Composite Higgses

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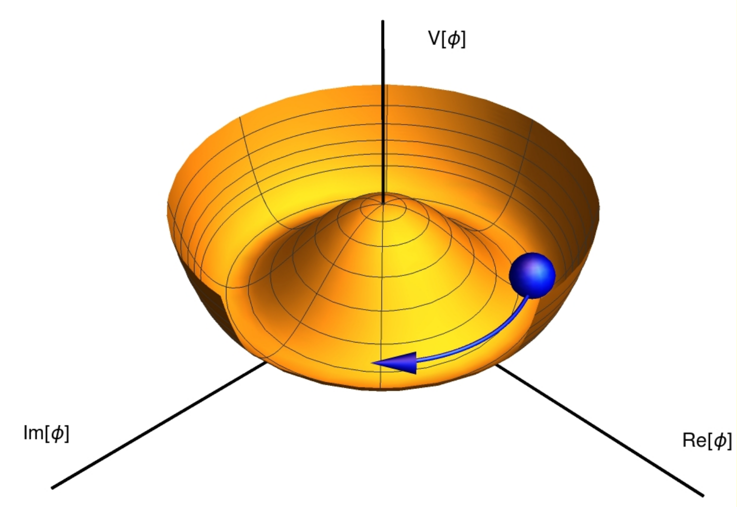
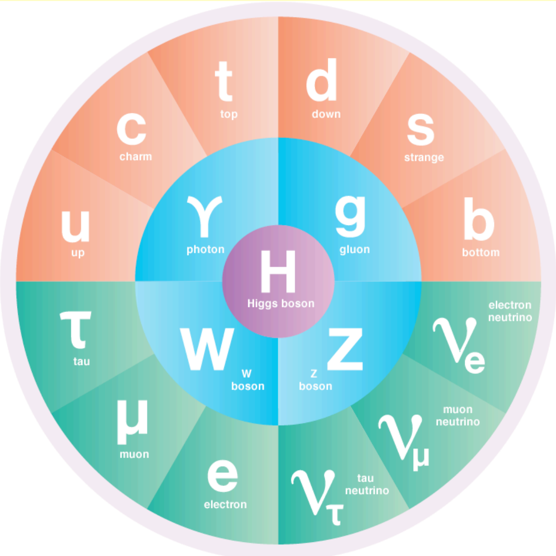
The Higgs

- Higgs discovery of 2012 establishes Higgs mechanism with a Higgs particle

$$V(H) = \lambda(|H|^2 - \frac{v^2}{2})^2$$

$$\langle H \rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix}$$





The Higgs

- Just a Landau-Ginzburg theory of superconductivity (in fact it was literally borrowed from there in 60's)

$$V(H) = \lambda(|H|^2 - \frac{v^2}{2})^2$$

- Except: in superconductivity: H is a bound state (Cooper pair), not an elementary field

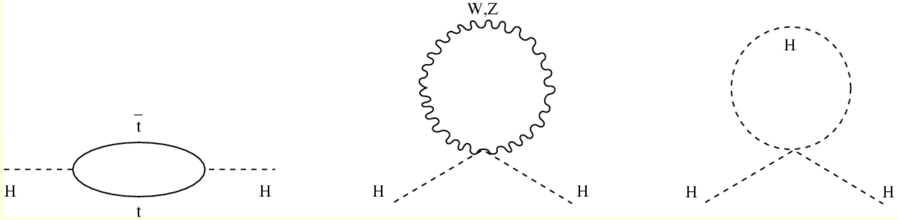
- What is H in particle physics?

- If elementary very problematic - hierarchy problem

Hierarchy problem

All elementary scalars expected to be **ultra heavy**

$$\Delta m_H^2 \propto \frac{g^2}{16\pi^2}\Lambda^2$$



Mass of Higgs not protected by symmetries (like fermion, gauge boson)

- Fermions protected by chiral symmetry
- Spin 1 gauge bosons protected by gauge symmetry

- In the limit **m→0** a new symmetry appears
- Symmetry forbids mass generation $\mathbf{\Delta m^2 \propto m^2}$
- Small masses could be natural

Possible solutions to the hierarchy problem

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FOCUS OF THIS TALK

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Composite Higgses

- We assume that Higgs NOT elementary, but composite. Most naive assumption: scale of compositeness Λ ~ 10 TeV

- Why 10 TeV? We know from LEP experiments that SM very good approximation up to operators suppressed by ~ $1/\Lambda^2$ where Λ>~ 5-10 TeV

- New bound states show up at Λ. What would be expected Higgs mass?

$$\Delta m_H^2 \propto \frac{g^2}{16\pi^2}\Lambda^2$$

- For Λ~10 TeV this is still ~ (1 TeV)^2 about 100 times too large…

The pNGB Composite Higgses

- Need an additional ingredient that further lowers the Higgs mass.

- Idea: Higgs also a pNGB

- What does this mean?

- Strong dynamics has a global symmetry G

- During confinement G→H breaking, which produces GB's. Some of these will be identified with SM Higgs

The pNGB Composite Higgses

- Why is this useful?

