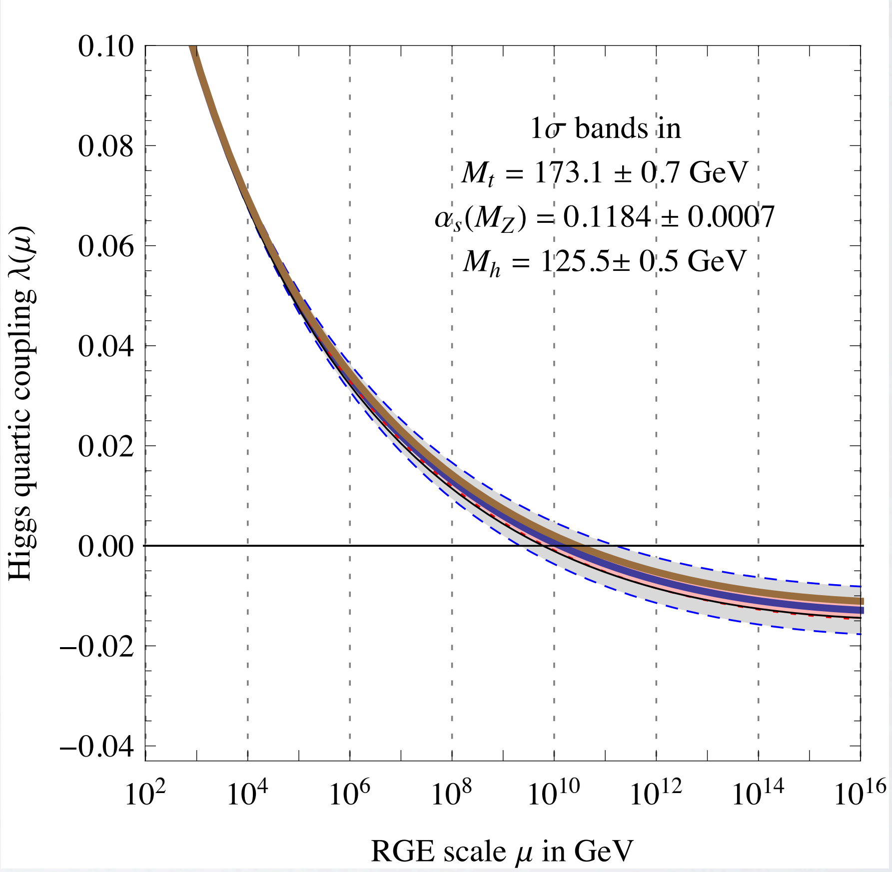
Gauge contribution:

$$V(h)_{\text{gauge}} = \frac{9}{2}\int \frac{d^4p}{(2\pi)^4} \ln\left[1 + F(p^2)\,\sin^2\frac{h}{f}\right]$$

$$V(h)_{\text{gauge}} \approx \frac{9}{4}\frac{g^2}{16\pi^2}\frac{m_\rho^4}{g_\rho^2}\ln\left[\frac{m_\rho^2 + m_{a_1}^2}{2m_\rho^2}\right]\sin^2\frac{h}{f}$$

$$\lambda(m_\rho)^{\text{leading}}_{\text{gauge}} \approx -3g^2 \log\frac{3}{2}\frac{g_\rho^2}{(4\pi)^2}$$





- Tuning with leading terms:

$$\lambda(\Lambda) \sim g_{\rm SM}^2 \frac{g_\rho^2}{(4\pi)^2} \sim {\rm few}\, 10^{-2}$$

125 GeV Higgs implies weak coupling (large n)

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125 GeV Higgs implies weak coupling (large n)

- Tuning with sub-leading terms

$$\lambda(\Lambda) \sim \frac{g_{\rm SM}^4}{(4\pi)^2} \sim 10^{-3}$$

Model I:

$$V_{\rm fermions} \sim \frac{N_c\, \lambda_t^2}{16\pi^2} \Lambda^2 f^2 \sum_{\alpha=1}^{2} |{\rm Tr}[\Pi_t^\alpha \cdot U]|^2 \qquad \propto \sin^2 \frac{h}{f}$$

CONCLUSIONS

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- The idea of the Higgs as Goldstone boson can be naturally merged with axions if $\Lambda \sim 10^{11}\,\mathrm{GeV}$

CONCLUSIONS

- So far everything is consistent with the SM being valid up to a very large a scale.

- The idea of the Higgs as Goldstone boson can be naturally merged with axions if $\Lambda \sim 10^{11}\,\mathrm{GeV}$

- Giving up naturalness, strong CP, dark matter, Higgs mass can be explained. Unification and neutrino masses could also fit into the picture.

