Composite Higgs: Model Building and Phenomenology

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Plan of Talk

- Motivation
- The Composite Higgs program
- Minimal & Non-Minimal Frameworks
- Constraints and phenomenology
- UV completion
- Conclusions

Quest for Naturalness!

SM particle content:

(1) Fermions ⇨ Chiral symmetry

(2) Vector bosons ⇨ Gauge symmetry

(3) Higgs Fields ⇨ ?

Decades of intense research:

Supersymmetry & **Shift-Symmetry**

⇩

Composite Higgs Models as PNGBs

Unitarity, Naturalness and New Physics

- No Higgs → Unitarity violation
- Adding new scalar →Gauge Hierarchy → NP at the TeV Scale

Higgs is elementary with SM like couplings.
NP responsible for making the theory NATURAL

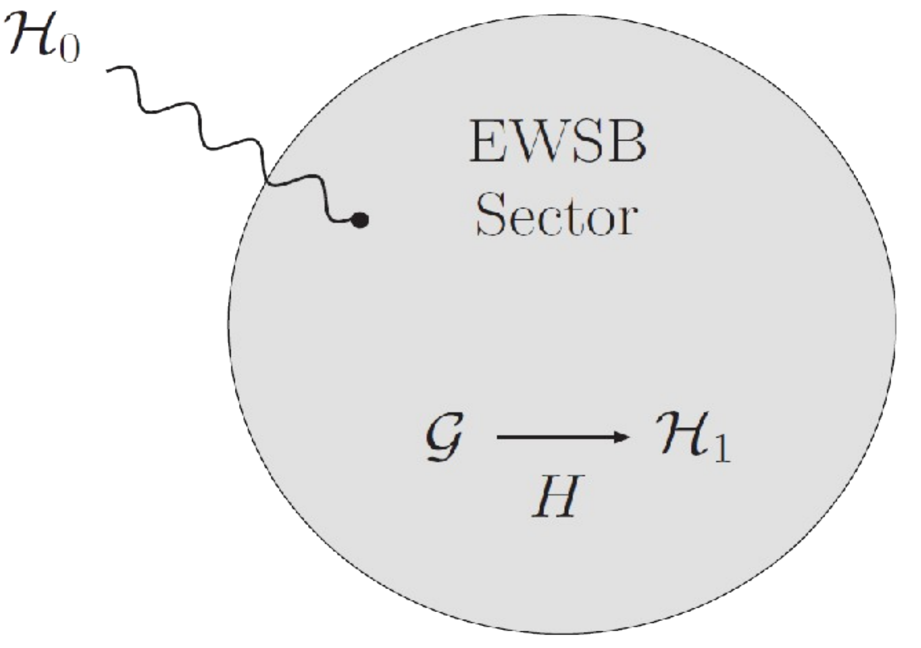
SUSY

Higgs is composite thus natural, but couples to the elementary SM fields through momentum dependent structure functions. NP responsible for unitarizing the theory

COMPOSITE HIGGS

Composite Higgs as PNGB

- Consider a large symmetry group G that spontaneously breaks to a subgroup H_1 due to some strong dynamics at scale ***f.***
- Consider that: H_1 contains H_0 = $SU(2)_W \times U(1)_Y$
- The spontaneous breaking will lead to Goldstone modes that live in the coset space: H = G /H_1
- If the original gauge group is slightly perturbed, the Goldstone modes will acquire mass and become pseudo-Goldstone Bosons



Couples to SM fields → nontrivial derivative couplings → **Unitarity violation** (assume strong sector take care of this)

The masses of the pseudo-Goldstone modes are naturally light by the Goldstone theorem (Shift-Symmetry).
They are insensitive to dynamics beyond strong coupling scale f.
SOLUTION TO HIERARCHY PROBLEM.