Global symmetry breaking scale: f

Cutoff scale (scale of generic composites): **Λ**

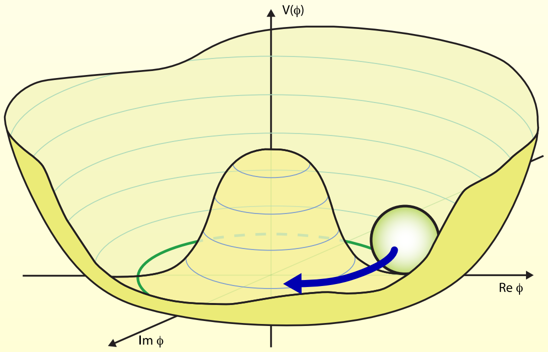
$$\Lambda \sim 4\pi f$$

- For **Λ**~10 TeV we find f~1 TeV, and IF corrections given by $f^2/(4\pi)^2$ then Higgs mass can be natural…
- New particles at f~1 TeV (top and spin 1 partners)

- This is eventually what is called ``composite Higgs model" - but need to understand details…

Theory of Goldstone bosons

- Best analogy is pions of QCD



- Use non-linear field

$$U(x) = e^{i\frac{\pi^a(x)}{f}T^a}\, U_0\, e^{i\frac{\pi^a(x)}{f}T^a} = e^{2i\frac{\pi^a(x)}{f}T^a}$$

- Pion has shift symmetry, forbids the potential

$$\pi'^a(x)T^a = \pi^a(x)T^a + f c^a T^a.$$

- Explicit breaking terms (quark mass, QED charges) will generate potential

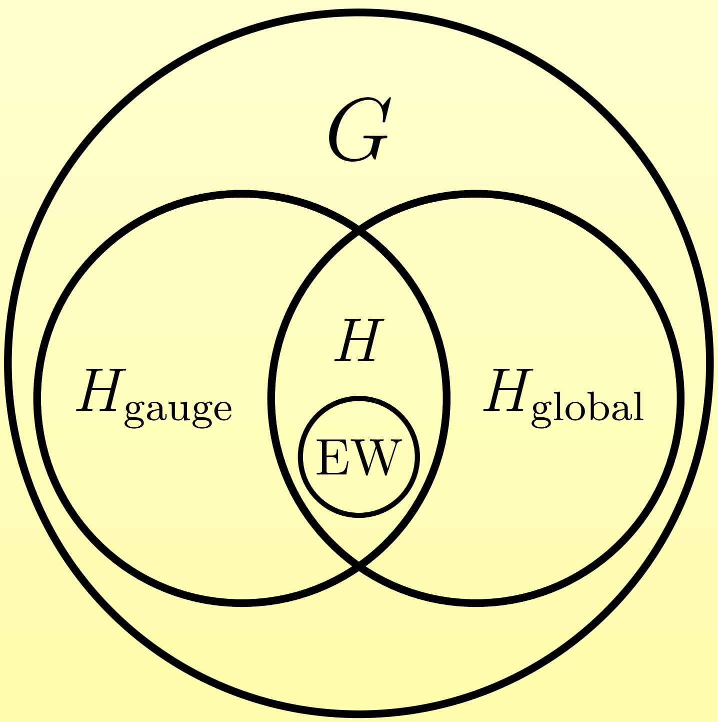
$$\Delta\mathcal{L} \sim \mathrm{Tr}\left[M U(x)\right] \sim \mathrm{Tr}\left[M\left(\frac{\pi^a(x)}{f}T^a\right)^2\right] + \cdots$$

$$\Delta\mathcal{L} \sim e^2\mathrm{Tr}\left[Q U(x)^\dagger Q U(x)\right]$$

General setup of pNGB Higgs

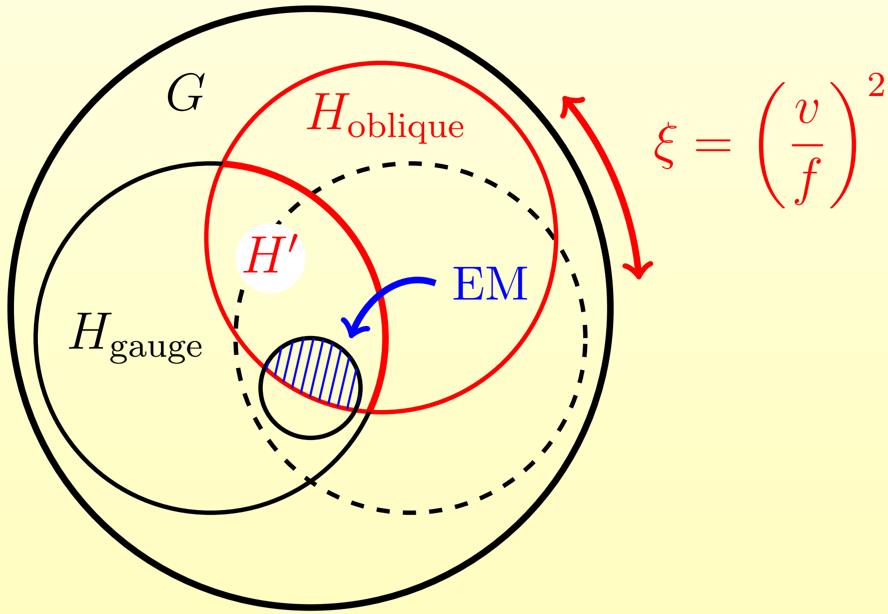
- Global symmetry breaking $G \to H_{\rm global}$

- Some subgroup $H_{\rm gauge}$ is gauged which contains $\mathrm{SU}(2)_{\rm L} \times \mathrm{U}(1)_{\rm Y}$. This is an explicit breaking - will generate a Higgs potential.



