Composite GUTs: model building and expectations at the LHC

M. Frigerio  J. Serra  A. Varagnolo

based on 1103.2997 [hep-ph], JHEP 1106:029,2011

Supersymmetry 2011, Fermilab
Composite GUTs: model building and facing the LHC

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Outline

1 Motivations and Intro
   - SUSY & the ALTERNATIVES
   - Some tools

2 Model Building
   - The idea, and real life
   - Our pNGBs, our Exotics and the EWPTs

3 Some phenomenology
   - Some doubts
   - Some hope
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Motivations for CompoGUTs

- **Unification** and its many appealing virtues
  - charge quantization
  - gauge quantum numbers of fermions
  - chiral anomalies cancellation
  - relative low energy values of SM gauge couplings
  - and more (DM stability, masses of $\nu$s,...)

- solution to the Hierarchy Problem (orthogonal to SUSY)
- predict properties of lightest states coming from the new Strong Sector: partners of Higgs and top
- accept the LHC challenge
Why we love SUSY:

- Solution to the Hierarchy Problem
- Improves Unification (with full perturbativity up to $M_{GUT}$)
- Rich Pheno: new states predicted (Dark Matter?)

Of course, we do have some complaints/doubts:

- need for extra symmetry to avoid, e.g., p-decay (R-parity)
- parameter space for simplest models of SUSY shrinking
- nature has shown us other ways (QCD, SC)

All in all, not unwise to consider alternatives
The **big thing**: Solve the HP.

Many candidates: Technicolour, Higgsless, Extra Dimensions, ...Composite Higgs.
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Focus on CH scenario:

- **Solution** to HP $\rightarrow$ move to the little HP (Fine Tuning!)
- ?? Unification ?? not perturbative!
- ?? New states ?? Huge model dependence $+$ some of them we **cannot control** (heavy resonances) $\leftarrow$ the price of having a Low E effective description
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One step at a time. *Why* can’t we tell if our model unifies?
Do you know your beta functions?
Or: how to check if Unification occurs

**SM: Unif fails**

Higher Orders: NO help

**MSSM: Good Unif (@ 1-loop)**

Higher Orders: a bit worse

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**Alvise Varagnolo**

**Compo GUTs**
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What about Composite Higgs (+ top)? Can we calculate?
Do you know your beta functions?
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Compositeness vs Unif

Leading order UNKNOWN

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Leading order **UNKNOWN**

Our ignorance is partial

\[
\frac{d}{d \ln \mu} \left( \frac{1}{\alpha_i} \right) = \frac{b_{i}^{\text{elem}}}{2\pi} + \frac{b_{i}^{\text{comp}}}{2\pi},
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Notice: the differential running determines unification\(^1\).

\(^1\)provided no Landau pole is hit
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Or: how to check if Unification occurs

Compositeness vs Unif

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Figure 1:

\[ \frac{d}{d \ln \mu} \left( \frac{1}{\alpha_i} \right) = \frac{b_{i}^{\text{elem}}}{2\pi} + \frac{b_{i}^{\text{comp}}}{2\pi}, \]

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Notice: the differential running determines unification\(^1\). A good measure: \( R \equiv (b_1 - b_2)/(b_2 - b_3) \). Numerically, we have:

\( R_{\text{exp}} = 1.395 \pm 0.015 \) vs \( R_{\text{SM}}^{th} \approx 1.9 \) vs \( R_{\text{MSSM}}^{th} = 1.4 \) vs ??

\(^1\)provided no Landau pole is hit

Alvise Varagnolo  Compo GUTs
Composite Higgs

New Strong Dynamics triggers $G/K$ global symm breaking, 
NGBs $\pi$ s.t. $\pi \supset H$, with $\sigma$-model scale $f$

@ Low E: $\mathcal{L} = \mathcal{L}_{\text{elementary}}^{G_{\text{SM}}} + \mathcal{L}_{\text{composite}}^{G_{\text{SM}}} + \mathcal{L}_{\text{mixing}}^{G_{\text{SM}}}$

The mixing term will generate (CW) a $V_{\text{eff}}(\pi) \neq 0$. Fine Tuning measure: $\xi = v^2/f^2$. Resonances @ scale $m_\rho \sim \text{few TeV}$, inter-compo coupling: $g_\rho = m_\rho/f$, $g_{\text{elem}} \leq g_\rho \leq 4\pi$

Composite Top

A closer look: $\mathcal{L}_{\text{mixing}}^{G_{\text{SM}}} = \lambda_{\psi_L} \bar{\psi}_L O_{\psi_L} + \lambda_{\psi_R} \bar{\psi}_R O_{\psi_R} + g_i A_{i\mu} J^\mu$

Yukawa: $y_\psi \simeq \lambda_{\psi_L} \lambda_{\psi_R}/g_\rho \rightarrow \text{top mostly/totally composite. Must choose } t_R$, otherwise big troubles\textsuperscript{a} with $Zb\bar{b}$

Also: $\hat{T} \simeq v^2/f^2 \rightarrow$ Better impose Custodial Symmetry $(SU(2)_L \times SU(2)_R)$ on the whole Strong Sector

\textsuperscript{a}Can cure this by extending CS with LR parity. Check r-h coupling!
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A way out

$G/K \rightarrow$ Composite stuff (i.e. Higgs, top, heavy resonances)

Agashe, Contino, Sundrum (2005) realized that if $G_{SM} \subset G$ simple $\Rightarrow$ contribution of strong sector to $b_i$s above compositeness scale becomes universal! ($b_i^{\text{compo}} \rightarrow b^{\text{compo}}$)

Then $b_i - b_j = b_i^{\text{elem}} - b_j^{\text{elem}}$ and we can compute! (modulo small corrections from Low E region, if $K$ is not simple)

Equivalently: we subtract the contributions of composite modes to the differential running, i.e.

$$R(SM) \rightarrow R(SM \setminus \{\text{Composite stuff}\})$$

We are thus in a position to investigate Composite Unification.
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We are thus in a position to investigate Composite Unification.