The Composite Higgs Program

Symmetry Breaking vev

Coset

Identify your Coset: G /H$_1$

$$\Sigma \equiv \Sigma_0 Exp(\Gamma(x)/f)$$

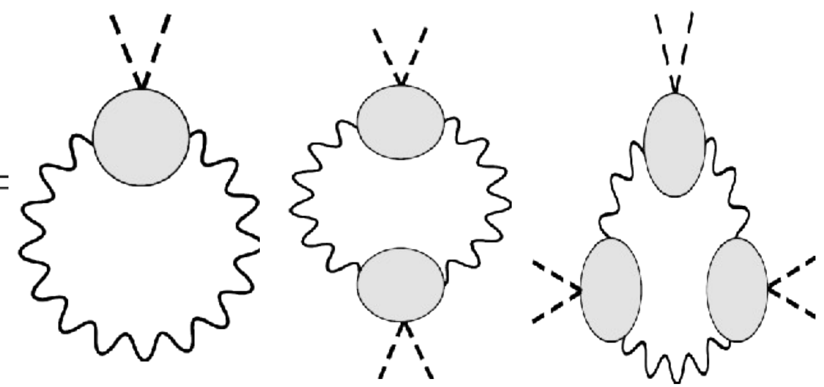
$$\mathcal{L} = \frac{1}{2}(P_T)^{\mu\nu}\left[\Pi_0(q^2)\,\mathrm{Tr}(A_\mu A_\nu) + \Pi_1(q^2)\,\Sigma A_\mu A_\nu \Sigma^t\right],$$

Choose your Fermion representations

$$\mathcal{L}_f = \sum_{r,s=q_L,u_R,d_R} \mathrm{tr}\left(\overline{\Psi}_r\, \not{p}\left[\Pi_0^{rs}(q) + \Pi_1^{rs}(q) g(\Sigma)\right] \Psi_s\right) + \sum_{r=u_R,d_R} \mathrm{tr}\left(\overline{\Psi}_r \left[M_0^r(q) + M_1^r(q) g(\Sigma)\right] \Psi_{q_L}\right)$$

Compute the Coleman-Weinberg Potential

$$\mathbf{V}(\mathbf{\Sigma}) =$$



Contino, arXiv:1005.4269 [hep-ph]

Structure Functions: Effective Description

Schematically the entire Lagrangian can be written as

$$\mathcal{L}_{tot} = \mathcal{L}_{strong} + \mathcal{L}_{mix} + \mathcal{L}_{SM+Higgs}$$

Interestingly one can do without describing the strong sector. One simply need to assume a linear mixing between the two sectors:

$$\mathcal{L}_{\rm mix} = \bar{q}_L \mathcal{O}_R + \bar{t}_R \mathcal{O}_L + A_g^\mu \mathcal{J}_\mu + \dots$$

Integrating out the composite operators and using the large N approximation one finds:

$$\mathrm{M}(\mathrm{p}^2) \sim \langle \mathcal{O}_L(p) \bar{\mathcal{O}}_R(-p) \rangle \sim \sum_{n=1}^{\infty} \frac{b_n F_n^L F_n^{R*} m_{Q_n}}{p^2 - m_{Q_n}^2} \Big|_{largeN}$$