HIGGS + DFSZ AXION

Dine-Fischler-Srednicki-Zhitnitsky:
Two Higgs doublets and complex singlet

$$\sigma \to e^{4i\alpha}\sigma, \qquad q_{L,R} \to e^{i\alpha} q_{L,R} \qquad H_u \to e^{-2i\alpha} H_u, \qquad H_d \to e^{-2i\alpha} H_d$$

$$f = \sqrt{v_u^2 + v_d^2 + |\sigma|^2}$$

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Ex:

$$\frac{G}{H} = \frac{SU(6)}{SO(6)} \qquad SO(6) \supset SO(4) \otimes \mathrm{U}(1)_{\mathrm{PQ}}$$

$$\mathbf{20'} = (\mathbf{2},\mathbf{2})_{\pm\mathbf{2}} \oplus (\mathbf{1},\mathbf{1})_{\pm\mathbf{4}} \oplus (\mathbf{1},\mathbf{1})_{\mathbf{0}} \oplus (\mathbf{3},\mathbf{3})_{\mathbf{0}}$$

UV realization: SO(n) gauge theory with 6 flavors

Fermions	$\text{U}(1)_Y$	$SU(2)_L$	$SU(3)_c$	$SO(n)_{\text{TC}}$	$\text{U}(1)_{\text{PQ}}$
L	$-\frac{1}{2}$	2	1	n	0
$\bar{L}$	$\frac{1}{2}$	$\bar{2}$	1	n	0
N	0	1	1	n	2
$\bar{N}$	0	1	1	n	-2

$$H_1 \sim LN$$

$$\langle L\bar{L}\rangle = \langle N\bar{N}\rangle = \Lambda^3$$

$$H_2 \sim \bar{L}\bar{N}$$

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Yukawas must respect PQ

$$\frac{1}{\Lambda_t^2}(q_L t_R^c)^\dagger (L\,N) + \frac{1}{\Lambda_b^2}(q_L b_R^c)^\dagger (\bar{L}\,\bar{N}) + \mathrm{h.c.}$$

Anomalies:

$$E_{TC} = 0$$

$$\frac{E}{N} = \frac{8}{3}$$

Neutrino masses can be generated by see-saw mechanism

$$\frac{1}{\Lambda_\nu^2}(L\nu_R^c)^\dagger(\bar{L}\,\bar{N}) + m^2(\nu_R^c)^2 + h.c.$$

$$m_\nu \sim \frac{v}{m}^2$$

If no right-handed neutrinos

$$\frac{1}{\Lambda_\nu^4}(\ell\bar{L})^2 N^2 \to \frac{1}{\Lambda_\nu^3}(\ell H_u)^2\sigma^2 + \cdots$$

Same order of magnitude.

PARTIAL COMPOSITENESS

$$\frac{G}{H} = \frac{SO(6)}{SO(5)} \simeq \frac{SU(4)}{\mathrm{Sp}(4)}$$

Gripaios, Pomarol, Riva, Serra '09
Redi, Tesi '12
Galloway et. al. '10

5 GBs:

$$5 = (2,2) + 1$$

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Gauging of SM gauge symmetry preserves

$$SU(2)_L \times U(1)_Y \times U(1)_{PQ}$$

Under $U(1)_{PQ}$ singlet shifts.

Sp(n) theories with 4 flavors

Fermions	$\mathrm{U}(1)_Y$	$SU(2)_L$	$SU(3)_\mathrm{c}$	$\mathrm{Sp}(n)_\mathrm{TC}$	$\mathrm{U}(1)_\mathrm{PQ}$
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Difficult to generate QCD anomaly

$(qu)(DS)$ $\qquad$ $(qu)(DS)(S\bar{S})$

We can be build models with partial compositeness

$$m\psi\Psi + M\Psi\Psi + g_{\mathrm{TC}}\Psi\Psi H$$

Fermions can couple to 6=(2,2)+2 × 1

$$q_L \to \frac{1}{\sqrt{2}} \begin{pmatrix} b_L \\ -ib_L \\ t_L \\ it_L \\ 0 \\ 0 \end{pmatrix} \qquad t_R \to \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ i\cos\theta\, t_R \\ \sin\theta\, t_R \end{pmatrix}$$

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For $\theta = \frac{\pi}{4}$ singlet becomes exact GB

PQ symmetry is anomalous due to tR rotations

$$E = 2\left[\left(\frac{4}{9}+\frac{1}{9}\right)3+1\right]N_F + E_{\rm TC}$$

$$\frac{E}{N} = \frac{8}{3} + \frac{E_{\rm TC}}{6} \qquad E_{TC} \sim n$$