Composite Models at the LHC

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BMG, A. Pomarol, F. Riva, J. Serra, JHEP 0904:070,2009, arXiv:0902.1483

BMG, arXiv:0910.1789

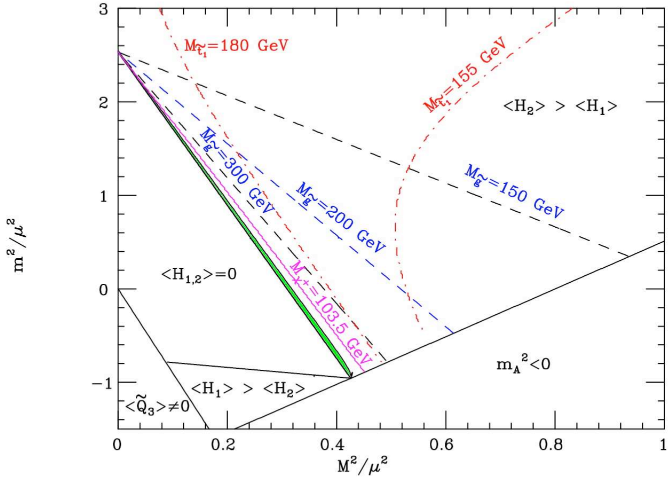
Outline

Why strong EWSB?

Why *not* weak EWSB?

What about the hierarchy?

If it's SUSY, why haven't we seen any superpartners yet?



Giudice and Rattazzi, 0606105

Why strong EWSB?

Why strong EWSB?

- A natural hierarchy, *cf* QCD
- cf. Condensed matter
- Calculability via AdS/CFT

Why *not* strong EWSB?

Why *not* strong EWSB?

- Electroweak precision tests
- Flavour changing neutral currents

Strong EWSB and FCNC

$\Lambda_{IR} \ll E \ll \Lambda_{UV} \implies$ The language of hierarchy is CFT

Natural hierarchy $\implies d[\mathscr{O}] \gtrsim 4$

Two ways to get fermion masses:

- Bi-linear:

$$\mathscr{L} = y f_L \mathscr{O}_H f_R, \;\; \mathscr{O}_H \sim (1,2)_{\frac{1}{2}}$$

- Linear:

$$\mathscr{L} = y_L f_L \mathscr{O}_R + y_R f_R \mathscr{O}_L + m \mathscr{O}_L \mathscr{O}_H \mathscr{O}_R, \;\; \mathscr{O}_R \sim (3,2)_{\frac{1}{6}}$$

D. B. Kaplan, 1991

Bi-linear fermion masses

$$\mathcal{L} = \frac{f_L \mathcal{O}_H f_R}{\Lambda_F^{d-1}} + \frac{f_L f_R f_L f_R}{\Lambda_F^2}$$

$$\text{FCNC} \implies \Lambda_F \gtrsim 10^{3-4}\,TeV \implies d \lesssim 1.2 - 1.3$$

- RS: $d \to \infty$
- TC: $d \sim 3$
- WTC: $d \sim 2$
- SM: $d \sim 1$ (but then $d[\mathcal{O}_H^\dagger \mathcal{O}_H] \sim 2$)

Strassler, 0309122

Luty & Okui, 0409274

Rattazzi, Rychkov & Vichi, 0807.0004

Rychkov & Vichi, 0905.2211

Linear fermion masses

$$\mathscr{L} = y_L f_L \mathscr{O}_R + y_R f_R \mathscr{O}_L + m \mathscr{O}_{L,R} \mathscr{O}_H \mathscr{O}_{L,R}$$

- $\mathscr{O}_{L,R}$ can be relevant
- Flavour can be decoupled
- RS-GIM

Gherghetta & Pomarol, 0003129

Huber & Shafi, 0010195

Agashe, Perez & Soni, 0406101

Agashe, Perez & Soni, 0408134

Agashe, Contino & Pomarol, 0412089

Strong EWSB and EWPT:

Contributions to EWPT $\sim \frac{m_W^2}{m_\rho^2}$ are too large.