Minimal Composite Higgs

Identify your Coset: G /H$_1$

$$SO(5)/SO(4) \equiv 4NGB's$$

$$\Sigma = \frac{\sin(h)}{h}(h^1, h^2, h^3, h^4, h\cot(h/f))$$

$$h = \Sigma_{i=1}^{4} h_i^2$$

Choose your Fermion representations

$$Q_L = Q_R \sim 5, 10$$

$$L_{top;5} = \frac{\sin(h/f)\cos(h/f)}{\sqrt{2}}\bar{t}_L M_1^t(P) t_R + h.c.$$

Compute the Coleman-Weinberg Potential

$$V(h) \sim \alpha \sin^2(h/f) - \beta \sin^2(h/f)\cos^2(h/f)$$

$$m_h^2 \sim \frac{8\beta}{f^2}\langle s_h^2 c_h^2 \rangle$$

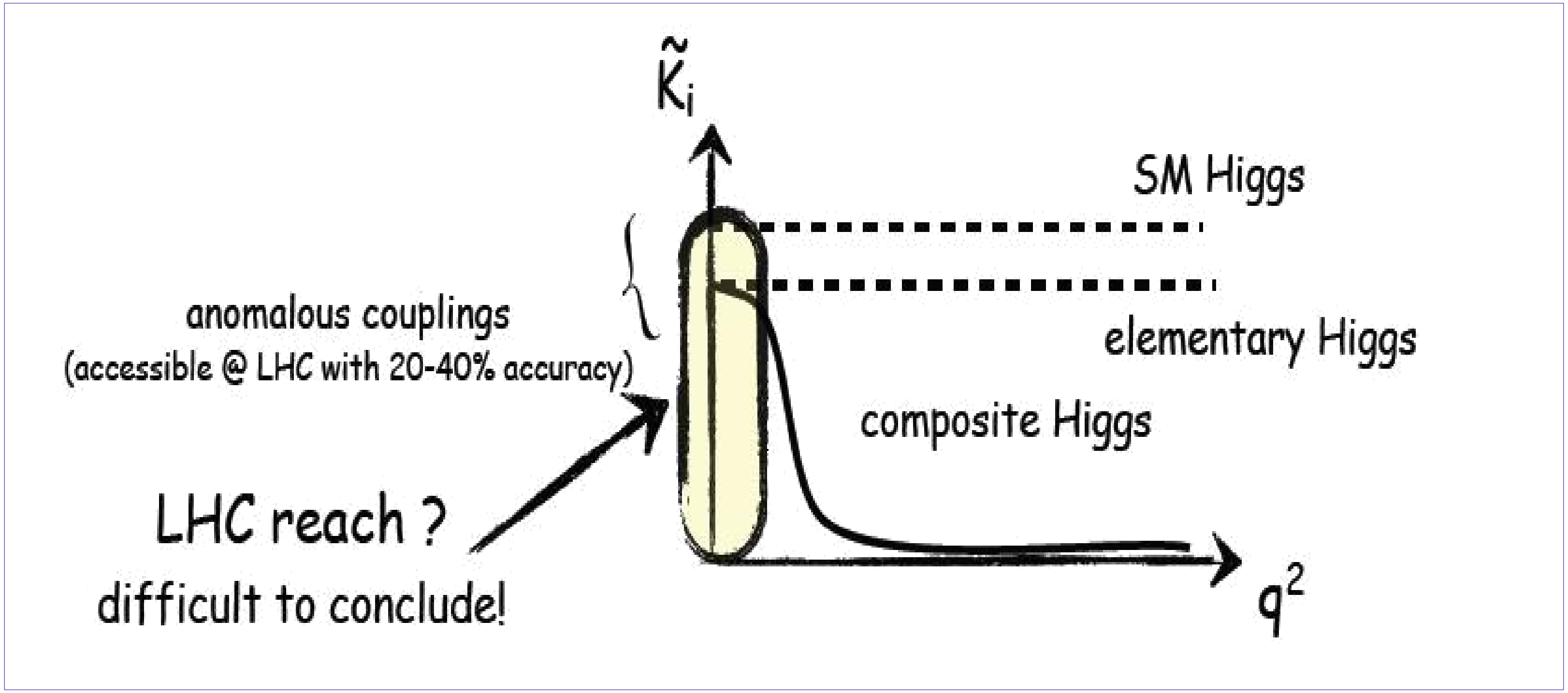
Incomplete List of Other Cosets in the Literature

Dark matter possibility

N_G	$\mathcal{G}$	$\mathcal{H}_1$	Fermion rep.	Authors	References
4	SU(3)	SU(2) × U(1)	3	Contino et al	arXiv:hep-ph/0306259v1
4	SO(5)	SO(4)	4	Agashe et al	arXiv:hep-ph/0412089v2
4	SO(5)	SO(4)	5,10	Contino et al	arXiv:hep-ph/0612048v1
5	SO(6)	SO(5)	6	Gripaios et al	arXiv:0902.1483v1 [hep-ph]
8	SO(6)	SO(4)×SO(2)	6,(20,1)	Mrazek et al	arXiv:1105.5403v1 [hep-ph]
8	SU(5)	SU(4)× U(1)	5,10	Bertuzzo, Savoy Sandes, TSR	JHEP **1305** (2013) 153
8	Sp(6)	Sp(4) ×SU(2)	14,21		
8	SO(9)	SO(8)	9,16		
9	SU(5)	SU(4)	5,10		