General setup of pNGB Higgs

- Due to the explicit breaking, there will be a vacuum misalignment generating the electroweak scale



- Misalignment angle $\xi = \left(\frac{v}{f}\right)^2$ separation of v and f

- ξ=0: SM limit. ξ=1: no separation, technicolor (like QCD, but large EWP corrections)

Collective symmetry breaking

- Generically explicit breaking reintroduces the quadratic divergence of the Higgs potential!
- Explicit breaking has to have a very special form to avoid quadratically divergent corrections!
- Basic idea: No single explicit breaking term itself will completely break the global symmetry
- Need 2 (or more) explicit breaking terms simultaneously to given mass to Higgs
- Presence of several insertions usually softens divergence and makes potential finite (or log div)

Simplest example of collective breaking

- Take SU(3)/SU(2) coset - will produce a doublet GB (+singlet - ignore for simplicity)

$$\mathcal{H} = \exp\left[\frac{i}{f}\begin{pmatrix} 0_{2\times 2} & H \\ H^\dagger & 0 \end{pmatrix}\right]\begin{pmatrix} 0 \\ 0 \\ f \end{pmatrix} = \begin{pmatrix} iH \\ f \end{pmatrix} - \frac{1}{2f}\begin{pmatrix} \\ H^+H \end{pmatrix}$$

- Enlarge SM fermion doublet to triplet $Q \to \Psi = \begin{pmatrix} Q \\ T \end{pmatrix}$

- T is top partner, and we need two right handed tops now (one for SM, one top partner)

- Yukawa coupling: $\mathcal{L}_{Yuk} = \lambda_1 \Psi \mathcal{H} t_c^1 + \lambda_2 f T t_c^2$

Simplest example of collective breaking

$$\mathcal{L}_{Yuk} = \lambda_1 \Psi \mathcal{H} t_c^1 + \lambda_2 f T t_c^2$$

- First term SU(3) invariant. Second term does not contain Higgs field. Need BOTH terms to make Higgs a pNGB and generate potential!

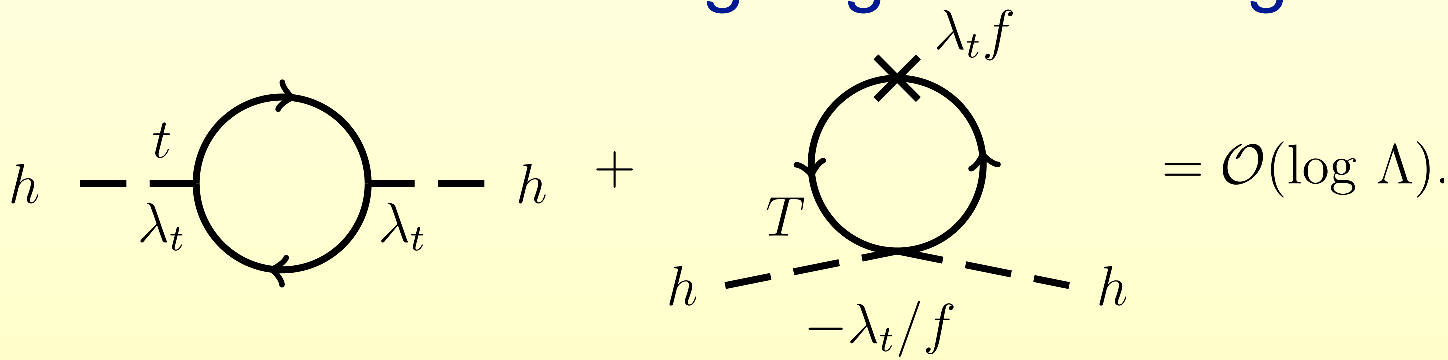
- Let us expand now $\mathcal{H}$ to get form of Yukawa coupling

$$\lambda_1 H(iQ) t_c^1 + \left(f - \frac{H^\dagger H}{2f} \right) T \lambda_1 t_c^1 + \lambda_2 f T t_c^2$$

- One loop quadratic divergence will cancel by collective breaking of SU(3) symmetry!

Simplest example of collective breaking

$$\lambda_1 H(iQ)t_c^1 + \left(f - \frac{H^\dagger H}{2f}\right) T\lambda_1 t_c^1 + \lambda_2 f T t_c^2$$

- Easiest to do WITHOUT going to mass eigenbasis
- 

- Leading pieces of two diagrams cancel - seems like a miracle but really governed by underlying symmetry

Minimal Composite Higgs (MCH)

- Most commonly used example. Reason: minimal setup where so called T-parameter is protected.