Strong EWSB and EWPT:

Effective Lagrangian at M_W:

$$\mathscr{L} = \Pi_{+-} W^+ W^- + \Pi_{33} W^3 W^3 + \Pi_{3Y} W^3 B + \Pi_{YY} BB$$

- $\Pi(q^2) = \Pi(0) + q^2 \Pi'(0) + \dots$
- $\Pi_{ab} \sim \langle J_a J_b \rangle$
- $\Pi_{+-} - \Pi_{33} \sim T$
- $\Pi'_{3Y} \sim S$

Peskin & Takeuchi, 1990; 1992

Strong EWSB and EWPT: T

$$\frac{SU(2)_L \times U(1)_Y}{U(1)_Q} \longrightarrow \frac{SU(2)_L \times SU(2)_R}{SU(2)_V} = \frac{SO(4)}{SO(3)}$$

Sikivie, Susskind, Voloshin & Zakharov, 1980

- $Y = T_{3R}$
- $\mathbf{3} \otimes \mathbf{3} = \mathbf{1} \oplus \mathbf{3} \oplus \mathbf{5}$
- T is **5** of $SU(2)_V$
- $SU(2)_V \implies T = 0$

Strong EWSB and EWPT: S

Second problem is S

- S contains a $\mathbf{1}$ of $SU(2)_V$
- $SU(2)_V$ doesn't protect S
- Nothing protects S
- $S > 0 \implies$ no cancellation
- Make S small somehow?

Strong EWSB and EWPT: S

There is a symmetry for S: $SU(2)_L$

Inami, Lim & Yamada, 1992

- $\implies S \sim v^2/\Lambda^2$
- $v \ll \Lambda$?
- Put back Higgs: $SO(4)/SO(3) \to SO(5)/SO(4)$

Agashe, Contino & Pomarol

- NGBs a **4** of $SO(4)$
- v/Λ dynamical

Georgi, Kaplan

- Higgs screens IR contribution to S

Strong EWSB and EWPT: $Z \to b\bar{b}$

$Z \to b_L \bar{b}_L$ coupling fits SM within 0.25 *per cent*

$$\frac{g}{\cos\theta_W}(Q_L^3 - Q\sin^2\theta_W)$$

- $P_{LR} : SU(2)_L \leftrightarrow SU(2)_R$
- P_{LR} and $U(1)_V \implies \delta Q_L^3 = 0$
- $b_L \in \mathbf{4}$ of $O(4)$

Agashe, Contino, Da Rold & Pomarol, 0605341

The Minimal Composite Higgs Model

Agashe, Contino & Pomarol, 0412089

Desiderata

FCNC

- Linear fermion masses:
  $\mathscr{L} = y_L f_L \mathscr{O}_R + y_R f_R \mathscr{O}_L + m \mathscr{O}_L \mathscr{O}_R$

D. B. Kaplan, 1991

EWPT

- T: Custodial $SO(4)/SO(3)$

Sikivie, Susskind, Voloshin & Zakharov, 1980

- $Z \to \bar{b}b$: $O(4)/O(3)$, $q_L \in (\mathbf{2},\mathbf{2})$

Agashe, Contino, Da Rold & Pomarol, 0605341

- S: $v \lesssim f$, $O(5)/O(4)$

Agashe, Contino & Pomarol, 0412089

The Minimal Composite Higgs Model

- $SO(5)/SO(4)$: NGBs a **4** of $SO(4)$
- Light d. o. f.: SM Higgs
- Look for deviations from SM couplings ($gg \to h$) ?

Giudice, Grojean, Pomarol & Rattazzi

Falkowski

Rattazzi & Vichi

- Look for light top partners?

Beyond The Minimal Composite Higgs Model

Why go beyond?

- Nature doesn't always choose minimal option
- Phenomenology can change drastically
- Implications for LHC searches

Going Beyond

Plenty of possible groups with desiderata

- $SO(6)/SO(4) \times SO(2)$
- $SO(6)/SO(5)$
- $SO(7)/SO(6)$
- $SO(7)/SO(4) \times SO(3)$
- $\dots$
- $SO(11)/SO(10)$
- $SO(6) \times SO(6)/SU(3) \times U(1) \times SO(5)$
- $\dots$

Higgs

$SO(6)/SO(5)$

Focus on $SO(6)/SO(5)$:

- A single Higgs doublet plus a singlet
- ($SO(6) = SU(4) \implies$ Anomalies, WZW, cf. $\pi \to 2\gamma$)

Gripaios, 0803.0497

$SO(6)/SO(5)$ Higgs sector

- PNGBs a **5** of $SO(5)$
- **4** $+$ **1** of $SO(4)$

Get SM Higgs doublet H and electroweak singlet η

$SO(6)/SO(5)$ Gauge couplings

- Gauge $SU(2)_L \times U(1)_Y$
- Breaks $SO(6)$ to $SU(2)_L \times U(1)_Y \times U(1)_\eta$

Singlet η gets no potential from gauge loops

$SO(6)/SO(5)$ Yukawa couplings

How do the PNGBs couple to SM fermions?