Custodial and flavor-safe natural C2HDM

Modified Higgs Interactions



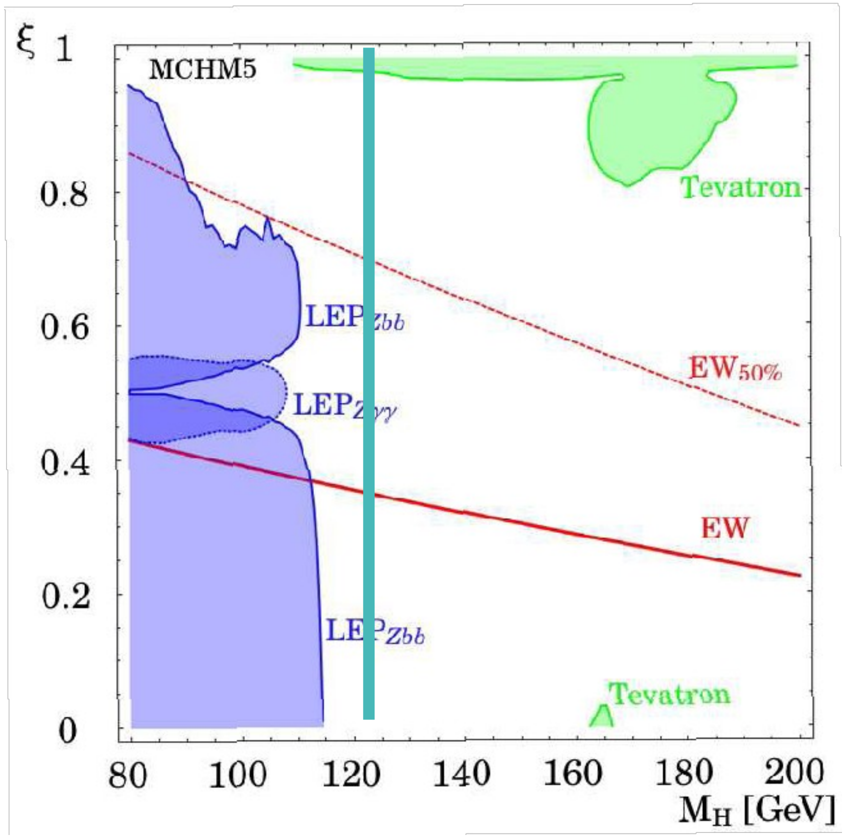
No chance of examining the scaling of the coupling at LHC/ILC.
Can only probe deviations from SM value at low scale.

Taken from a talk by Grojean, Planck, 2011

Modified Higgs Interactions and the Electroweak Precision Tests

$$g_{hxx} = g^{SM}_{hxx}\sqrt{1-\xi} \quad g_{hhxx} = g^{SM}_{hhxx}(1-2\xi)$$

$$\xi = \frac{v^2}{f^2}$$

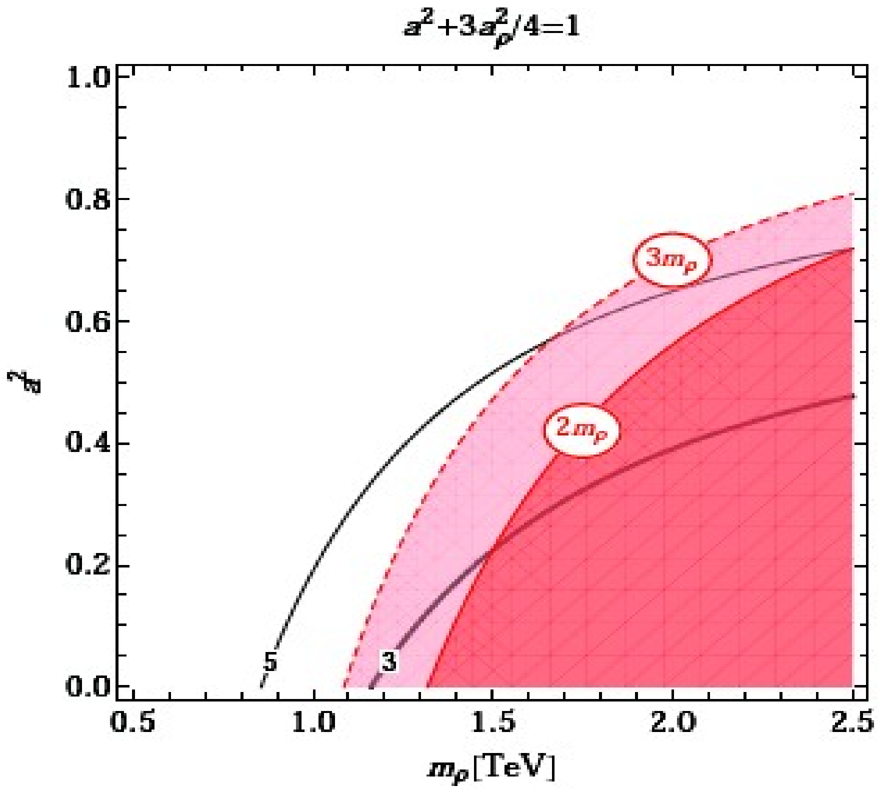


- Coset has a large enough residual symmetry to protect the T parameter at tree level
- The embedding of the fermions in 5,10 provides a global symmetry to protect the Zb$_L$ b$_L$ coupling
- Theory is constrained mainly from the non-decoupling contribution to the S parameter