- G=SO(5), H=SO(4) = $SU(2)_L$ x $SU(2)_R$

$\mathrm{SO}(5) \to \mathrm{SO}(4)$ breaking via VEV of SO(5) vector

$$\langle\Sigma\rangle = (0,0,0,0,1)^T$$

- 4 Goldstone bosons - identified with Higgs

$$\Sigma = e^{ih^{\hat{a}}(x)T^{\hat{a}}/f}\langle\Sigma\rangle = \frac{\sin(h/f)}{h}\left(h^1, h^2, h^3, h^4, h\cot(h/f)\right).$$

$$H = \frac{1}{\sqrt{2}}\begin{pmatrix} h^1 + ih^2 \\ h^3 + ih^4 \end{pmatrix}.$$

Partial compositeness

- Best way to introduce fermionic partners: they will be assumed to be composite fermions from the strong sector.

- To couple them (for flavor physics): small mixing between SM (elementary) and heavy fermions

$$\Delta\mathcal{L} \sim \bar{Q}_L \mathcal{O}_{Q_L}$$

- Will result in

$$|\text{observed particle}\rangle \sim |\text{elementary}\rangle + \epsilon|\text{composite}\rangle.$$

- ε will control the flavor properties of the model - has wonderful automatic RS GIM mechanism (separate talk needed for that)

Classification of composite Higgs models

- There are many kinds of composite Higgs models - ``little Higgs", ``holographic Higgs", ``twin Higgs", ... What is the difference?

- The actual structure of the Higgs potential and the top/spin 1 partners cancelling the divergence

- SM Higgs potential:

$$V(h) = -\mu^2|H|^2 + \lambda|H|^4 \quad \longrightarrow \quad -\frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4}h^4$$

$$v^2 = \langle h \rangle = \frac{\mu^2}{\lambda} = 246 \text{ GeV} \qquad\qquad m_h^2 = 2\mu^2 = (125 \text{ GeV})^2 \,,$$

$$\mu = 89 \text{ GeV} \qquad\qquad \lambda = 0.13.$$

Classification of composite Higgs models

- Parametrization of the composite Higgs potential

$$V(h) = \frac{g_{\rm SM}^2 M^2}{16\pi^2}\left(-ah^2 + \frac{b}{2f^2}h^4\right)$$

- Assume potential loop induced (via explicit breaking) and cut off by partners of mass $M = g_* f$.

- Models differ by prediction for a, b and value of g_*

- Main difference quartic loop or tree-level

Classification of composite Higgs models

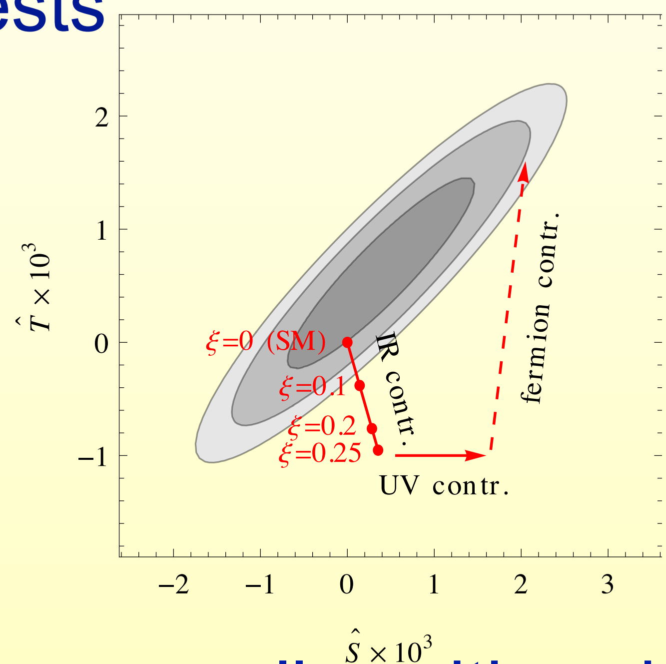
MODEL	$\mathcal{O}(a)$	$\mathcal{O}(b)$	$\mathcal{O}(g_*)$	COMMENTS
Bona-fide composite Higgs	1	1	4π	Requires tuning of both a and b.
Little Higgs	1	$\frac{16\pi^2}{g_*^2}$	$\ll 4\pi$	Tree level quartic, h too heavy.
Holographic Higgs	1	1	$\ll 4\pi$	$\sim$ little Higgs with loop-level quartic.
Twin Higgs	1	$1 - \frac{16\pi^2}{g_*^2}$	g_{SM}	$\mathbb{Z}_2$ rather than collective breaking.
Dilatonic Higgs	SEE TEXT			Related to RS radion Higgs.

