THE DYNAMICAL COMPOSITE HIGGS

Gero von Gersdorff

São Paulo, 27/11/2015

Based on work with E. Pontón and R. Rosenfeld
(and work in progress with S. Fichet)
INTRODUCTION
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Electroweak Symmetry Breaking is far from understood!

EW scale quadratically sensitive to any New Physics threshold
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SUSY
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- SUSY
- Extra Dim’s
- Composite
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The Composite Higgs

- If the Higgs is a “meson”, why don’t we see the higher excitations? (why $m_{res} >> m_h$? “Little Hierarchy”)
- Higgs as the pNGB of a spontaneously broken global symmetry:
  - $SU(3) \rightarrow SU(2)_L \times U(1)$
  - $SO(5) \rightarrow SU(2)_L \times SU(2)_R$ Custodial Symmetry!  

Georgi + Kaplan ‘84
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$\mu = 246$ GeV
$m_h = 125$ GeV

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- $m_h = 125$ GeV
- $f > 600$ GeV
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- TUNING
  - \( v = 246 \text{ GeV} \)
  - \( m_h = 125 \text{ GeV} \)

Georgi + Kaplan ‘84
Can one have an SO(5) global symmetry?

- Renormalizable (gauge) theories typically have larger (accidental) global symmetry groups (breaking patterns classified in Peskin 1980)

What is the UV theory (the constituents of the CH)?
- Can it be made out of Standard Model fermions?

What is the dynamics causing the global symmetry breaking?
- Is there an SO(5) “Higgs boson”?
In this talk, I will present a model that

- Possesses just $\text{SO}(5)$ global symmetry
- Accomplishes $\text{SO}(5)$ as well as EW breaking dynamically
- Features a CH made out of an (extended) top sector
- Has $\text{SO}(5)$ Higgs particle whose self coupling is predicted
- Has few parameters and is compatible with all constraints

This model is largely inspired by the seminal paper:
“Minimal Dynamical Symmetry Breaking of the Standard Model”,
Bardeen, Hill, Lindner ‘90
MINIMAL DYNAMICAL EWSB
(IT DOESN’T WORK)
**The Top Condensation Mechanism**

- EWSB triggered from 4-fermion (NJL) interaction:

  \[ \mathcal{L} = G (\bar{q}_L t_R)^2 \]  

  Bardeen et al 1990
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Same interaction can be written with auxiliary "Higgs" field

\[ \mathcal{L} = -\frac{1}{G} |H|^2 - H(\bar{q}_L t_R) \]
**The Top Condensation Mechanism**

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  \[ \mathcal{L} = - \frac{1}{G} |H|^2 - H(\bar{q}L t_R) \]

- **Radiative correction make Higgs dynamical:**
  \[ \mathcal{L} = \frac{1}{G_c \Lambda^2} \log \frac{\Lambda}{\mu} |D H|^2 - \left( \frac{1}{G} - \frac{1}{G_c} \right) |H|^2 - H(\bar{q}L t_R) - \frac{1}{G_c \Lambda^2} \log \frac{\Lambda}{\mu} |H|^4 \]

\[ G_c = \frac{8\pi^2}{N_c \Lambda^2} \]
The Top Condensation Mechanism

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- EWSB occurs for \( G > G_c \)

- The ratio of top and Higgs mass is fixed: \( m_h = 2 m_t \)

\[ G_c = \frac{8\pi^2}{N_c \Lambda^2} \]
Equivalently, consider beta functions

\[
16\pi^2 \beta_{y_t^2} = 2N_c y_t^4 + 3 y_t^4 \\
16\pi^2 \beta_{\lambda} = 4N_c y_t^2 \lambda - 2N_c y_t^4 + 24\lambda^2
\]
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- With just the fermion loops, IR fixed point \( m_h = 2 m_t \)
- Including scalar loops, IR fixed point \( m_h = 1.3 m_t \)
- Including gauge loops, nonlinear relation between \( m_h \) and \( m_t \)
**Top Condensation: Beyond Large $N_C$**

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- Compositeness scale are Landau Poles for Yukawas