Espinosa et al, JHEP 1005:065,2010

Search for Resonances of the Strong Sector

There will be weak vector resonances in the strong sector that will unitarize the theory.



$$\rho^{\pm} \to W^{\pm} Z \to 3l + \nu.$$

Bellazzini, Csaki, Hubisz, Serra and Terning, JHEP 1211 (2012) 003

Composite Higgs Mass - Top Partner Connection: Minimal Model

The Higgs potential is radiatively generated by the Higgs couplings that explicitly break the global symmetry. These are the Yukawa and gauge interactions.

$$\mathcal{L}_{\rm eff} = \bar{t}_L \not{p} \left[\Pi_L^0(p^2) + \mathcal{Y}_L(h/f)\Pi_L^h(p^2)\right] t_L + \bar{t}_R \not{p} \left[\Pi_R^0(p^2) + \mathcal{Y}_R(h/f)\Pi_R^h(p^2)\right] t_R + \left[\bar{t}_L \mathcal{Y}_M(h/f) M(p^2) t_R + \text{h.c.}\right],$$

Computation of the C-W potential with the Lagrangian.

$$V_{\rm eff}(h) = -2N_c \int \frac{d^4 p_E}{(2\pi)^4} \ln\left(-p_E^2 \left[\Pi_L^0(p_E^2) + \mathcal{Y}_L(h/f)\Pi_L^h(p_E^2)\right]\left[\Pi_R^0(p_E^2) + \mathcal{Y}_R(h/f)\Pi_R^h(p_E^2)\right] - \left|\mathcal{Y}_M(h/f) M(p_E^2)\right|^2\right),$$

$$\Pi_{L/R}(p^2) = \sum_{n=1}^{\infty} \frac{a_n |F_n^{L/R}|^2}{p^2 - m_{Q_n}^2}, \qquad M(p^2) = \sum_{n=1}^{\infty} \frac{b_n F_n^L F_n^{R*} m_{Q_n}}{p^2 - m_{Q_n}^2},$$

Minimizing the potential to get the Higgs mass

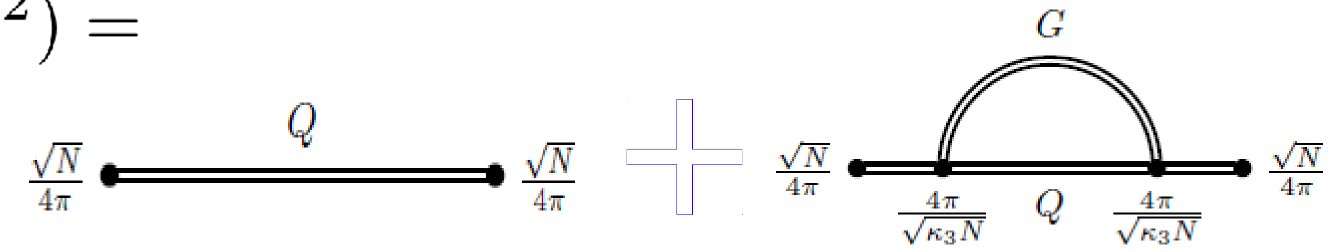
$$\mathrm{m}_h^2 \geq \frac{2N_c}{\pi^2}\frac{m_t^2}{f^2}\int_0^\infty dp\, p \left|\frac{M_1^t(p)}{M_1^t(0)}\right|^2 \sim \frac{3}{\pi^2}\frac{m_t^2}{f^2} m_Q^2,$$

Beyond Minimal Framework:
One Loop Correction to the Strong Sector from KK Gluon

The strong sector that mixes with the SM linearly should also include the SU(3) color and correspondingly colored ρ mesons!