- Initially little Higgs was most useful, since no little hierarchy there, v/f ~ 1/4π - completely natural EWSB BUT prediction for Higgs mass too high

- Now most popular holographic higgs, twin higgs

Experimental Signals of Composite Higgs

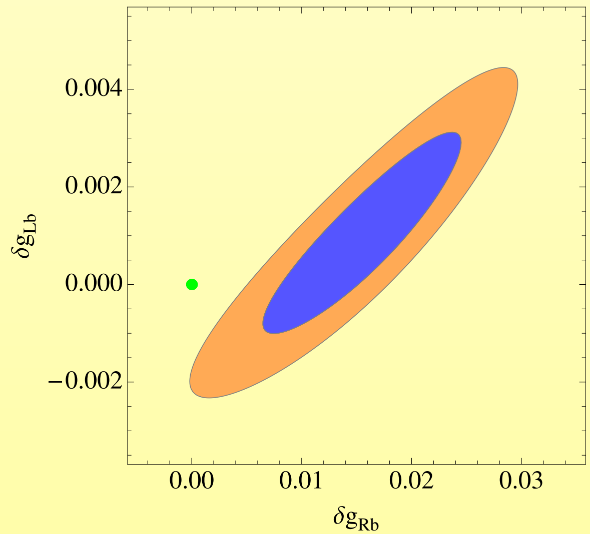
- **Electroweak precision** tests



- Universal (oblique)

- Non-universal (Zbb): fits favor small positive shift as in CH

$$\frac{\delta g_{Lb}}{g_{Lb}^{SM}} \sim \frac{y_t^2}{16\pi^2}\frac{v^2}{f^2}\log\frac{\Lambda^2}{m_\Psi^2}$$

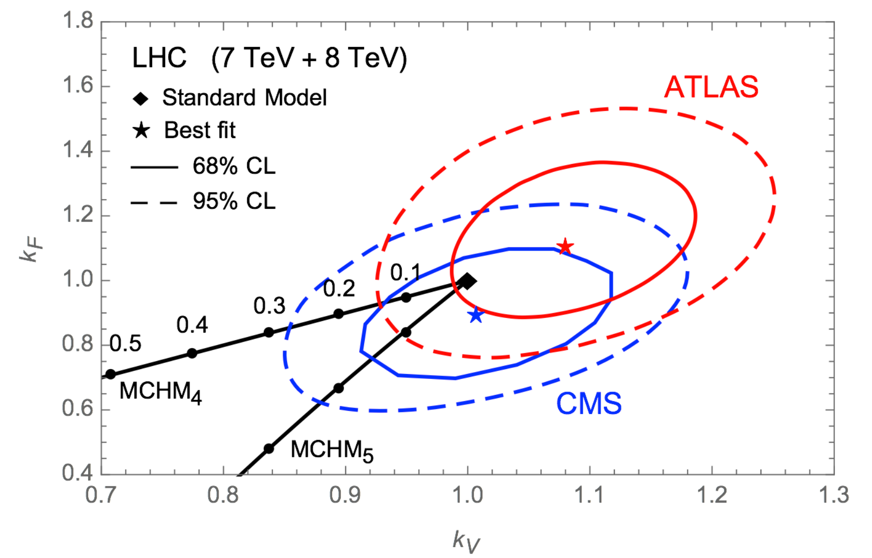


• Higgs physics

Single Higgs production

$$\mathcal{L}_{eff}^{(h)} = \left(c_V\left(2m_W^2 W_\mu^+ W^{-\mu} + m_Z^2 Z_\mu^2\right) - c_t m_t \bar{t}t - c_b m_b \bar{b}b - c_\tau m_\tau \bar{\tau}\tau\right)\frac{h}{v}$$
$$+\left(\frac{c_{\gamma\gamma}}{2}A_{\mu\nu}A^{\mu\nu} + c_{Z\gamma}Z_{\mu\nu}\gamma^{\mu\nu} + \frac{c_{gg}}{2}G^a_{\mu\nu}G^{a,\mu\nu}\right)\frac{h}{v},$$

coupling	SM	MCHM	Dilaton
c_V	1	$\sqrt{1-\xi}$	$\sqrt{\xi}$
c_ψ	1	$\frac{1-(1+n_\psi)\xi}{\sqrt{1-\xi}}$	$(1+\gamma_\psi)\sqrt{\xi}$
$c_{\gamma\gamma}$	0	0	$\frac{\alpha}{4\pi}(b_{IR}^{(EM)} - b_{UV}^{(EM)})\sqrt{\xi}$
$c_{Z\gamma}$	0	0	$\frac{\alpha}{4\pi t_W}(b_{IR}^{(2)} - b_{UV}^{(2)})\sqrt{\xi}$
c_{gg}	0	0	$\frac{\alpha_s}{4\pi}(b_{IR}^{(3)} - b_{UV}^{(3)})\sqrt{\xi}$