But careful: \( b^{\text{compo}} < 10 \), or you hit a Landau pole before \( M_{GUT} \)!
Requirements on $G/K$

(A) $G/K \rightarrow$ NGBs contain the Higgs, or a $(2, 2)_0$ repr of $SU(2)_L \times SU(2)_R \times U(1)'$

(B) $K_{min} = SU(3) \times SU(2)_L \times SU(2)_R \times U(1)'$

(C) $G$ a simple group s.t. $G_{SM} \subset G$

$A + B + C \Rightarrow \text{rank}(G) \geq 5$: $G = SO(10)$? Life’s not that easy…

Minimal rank sol’ns:

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Need to define hypercharge & to impose extra $U(1)_B \times U(1)_L$

To fit fermion $Y$ & to prevent $p$-decay and too large $\nu$ masses
What about fermions?

Which repr of $SO(10)$ contains $t_R$? Obvious\(^2\) answer is: $\overline{16} \supset t_R$, as typical in canonical GUTs. Then, however, $t_R$ comes with a plethora of new composite massless (before EWSB) states: exotics $\overline{16} = (x_R, t_R)$. In order to

- avoid experimental constraints on masses of extra fermions
- cancel anomalies

we need to pair them to a $16 \setminus t'_L = x_L$ of \textit{elementary} fields!

Consequence for unification: $R \rightarrow R(SM \setminus \{H, t_R, t'^c_R\})$

Bottom line: for $K$ simple unification is guaranteed.

Numerically: $R \simeq 1.45$ vs. $R_{exp} = 1.395$ vs. $R_{SUSY} = 1.4$

Higher orders: \textit{hard} to evaluate, very model dependent.

\(^2\)But one can engineer, e.g., $t_R \subset 10$
The masses are predicted as follows:

\[ m_h^2 \simeq N_x \frac{\lambda_x^4}{16\pi^2} v^2 \simeq (440\text{GeV})^2 (\lambda_x/2.5)^4, \]

\[ m_T^2 \simeq N_g \frac{g_s^2}{16\pi^2} m_\rho^2 \simeq (1.2\text{TeV})^2 (m_\rho/4.5\text{TeV})^2, \]

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**Important #1:** couplings of pNGBs (⊃ H) come with factor \( \sqrt{1 - v^2/f^2} \). Numerically, \( f \simeq 750 \text{ GeV} \) easily realized (in region allowed by EWPTs) \( \Rightarrow \) factor 0.95 (lower possible).
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We use **exact** formulae for $V_{\text{eff}}, m_H, m_T \ldots \Rightarrow$ numerics! But ...
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**T’s & Exotics’ Pheno @ LHC → to be revised!**

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<th>$b'$</th>
<th>$l^c$</th>
<th>$\nu'$</th>
<th>$e'$</th>
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<td>3</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
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<td>1</td>
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<td>1</td>
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</tr>
<tr>
<td>$U(1)_Y$</td>
<td>$-\frac{1}{6}$</td>
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<td>0</td>
<td>$-1$</td>
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Mostly pair produced via gauge int’s: @ 14 TeV LHC cross section $\sim 0.01$ (0.05) pb for masses $\sim 1$ TeV for coloured scalars (fermions).

Depending on $B$, lightest state can be stable (baryon triality).

Assume $T$ stable.

LHC produced: hadronizes $T^0 = T\bar{d}$ or $T^- = T\bar{u}$:

$T^0 \sim$ missing $E_T$;

$T^- \sim$ heavy $\mu$

(both should come with pairs of $t$’s or $b$’s)

If $N$ (mix of $l^c$ and $\nu'$) stable:

missing $E_T + (t$’s & $b$’s pairs)

$N$ can be DM candidate, but need to be mostly $\nu'$ to avoid direct detection & relic density ($\neq$ SUSY annihil'n).

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-Alvise Varagnolo

Compo GUTs
Higgs: surviving @ LHC

CMS 22/08: excluded SM Higgs for $140 \, \text{GeV} \leq m_H \leq 440 \, \text{GeV}$

The **good** properties of *our* Higgs:
- it’s typically **heavy** (from 400 GeV upwards)
- couplings & cross sections reduced wrt SM Higgs’
It’s been known for some years that it is possible to investigate Unification in Composite $H$ & $t$ scenarios, thus combining this elegant solution to the HP and the properties of GUTs. Now:
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- explicit (albeit not UV-complete) model $\rightarrow$ predictions
- $H$ and $t_R$ bring along partners lighter than compositeness scale (comparts), with fixed QN (modulo $B$)
- amount of FT is perfectly acceptable, if masses of comparts are $\leq 1 - 2 \ TeV$
- lightest of comparts might be stable; production @ LHC might be significant
Summary

It’s been known for some years that it is possible to investigate Unification in Composite $H$ & $t$ scenarios, thus combining this elegant solution to the HP and the properties of GUTs. Now:

- **explicit** (albeit not UV-complete) model $\rightarrow$ predictions
- $H$ and $t_R$ bring along partners lighter than compositeness scale (comparts), with fixed QN (modulo $B$)
- amount of FT is perfectly acceptable, if masses of comparts are $\leq 1 - 2$ TeV
- lightest of comparts might be stable; production @ LHC might be significant (problem?)

**to do list**

- check attentively LHC signals: do we survive? more FT?
- attempt the construction of UV-completion
Until next time...