Including the colored mesons we should get:

$$\mathrm{M}(\mathrm{p}^2) =$$

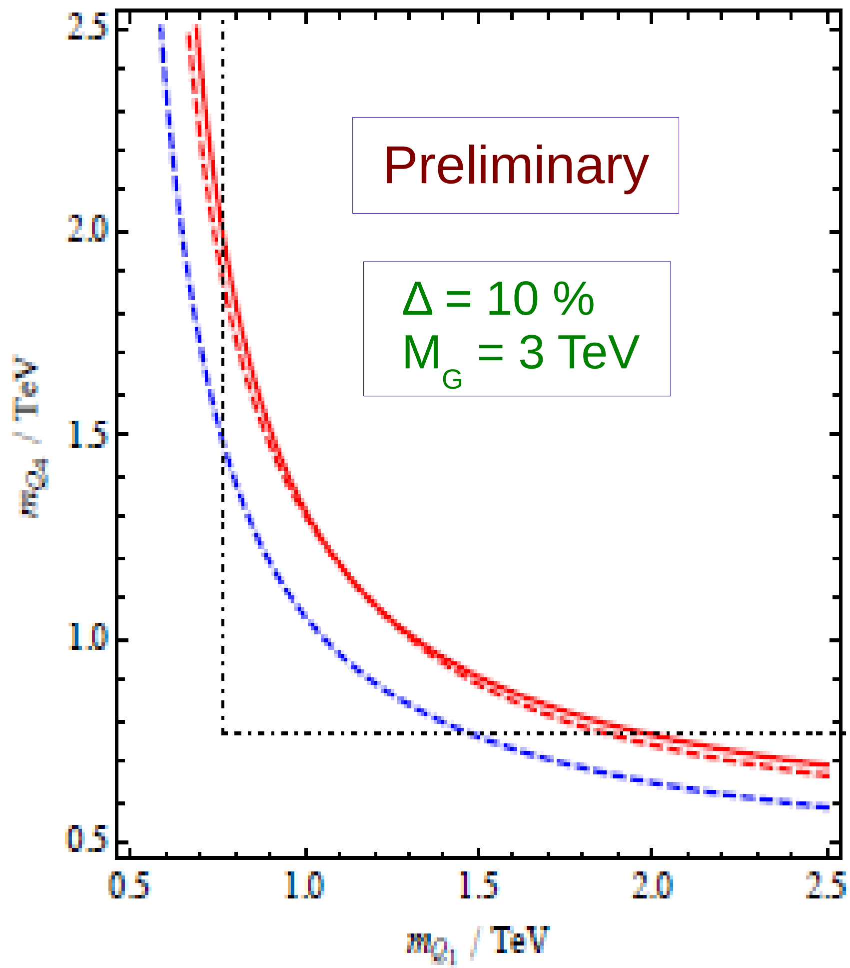


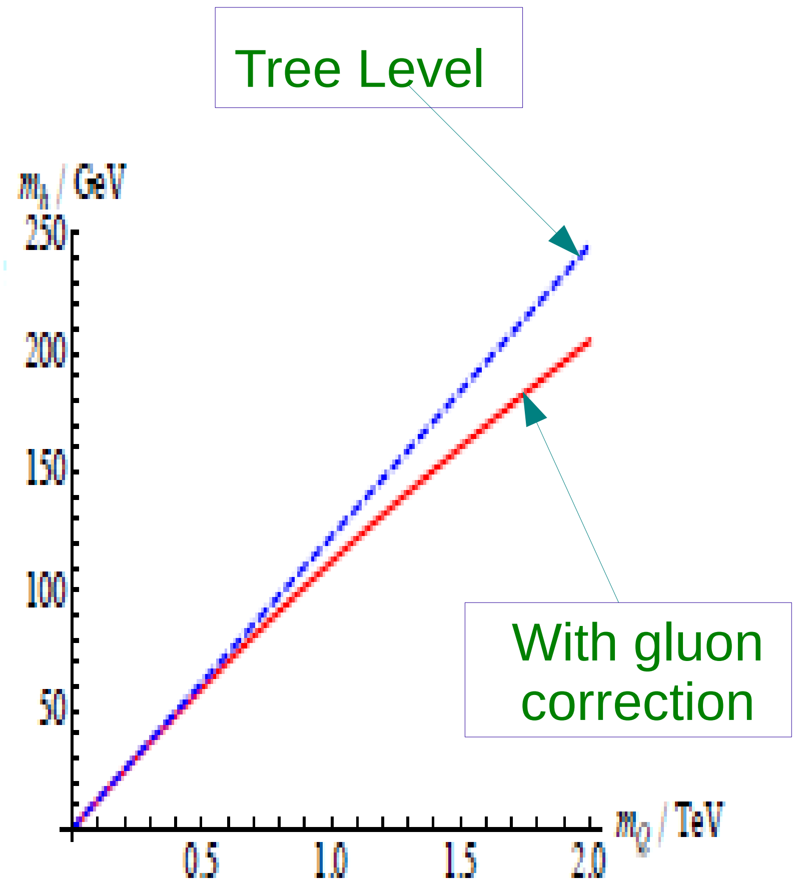
$$\frac{\text{one loop}}{\text{tree}} = \frac{(N/16\pi^2) \times (16\pi^2/\kappa_3 N) \times (C_2(N_c)/16\pi^2)}{(N/16\pi^2)} \approx \frac{1}{\pi}$$