- Physical Yukawa $\sim 1$ is too small

- Top Seesaw: Enlarge top sector

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Dobrescu et al '97/'98
THE DYNAMICAL COMPOSITE HIGGS
Dynamical Composite Higgs

- Generalize Top Condens. to $\text{SO}(5) \times \text{U}(1)_X$ Composite Higgs
- Fermion content: $(F_L = 5_{2/3}) + (S_R = 1_{2/3})$ (both are 3 of $\text{SU}(3)_C$)
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$$\mathcal{L}_{\text{kin}} = i\bar{F}_L \phi F_L + i\bar{S}_R \phi S_R$$

Invariant under $\text{U}(5)_L \times \text{U}(1)_R$
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- Invariant under $\text{U}(5)_L \times \text{U}(1)_R$
- Invariant under $\text{SO}(5) \times \text{U}(1)_X$

- Choice $G = G'$, invariant under $\text{U}(5)_L \times \text{U}(1)_R$
  - more scalar states, (2HDM) Dobresci, Cheng + Gu '14
- Take only $G$ supercritical $\Rightarrow$ minimal model GG, Ponton, Rosenfeld '15
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  - more scalar states, (2HDM) \( \text{Dobresci, Cheng + Gu '14} \)
- Take only \( G \) supercritical \( \rightarrow \) **minimal model** \( \text{GG, Ponton, Rosenfeld '15} \)

- The composite scalar \( \Phi = (S_R F_L + \bar{F}_L S_R) \) is a \( 5_0 \) of \( \text{SO}(5) \)
- 5 real d.o.f: pNGB Higgs + one SM singlet, the **radial mode**
Again Rewrite 4-fermion interaction

\[ \frac{G}{2} (\bar{S}_R F_L + \bar{F}_L S_R)^2 = - \frac{1}{2G} \Phi^2 - \Phi (\bar{S}_R F_L + \bar{F}_L S_R) \]
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Loops make \( \Phi \) dynamical and create a potential that breaks the global SO(5) symmetry \( \langle \Phi \rangle = (0, 0, 0, 0, \hat{f}) \)
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Due to the presence of the IR fixed point, the quartic \( \lambda \) and hence the mass of the radial mode become a prediction of the model

\[ m_H^2 = \frac{24}{13} m_S^2 \]
The Full Top Sector

- Weakly gauge SU(2) x U(1)$_Y$ subgroup of SO(5) x U(1)$_X$
- Hypercharge embedded as $Y = Q_X + T_{R3}$
- Need to have chiral field content of the SM: ($q_L = 2_{1/6}$) + ($t_R = 1_{2/3}$)
  ➔ Add incomplete multiplets
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Minimal Model:

$Q_{L1} + Q_{L2} + S_L + S_R + Q_{R2} + t_R$
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  - Add incomplete multiplets

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\begin{array}{cccccccc}
& Q & Q & S & S & Q & Q & q & t \\
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**Minimal Model:**
\[ Q_{L1} + Q_{L2} + S_L + S_R + Q_{R2} + t_R \]

**Extended Model:**
\[ Q_{L1} + Q_{L2} + S_L + S_R + Q_{R1} + Q_{R2} + q_L + t_R \]
The full Top Sector

Complete multiplets have mass mixings with incomplete ones

\[ \mathcal{L}_{\text{mix}}^{\text{min}} = -\mu'_{QQ} Q^2_L Q^2_R - \mu_{tS} \bar{S}_L t_R \]

\[ \mathcal{L}_{\text{mix}}^{\text{ext}} = \mathcal{L}_{\text{mix}}^{\text{min}} - \mu_{QQ} Q^1_L Q^1_R - \mu_{qQ} \bar{q}_L Q^1_R \]

1) One additional parameter \( \mu_{SS} \bar{S}_L S_R \): equivalent to a tadpole \( \mathcal{L} = \tau \Phi_5 \)
THE FULL TOP SECTOR

Complete multiplets have mass mixings with incomplete ones\textsuperscript{1)}

\[ \mathcal{L}_{\text{mix}}^{\text{min}} = -\mu_{QQ} \bar{Q}_L^2 Q_R^2 - \mu_t S_L t_R \]