taken from 1506.01961

- **Higgs physics**

Double Higgs production

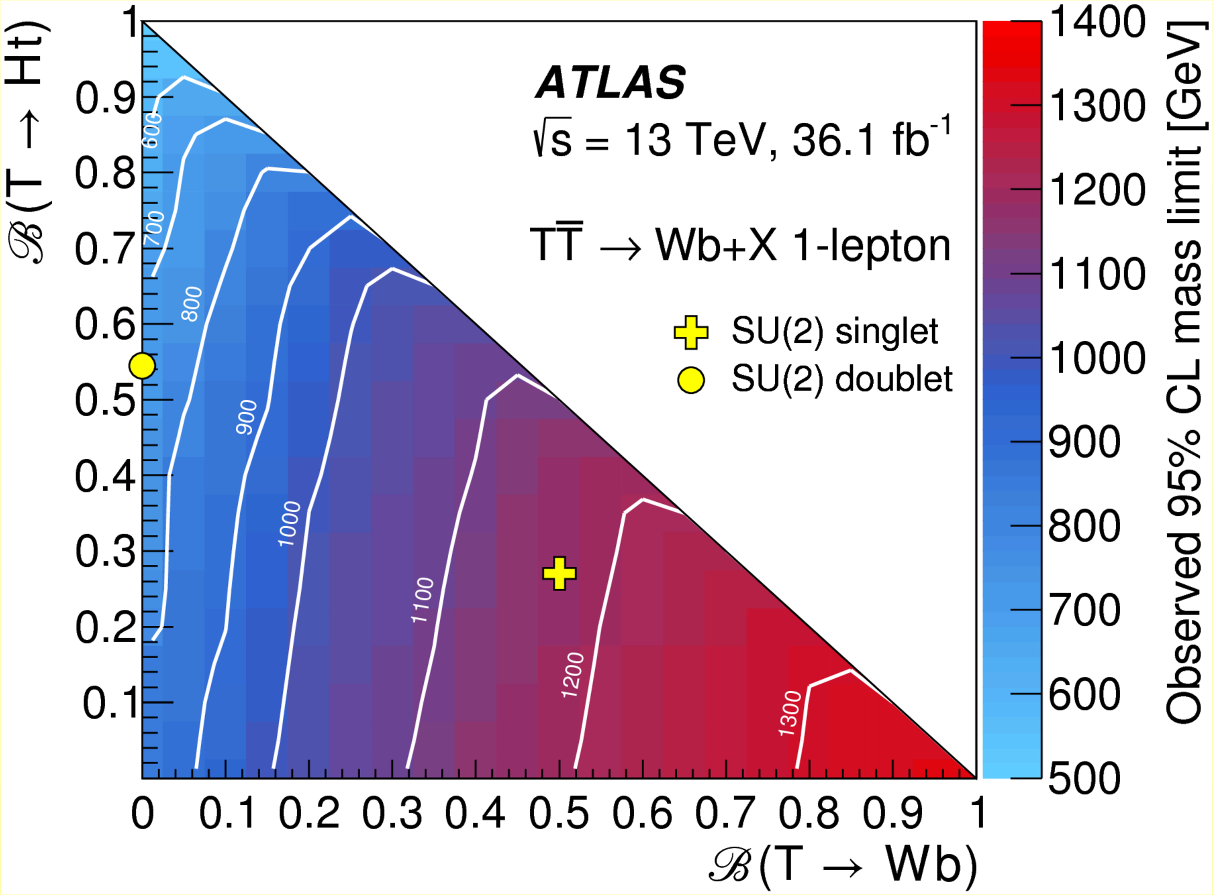
$$\mathcal{L}_{eff}^{(h^2)} = \left(\frac{d_V}{2} \left(m_W^2 W_\mu^+ W^{-\mu} + m_Z^2 Z_\mu^2 \right) - d_t m_t \bar{t}t - d_b m_b \bar{b}b - d_\tau m_\tau \bar{\tau}\tau \right) \frac{h^2}{v^2} + \left(\frac{d_{gg}}{2} G_{\mu\nu}^a G^{a,\mu\nu} \right) \frac{h^2}{v^2} - \frac{c_3}{2} \frac{m_h^2}{v} h^3 ,$$

coupling	SM	MCHM	Dilaton
d_V	1	$1-2\xi$	ξ
d_ψ	0	$\frac{-\xi(1+3n_\psi-(1+n_\psi)^2\xi)}{2(1-\xi)}$	$\frac{1}{2}\gamma_\psi\xi$
d_{gg}	0	0	$-\frac{\alpha_s}{8\pi}(b_{IR}^{(3)} - b_{UV}^{(3)})\xi$
c_3	1	$\frac{1-(1+\tilde{n}_\psi)\xi}{\sqrt{1-\xi}}$	$\frac{1}{3}(5 + d\beta/d\lambda)\sqrt{\xi}$