Large N, Holography and explicit 5d calculations give consistent result!

Tony Gherghetta, James Barnard, Anibal Medina,TSR, Under preparation

Higgs Mass and Light Top Partner Connection





KK Gluon correction leads to 10-15% change in Higgs mass

Gherghetta, Barnard, Medina, TSR, Under preperation

Situation may change in non-minimal models, work in progress, Volkas, Dutka, TSR

UV Completion: $\mathcal{L}_{\text{strong}}$

(1) Consider that the strong sector has conformal invariance and is holographic view of a 5d dual theory with warped geometry.

Gherghetta, arXiv:1008.2570 [hep-ph]

(2) The strong sector has a perturbative UV free Sieberg dual which is supersymmetric.

Caracciolo, Parolini, Serone, JHEP 1302 (2013) 066

(3) Is an entirely fermionic UV completion of the composite models possible?

Consider a set of fermions charged under some gauge group G_c , having a global exchange/flavor symmetry G. Certain gauge invariant fermion condensates can develop vev to break the global group G to H.

The question is whether G can be broken to a subgroup H in such a way that a mass term for the fermions charged under the unbroken symmetry is forbidden? Use NJL framework to study this.

Tony Gherghetta, James Barnard, TSR, Under preparation

Consider $(2N_f + 1)$ Weyl fermions Ψ and 1 additional state ξ with the following charges:

1

Gauge

Global

	$Sp(2N_c)$	$SO(2N_f+1)$
ψ	$\square$	$\square$
ξ	$\square$	1

The condition that the theory is UV free and confines at low scales is given by:

$$(11\ \mathrm{N}_c - 2N_f + 9) > 0$$

2

Leading order 4 fermion NJL Lagrangian:

No fermion mass terms from gauge+flavor invariance

3

$$\mathcal{L} = i\psi^{ia}\sigma^\mu\partial_\mu\bar{\psi}_{ia} + i\xi^i\sigma^\mu\partial_\mu\bar{\xi}_i + \frac{g_{AS}}{2N_c}(\epsilon_{ij}\psi^{ia}\psi^{jb})(\epsilon^{kl}\bar{\psi}_{ka}\bar{\psi}_{lb}) + \frac{g_{AB}}{2N_c}\left[(\epsilon_{ij}\psi^{ia}\psi^{jb})(\epsilon_{kl}\psi^{ka}\psi^{lb}) + \mathrm{h.c.}\right] + \frac{g_{FS}}{2N_c}(\epsilon_{ij}\psi^{ia}\xi^j)(\epsilon^{kl}\bar{\psi}_{ka}\bar{\xi}_l) + \frac{g_{FB}}{2N_c}\left[(\epsilon_{ij}\psi^{ia}\xi^j)(\epsilon_{kl}\psi^{ka}\xi^l) + \mathrm{h.c.}\right]$$

Let us introduce the auxiliary scalars:

$$M_A^{ab} = -\frac{g_{AS}}{2N_c}\epsilon_{ij}\psi^{ia}\psi^{jb}$$

$$M_F^a = -\frac{g_{FS}}{2N_c}\epsilon_{ij}\psi^{ia}\xi^j$$

M_A	1	$\begin{array}{c}\square\\[-4pt]\square\end{array}$
M_F	1	$\square$

Derive C-W Potential, M gets a vev: breaks $SO(2N_f+1) \rightarrow SO(2N_f)$

4

Conclusions

- Composite Higgs models provide a natural and predictive framework of electroweak symmetry breaking.

- Deviations in Higgs couplings and resonances of the strong sector are the main phenomenology of the theory. Experimental measurements already put considerable bounds on the parameter space.