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SPECTRUM:

\textsuperscript{1)} One additional parameter \( \mu_{SS} S_L S_R \) : equivalent to a tadpole \( \mathcal{L} = \tau \Phi_5 \)
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SPECTRUM:

Vector-Like Top-partners:

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Spectrum:

Vector-Like Top-partners:

\[ \frac{1}{2} \, m_S^2 = \xi^2 \hat{f}^2 + \mu_{tS}^2 \]

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THE FULL TOP SECTOR

Complete multiplets have mass mixings with incomplete ones\(^1\)

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SPECTRUM:

Vector-Like Top-partners:

\[
\begin{align*}
1_{\frac{2}{3}} & \\
m_S^2 &= \xi^2 \hat{f}^2 + \mu_{tS}^2 \\
2_{\frac{7}{6}} & \\
m_Q^2 &= \mu_{QQ}^2
\end{align*}
\]

\(^1\) One additional parameter \( \mu_{SS}^L S_L S_R \): equivalent to a tadpole \( L = \tau \Phi_5 \)
THE FULL TOP SECTOR

Complete multiplets have mass mixings with incomplete ones\(^1\)

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SPECTRUM:

Vector-Like Top-partners:

\[
1_{\frac{2}{3}} \quad m^2_S = \xi^2 \hat{f}^2 + \mu^2_{tS}
\]

\[
2_{\frac{7}{6}} \quad m^2_Q = \mu'^2_{QQ}
\]

\[
2_{\frac{5}{6}} \quad m^2_Q = \mu^2_{QQ} + \mu^2_{qQ}
\]

\(^1\) One additional parameter \(\mu_{SS} \bar{S}_L S_R\) : equivalent to a tadpole \(\mathcal{L} = \tau \Phi_5\)
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**Vector-Like Top-partners:**

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</tr>
<tr>
<td>( = \xi^2 \hat{f}^2 + \mu_{tS}^2 )</td>
<td>( = \mu_{QQ}^2 )</td>
<td>( = \mu_{QQ}^2 + \mu_{qQ}^2 )</td>
</tr>
</tbody>
</table>

**Top Quark:**

\[
m_t^2 = \frac{\sin^2 \left( \frac{\nu}{f} \right)}{2} m_S^2 \times c_R^2 s_R^2 \times s_L^2
\]

1) One additional parameter \( \mu_{SS} \bar{S}_L S_R \) : equivalent to a tadpole \( \mathcal{L} = \tau \Phi_5 \).
Spin-1 Sector

- Spin-1 states are also obtained from 4-fermion interactions:

\[ L_{4f}' = -\frac{1}{f_{\rho}^2} (\bar{F}_L T^a \gamma^\mu F_L)^2 = \frac{f_\rho^2}{4} (A_\mu^a)^2 + A_\mu^a \bar{F}_L T^a \gamma^\mu F_L \]

- Quantum corrections make \( A_\mu \) dynamical

- Combining with the scalar 4-fermion terms \( \Rightarrow \) Lagrangian of Spin-1 resonances + pNGB Higgs + Radial mode + Fermions
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  \[
  \mathcal{L'}_{4f} = -\frac{1}{f'_\rho^2} (\bar{F}_L T^a \gamma^\mu F_L)^2 = \frac{f^2}{4} (A^a_\mu)^2 + A^a_\mu \bar{F}_L T^a \gamma^\mu F_L
  \]

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Hidden Local Symmetry

- Equivalent to 2-site model

\[
f^{-2} = \frac{\hat{f}^{-2}}{f^2} + f^{-2}_\rho
\]
Spin-1 Sector

- Spin-1 states are also obtained from 4-fermion interactions:

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Hidden Local Symmetry

- Equivalent to 2-site model

\[ f^{-2} = \hat{f}^{-2} + f^{-2}_\rho \]

- Bando et al '88

Spectrum:

\[ SO(4) \quad m^2_\rho = \frac{g^2_\rho f^2_\rho}{2} \]

\[ SO(5) \quad m^2_a = \frac{m^2_\rho}{r_v} \]

\[ r_v = \frac{f^2}{\hat{f}^2} < 1 \]
Free parameters of the model:

- **Couplings**: $\xi, g_\rho$
- **SB scales**: $f, \hat{f}$
- **Mass mixings**: $\mu'_{QQ}, \mu_{tS}, (\mu_{QQ}, \mu_{qQ})$
Parameter Space

- Free parameters of the model:
  - Couplings: \( \xi, g_\rho \)
  - SB scales: \( f, \hat{f} \)
  - Mass mixings: \( \mu'_{QQ}, \mu_{tS}, (\mu_{QQ}, \mu_{qQ}) \)

- Physical parameters
  - Top/Top partner masses: \( m_t, m_S, (m_Q), m_{Q'} \)
  - Spin-1 masses: \( m_\rho, m_\alpha \)
  - Mixings: \( s_R = \mu_{tS}/m_S, s_L = \mu_{qQ}/m_Q \)
**Parameter Space**

- **Free parameters of the model:**
  - **Couplings:** $\xi$, $g_\rho$
  - **SB scales:** $f$, $\hat{f}$
  - **Mass mixings:** $\mu'_{QQ}$, $\mu_{tS}$, $(\mu_{QQ}, \mu_{qQ})$

- **Physical parameters**
  - **Top/Top partner masses:** $m_t$, $m_S$, $(m_Q)$, $m_{Q'}$
  - **Spin-1 masses:** $m_\rho$, $m_a$
  - **Mixings:** $s_R = \mu_{tS}/m_S$, $s_L = \mu_{qQ}/m_Q$

- EWSB (fixing correct values for $v$ and $m_h$) removes 2 parameters
  - **Spectrum alone fixes the parameters** of the model
- **Predictions:** $m_\phi$, couplings, EW mass splittings
**PNGB Potential**

- Tree-level: contributions to the Higgs potential vanish (GB!)
- 1-loop: soft SO(5) breaking \((g, g', \mu_{ts}, \ldots)\) generate a potential!
**PNGB Potential**

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- Spin-1/2 contributions are only soft (log divergence)
Tree-level: contributions to the Higgs potential vanish (GB!)

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Spin-1 contributions are super-soft (finite, cut off at \(m_\rho\))

Spin-1/2 contributions are only soft (log divergence)

New SO(5) Counterterm \(\delta m^2\)!

However, IR fixed point!

\[
\delta m^2 = r_* \mu_{eff}^2
\]

\[
\mu_{eff}^2 = 2\mu_{tS}^2 - \mu_{QQ}^2 - \mu'_{QQ}^2
\]

pNGB Higgs potential is fully calculable!
PHENOMENOLOGY
SCANS

- Perform scans over parameter space, fixing $m_t, m_h, \nu$
- Test against EWPT (S and T parameters)

Figure 4. Electroweak precision tests for the minimal model with $\tau \neq 0$ (left) and the extended model with $\mu_{QQ} = \mu_{QQ}'$, $\tau < 0$ (right). We scan over the ranges $f_2 \in [500, 2000]$ GeV, $r_v^2 \in [0.05, 0.95]$, $g_\tau^2 \in [0, 3\pi]$, $s_R^2 \in [0, 1]$ (and, for the right plot, $s_L^2 \in [0, 1]$). We fix $\tau$, $m_S$ and $m_Q$ from EWSB (Higgs vev and Higgs mass) plus the top mass, but requiring $m_S, m_Q > 500$ GeV.

In the left panel we also require $|\tau| \leq 1000$ GeV while in the right panel we impose $\tau \in [-3000, 0]$. All points reproduce the correct Higgs, top and Z masses. The contours correspond to 68%, 95% and 99% C.L. respectively [53].