- **Direct bounds**

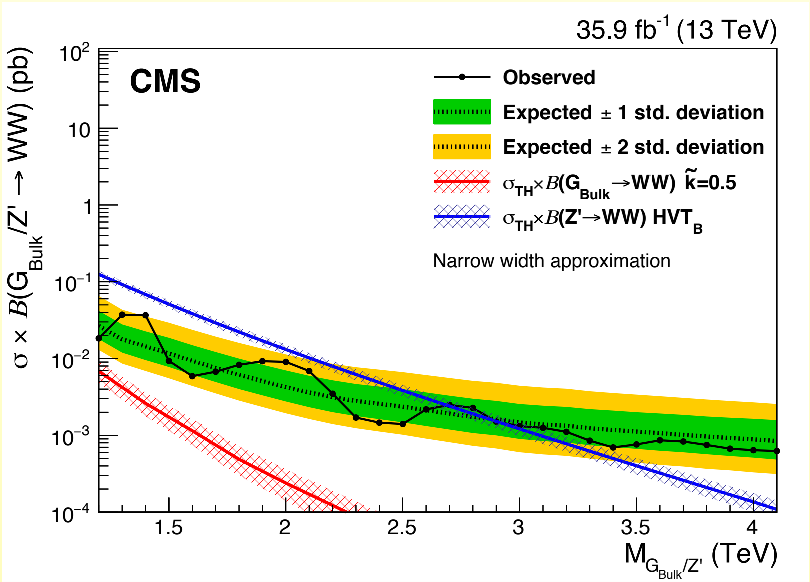
Spin 1/2 top partners

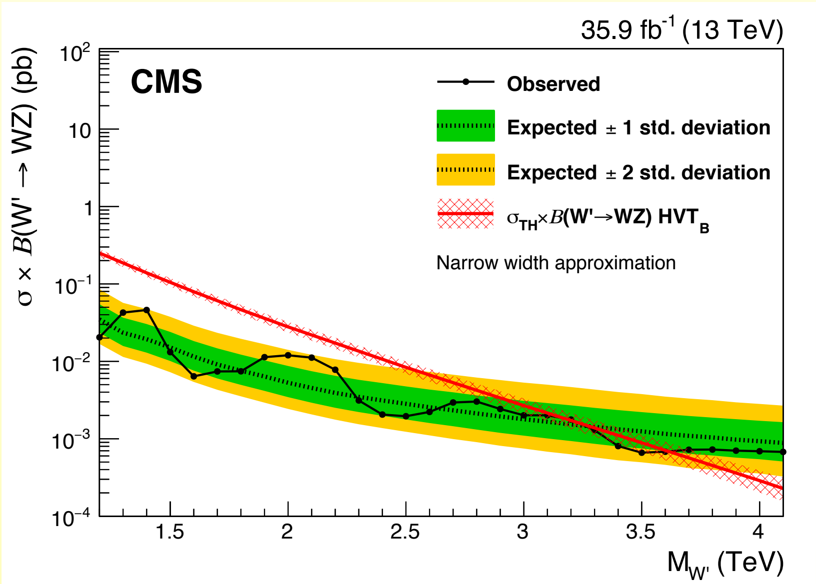
Recent CMS bound > 1.3 TeV



• **Direct bounds**

Spin 1 partners W', Z'





Recent new directions

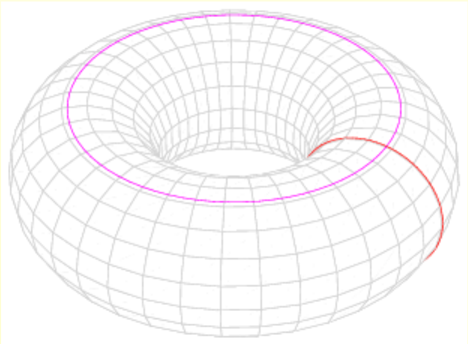
- First holographic CH with tree-level quartic - will help with tuning. Based on deconstruction of 6D model

- Maximal symmetry - a remnant of chiral symmetry of fermions will ensure minimal tuning of Higgs potential

Tree-level quartic for composite Higgs

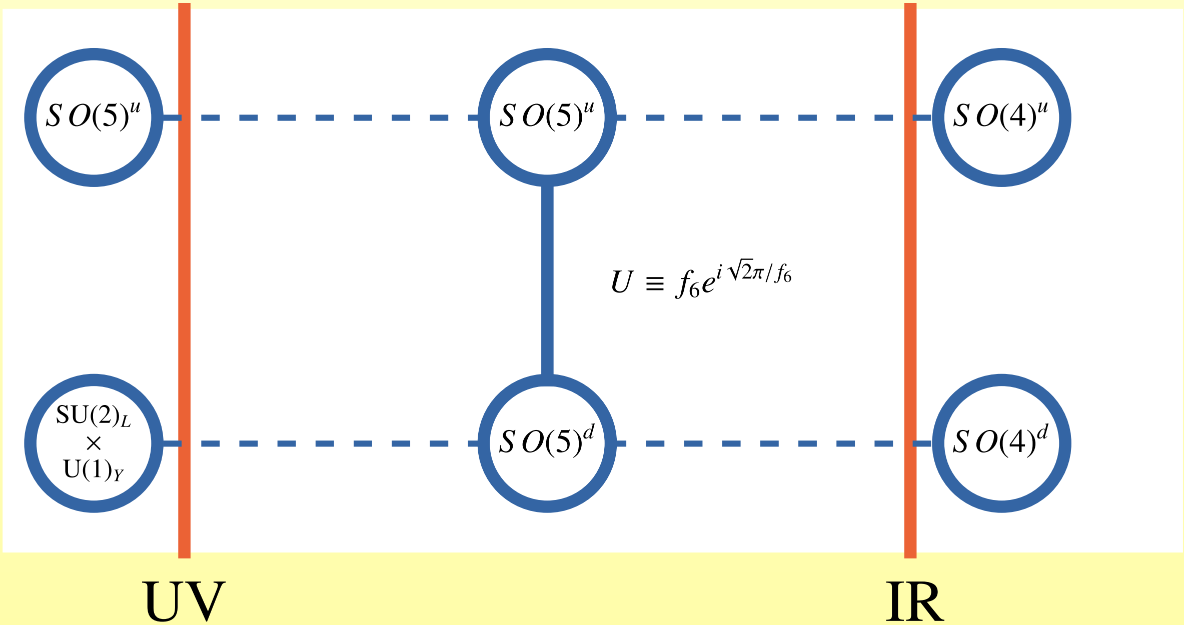
(Geller, Telem, C.C.)