- Going beyond the minimal framework provides potential relaxation with existing experimental tensions and deeper understanding about the theoretical foundations of the models.

- UV completion remains an open question which deserves greater attention.

Thank you!

Backup

Higgs Couplings & Unitarity

$$\mathcal{L}_H = \frac{1}{2}(\partial_\mu h)^2 + V(h) + \frac{v^2}{4}\mathrm{Tr}\left[(D_\mu\Sigma)^\dagger (D_\mu\Sigma)\right]\left(1 + \mathbf{2a}\frac{\mathbf{h}}{\mathbf{v}} + \mathbf{b}\frac{\mathbf{h^2}}{\mathbf{v^2}} + \ldots\right)$$

$$-\frac{v}{\sqrt{2}}\sum_{i,j}\left(\bar{u}_L^{(i)} d_L^{(i)}\right)\Sigma\left(1 + \mathbf{c}\frac{\mathbf{h}}{\mathbf{v}} + \cdots\right)\begin{pmatrix}\lambda_{ij}^u\, u_R^{(j)} \\ \lambda_{ij}^d\, d_R^{(j)}\end{pmatrix} + h.c.$$

Effective Lagrangian with structure functions to account for the derivative couplings of Goldstone mode

$$a, b, c \sim 1 - \epsilon_{a,b,c}(p)$$

Unitarity of WW scattering:

$$\mathcal{A}(\chi^+\chi^- \to \chi^+\chi^-) = \frac{s+t}{v^2}(1-a^2) + O\left(\frac{m_h^2}{E^2}\right)$$

Theory unitarized up to: $\sqrt{s} = 4\pi v/\sqrt{(1-a^2)}$.

SM: a=b=c=1

C2HDM:

$$\mathcal{L} = f^2 \left(\partial^\mu u^\dagger \partial_\mu u - u^\dagger \partial_\mu u \, \partial^\mu u^\dagger u\right) \quad [SU(5)/SU(4) \times U(1)]$$

$$= f^2 \left(\partial^\mu u^\dagger \partial_\mu u - \tfrac{3}{8} u^\dagger \partial_\mu u \, \partial^\mu u^\dagger u\right) \quad [SU(5)/SU(4)]$$

$$\mathcal{L} = f^2 \mathrm{tr} \left(\partial^\mu u^\dagger \partial_\mu u - u^\dagger \partial_\mu u \, \partial^\mu u^\dagger u\right) \quad (SU(4)/SU(2)^2 \times U(1))$$

$$\mathcal{L} = f^2 \mathrm{tr} \left(\partial^\mu u^\dagger \partial_\mu u - \partial^\mu u^\dagger u u^\dagger \partial_\mu u\right) \quad (Sp(6)/Sp(4) \times SU(2))$$

Special embedding may result in custodial symmetry

$$\frac{\mathcal{M}^2_{AB}}{g_A g_B} = u^\dagger \{T^A, T^B\} u - \kappa \, u^\dagger T^A u \, u^\dagger T^B u$$

Custodial symmetry breaking at tree level

$$\mathcal{L} = f^2 \mathrm{tr} \left(\partial^\mu u^T \partial_\mu u\right) \quad (SO(9)/SO(8))$$

This model has no tree level custodial symmetry violation owing to the simple structure of the coset metric!

Bertuzzo, TSR, Sandes, Savoy, JHEP 05 (2013) 153

More on the SO(9)/SO(8) Model

Embedding the SM in SO(8):

SO(8) → SU(2) x SU(2), SO(8) → SU(2) x SU(2) x U(1)

Composite Higgs:

$$8_V = (2,2)_{+1} + (2,2)_{-1}$$

Allows to distinguish between the two doublets

Vector boson masses:

$$\mathcal{L}_m = \frac{1}{2} g^2 f^2 \sin^2(\varphi/f) \left(W_\mu^+ W_\mu^- + \frac{1}{2\cos\theta_W} Z_\mu Z_\mu \right)$$

Fermion Embedding:

$$q_L \equiv 16 \to 8_c \to (2,2)_{-1}$$

$$u_R/d_R \equiv 16 \to 8_s \to (1,3)_0$$

Only Couples to the doublet with U(1) charge +1 :

Natural realization of Inert Higgs Scenario

Bertuzzo, TSR, Sandes, Savoy, JHEP 05 (2013) 153