In the minimal scenario, for $\tau > 0$ all points that lead to successful EWSB have a negative $T$ and do not satisfy EWPT. There exists however a possibility in the latter scenario to accommodate both the correct Higgs mass and EWPT with a large negative value for $\tau$. In fact, if $\tau$ is so large as to cancel a large negative $\mu_2$, we can escape the condition (4.3) and $1/2$ is not bounded by (4.6). This will however require a very large |$\tau|$, and both $\tau$ and $\mu_2$ show substantial cancellations between tadpole and other contributions. Notice that a large negative $\tau$ is bounded by the mass for the radial mode, Eq. (2.18). We show the $S$ and $T$ parameters of this model in the right panel of Fig. 4. We find that the interplay of EWSB and EWPT require in this case a peculiar hierarchy of fermion masses, $m_S < m_0_Q < m_Q$.
Figure 5. Electroweak precision tests (left) and fermion spectrum (right) for the extended model with $\mu_{QQ'} = \mu_{0Q}$. The plots in the upper row assume vanishing tadpole, while those in the lower row have a positive tadpole term. For $\lambda > 0$, we also impose $m_{Q} < m_{0Q}$. We scan over the ranges $f_2 [500, 2000]$ GeV, $\kappa \in [0.05, 0.95]$, $g_{\phi} \in [0, 3\pi]$, $s_R^2 \in [0, 1]$ and $s_L^2 \in [0, 1]$. In the plots of the upper row, we fix $m_S, m_Q$ and $m_{0Q}$ from EWSB (Higgs vev and Higgs mass) plus the top mass, but requiring $m_S, m_Q, m_{0Q} > 500$ GeV. In the lower row plots we instead fix $\lambda, m_S$ and $m_Q$ from EWSB plus the top mass, requiring $m_S, m_Q > 500$ GeV, while scanning over $m_{0Q}^2 [500, 3000]$ GeV and fixing $f_2 = 500$ GeV. The blue points pass EWPT at 95% C.L.
### Spectrum Features in the Lower Row Plots of Fig. 5

With fixed $f = 500$ GeV, the fermion masses in the range $\{500, 3000\}$ GeV. In addition, we require $m_Q < m_0 Q$ as otherwise $T$ is negative.

It is also interesting to know how much explicit violation of the global symmetry is required in the fermionic mass Lagrangian. We therefore plot in the right panel of Fig. 6 the quantity defined in Eq. (4.3) against the asymmetry parameter $\mu$. The point $\mu = \mu = 0$ corresponds to the $SO(5)$ preserving choice $\mu QQ = \mu_0 QQ = \mu tS$, while the deviations from $\mu = 0$ parameterize the breaking of the custodial symmetry in the "composite sector," to use the language of Section 2.2.

We see that $\mu \sim 15$ is required in order to obtain points that pass EWPT, while $\mu$ is always very small as expected from the general arguments above.

We summarize the various scenarios studied in this section in the following table:

<table>
<thead>
<tr>
<th>Model</th>
<th>$\tau = 0$</th>
<th>$\tau \neq 0$</th>
<th>$m_h$</th>
<th>EWPT</th>
<th>Spectrum</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimal</td>
<td>too light</td>
<td>$\checkmark$</td>
<td>$\times$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mu_{QQ} = \mu'_{QQ}$</td>
<td>$\tau = 0$</td>
<td>$\checkmark$</td>
<td>$\times$</td>
<td>$m_H &lt; m_S &lt; m'_Q &lt; m_Q$</td>
<td>$\epsilon \ll 1$</td>
<td></td>
</tr>
<tr>
<td>Extended</td>
<td>$\tau &gt; 0$</td>
<td>$\checkmark$</td>
<td>$\checkmark$</td>
<td>$m_Q &lt; m'_Q, m_S$</td>
<td>$\epsilon \ll 1$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau &lt; 0$</td>
<td>$\checkmark$</td>
<td>$\checkmark$</td>
<td>$m_Q &lt; m'_Q, m_S$</td>
<td>$\epsilon \ll 1$</td>
<td></td>
</tr>
</tbody>
</table>

$\epsilon \equiv \frac{\mu_{eff}^2}{2\mu_{tS}^2}$

- Combining EWSB, top mass and EWPT constraints is very restrictive
- Certain mass hierarchies can be identified
Fine Tuning?

- Fine tuning $\sim 1\%$, mainly due to $\delta m^2 = r \cdot \mu_{\text{eff}}^2$
  
  \[
  \mu_{\text{eff}}^2 = 2\mu_t^2 - \mu_{QQ}^2 - \mu_{QQ}^0^2
  \]

- Enhanced symmetry for
  \[
  \mu_{QQ} = \mu_{QQ}' = \mu_t
  \]
Fine Tuning?