- Linearly; what operators?
- $Z \to \overline{b}b \implies b_L \in \mathbf{4}$ of $SO(4)$
- Reps of $SO(6)$: $\mathbf{4}, \mathbf{6}, \ldots$

Fermions in the **6** of $SO(6)$

- $SO(6) \to SO(4) \times U(1)_\eta : \mathbf{6} \to \mathbf{4}_0 + \mathbf{1}_{+1} + \mathbf{1}_{-1}$
- Superposition for $f_R = f_R^1 + \varepsilon_f f_R^2$
- ε_f are parameters of interest

Fermions in the **6** of $SO(6)$

Two special values of ε_f:

- $\varepsilon_f = \pm 1 \implies U(1)_\eta \implies$ no η potential from f loops
- Yukawa couplings: $\bar{f}_L f_R h(\sqrt{1-\eta^2-h^2} + i\varepsilon_f \eta)$
- $\varepsilon_f = 0 \implies$ no linear ηff coupling

Phenomenology

Light singlet scenario

For $\varepsilon_f \to \pm 1$, light η, technically natural (cf. NMSSM)

For $m_\eta \to 0,$, $h \to 2\eta$ via $vf\eta^2\partial^2 hf^2$

$$\frac{\Gamma(h\to 2\eta)}{\Gamma(h\to 2b)} \sim 9\left(\frac{m_h}{120GeV}\right)^2\left(\frac{500GeV}{f}\right)^4$$

Decays to τ or c or g could dominate

LEP bound can go down as far as 86 GeV

STOP PRESS! New ALEPH limit $\to \sim 100GeV$ for τ decays.

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Light singlet scenario II

Non-standard Higgs decays from dynamics

e.g. Suppose quark couplings respect $U(1)_\eta$

Could decay into τ or c

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Other Phenomenology

- Singlet is odd under *CP* - baryogenesis
- Heavy singlet could violate flavour
- Flavour violating singlet decays $\eta \rightarrow tc$

Leptoquarks

Composite Leptoquarks

- Flavour $\implies$ fermion masses arise linearly
- Strong sector is coloured
- Coloured baryons $\implies$ coloured mesons?
- Unification
- TeV Leptoquarks

BMG, 0910.1789

Constraints

- Many stringent constraints on λ_{LQ}^2/M^2
- $\mu \to e\gamma, \tau \to \mu\gamma, B_d \to K\mu\mu$
- Natural suppression $\lambda_{LQ} \sim \frac{y_L y_R}{g_\rho}$

Constraints II

- Many stringent constraints on λ_{LQ}^2/M^2
- What is M?
- $M \sim TeV$
- $SO(11)/SO(10)$ or
  $SO(6) \times SO(6)/SU(3) \times U(1) \times SO(5)$
- or even $M \sim 300 GeV$ if PNGB

LHC searches

- Leptoquarks pair-produced by strong interactions
- Decay to third generation fermions
- $2b$ or $2t$ and 2τ or 2ν
- Tevatron: $M > m_t$ or $M > 220 GeV$
- Forget about HERA

Summary

Strongly-coupled models hard to reconcile with data

Weakly-coupled models hard to reconcile with data

What physics can we expect from composite models?

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- Top partners?
- Non-standard Higgs pheno.?
- Third-generation Leptoquarks?

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Flavour

- Different εs for different families
- $M_{ij} = m_i \Sigma_k U_{ik} \varepsilon_k U^\dagger_{kj}$
- Assume $U \sim V_{CKM}$
- Down: $\frac{\delta m_B}{m_B} \sim 10^{-15} (\frac{100 GeV}{m_\eta})^2$
- Up: $\frac{\delta m_D}{m_D} \implies m_\eta \gtrsim 100 GeV$
- Lepton: $\tau \to 3\mu \implies m_\eta \gtrsim$ few GeV
- Flavour decays: $\eta \to t\bar{c}$ can dominate