- From the original 6D model



$$\mathrm{Tr}[A_5, A_6]^2 \in F_{56}F_{56}.$$

- Can find a simple warped 5D model version

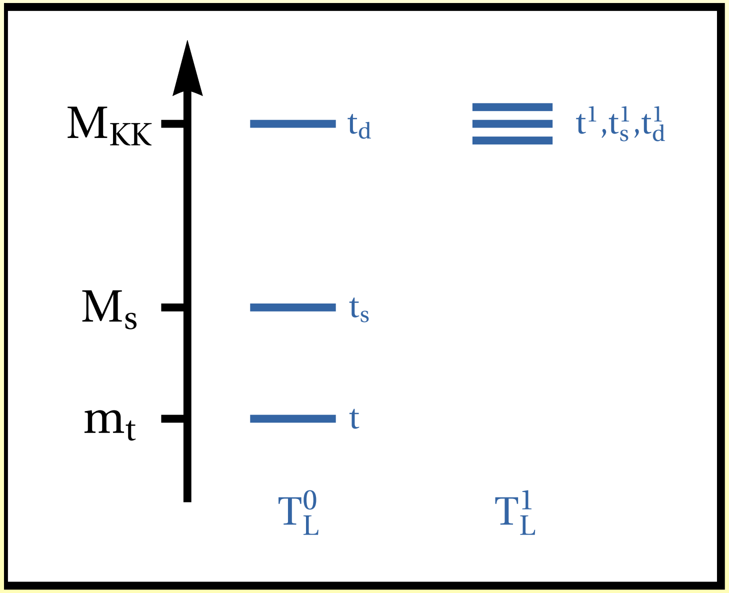


Tree-level quartic for composite Higgs

(Geller, Telem, C.C.)

• Tree-level quartic adjustable in model but need two Higgs doublets!

• Top sector can easily lift the second Higgs doublet



• Also double KK spectrum

• New charged Higgses
(2HDM model in the decoupling limit, 300-500 GeV states)

Maximal symmetry for Composite Higgs

- A novel symmetry in the top sector (Ma, Shu, C.C.)

- In many constructions there is an object called ``Higgs-parity” where H→ -H implemented by V.
  Eg. in SO(5) V=diag(1,1,1,1,-1) flips sign of Higgs

- In some interesting cases there could be novel kind of symmetry breaking patterns involving V

- Assume that composites fill out complete representation of SO(5) (in MCH implementation)

- Possible explicit breaking patterns:

$$M_Q - M_S = 0 \Rightarrow SO(5)_L \times SO(5)_R/SO(5)_V$$

$$M_Q + M_S = 0 \Rightarrow SO(5)_L \times SO(5)_R/SO(5)_{V'}$$

$$|M_Q| \neq |M_S| \Rightarrow SO(5)_L \times SO(5)_R/SO(4)_V$$

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$$|M_Q| \neq |M_S| \Rightarrow SO(5)_L \times SO(5)_R / SO(4)_V$$

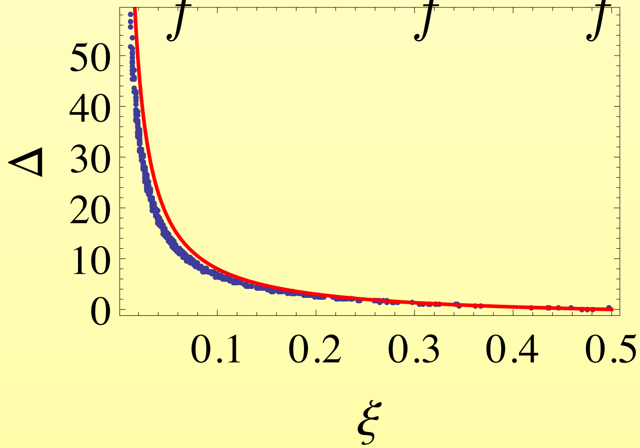
Maximal symmetry for Composite Higgs

(Ma, Shu, C.C.)

- An unusual symmetry $SO(5)_{V'}$ given by $L\, V\, R^{+} = V$
- Important: an explicit breaking (since it does NOT agree with the original SO(5)) but automatically collective! In fact Higgs potential automatically finite
- Turns out Higgs potential also automatically has minimal tuning (has Z_2 symmetry similar to Twin Higgs)

$$V \propto \sin^2 \frac{2h}{f} \propto \sin^2 \frac{h}{f} \cos^2 \frac{h}{f} \propto \sin^2 \frac{h}{f} - \sin^4 \frac{h}{f}$$

$$\Delta \simeq \frac{1}{2\xi}$$



Conclusions

- Composite pNGB Higgs may solve the hierarchy problem

- Need collective breaking for Goldstone's thm to actually help with divergences +partial compositeness for flavor

- Same spin partners would cancel divergences - this is what LHC is searching for (so far no luck)

- As bounds get stronger tuning will soon start increasing from those set by LEP

- New directions based on adjustable quartic/maximal symmetry could help reduce the tuning