- Fine tuning $\sim 1\%$, mainly due to $\delta m^2 = r_s \mu_{\text{eff}}^2$
  
  \[
  \mu_{\text{eff}}^2 = 2\mu_{tS}^2 - \mu_{QQ}^2 - \mu_{Q'Q}^2
  \]

- Enhanced symmetry for
  
  $\mu_{QQ} = \mu'_{QQ} = \mu_{tS}$

- Fine tuning, keeping $\mu_{\text{eff}}$ fixed $\sim 5\%$

- Can also be improved by going to less minimal top sectors
Looking for the SO(5) Higgs at the LHC

- Analysis for the channel: \( pp \rightarrow \phi \rightarrow VV \rightarrow JJ \)
- Shape analysis

**Figure 3.** A projection of the dijet background at 13 TeV extrapolated from an ATLAS 8 TeV analysis \([2]\). A signal for \( pp \rightarrow J J \) assuming \( f = 800 \text{ GeV}, V = 0.5, m = 3000 \text{ GeV} \) is shown in red.

**Figure 4.** Discovery Bayes factor for the global Higgs in the \( pp \rightarrow J J \) channel. The red, gray, yellow regions correspond respectively to weak, moderate, and strong evidence for the signal hypothesis.

However, the total width of the excess has also been fitted from the ATLAS data \([1]\). This provides an independent constraint that is complementary from the total rate. Using Fig. 6 of \([1]\) we conclude that the SO(5) scalar cannot fit the ATLAS excess, essentially because the ratio \( f_1/G \rightarrow f_1/H \) is too small in the case of the global Higgs.

4.4 An aside comment on the discovery and characterisation of resonances

Before conclusions, we open a parenthesis to point out an intriguing fact: searching for a resonance using the invariant mass of its decay products is not necessarily the optimal...
CONCLUSIONS

- The **Dynamical Composite Higgs** is (class of) models addressing various issues usually not considered
  - SO(5) global symmetry
  - **Dynamical breaking** of SO(5) (via NJL / 4-fermion)
  - Constituents of the Higgs (Extended top sector)
  - An SO(5) “Higgs” boson

- **Fully calculable** pNGB Higgs radiative potential
  - Allows for correct Higgs, Z and top mass
  - Various IR fixed points (**radial mode quartic coupling**, **GB mass**)
  - EWPT (oblique) can be satisfied
  - The radial mode could potentially be identified at the LHC13
BACKUP
**Enhanced Symmetry**

<table>
<thead>
<tr>
<th></th>
<th>Q</th>
<th>Q</th>
<th>S</th>
<th>S</th>
<th>Q</th>
<th>Q</th>
<th>q</th>
<th>t</th>
</tr>
</thead>
<tbody>
<tr>
<td>SO(5) x U(1)</td>
<td>5</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>SU(2)</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

- For $\mu_{QQ} = \mu'_{QQ} = \mu_{tS}$ unify $Q_{R1} + Q_{R2} + t_R \rightarrow F_R$
- Only $q_L$ remains “incomplete”

$$a_\mu = \frac{\mu'_{QQ} - \mu_{QQ}}{\mu'_{QQ} + \mu_{QQ}} \quad \epsilon = \frac{\mu_{eff}^2}{2\mu_{tS}^2}$$

**Mass Lagrangians**

$$\mathcal{L}_{\text{mix}}^{\text{min}} = -\mu'_{QQ} \bar{Q}_L^2 Q_R^2 - \mu_{tS} \bar{S}_L t_R$$

$$\mathcal{L}_{\text{mix}}^{\text{ext}} = -\mu_{QQ} \bar{Q}_L^1 Q_R^1 - \mu_{qQ} \bar{q}_L Q_R^1$$
THE FULL LAGRANGIAN

\[
\mathcal{L} = i(\bar{Q}_L, \bar{S}_L)\mathcal{D} \left( \begin{pmatrix} Q_L \\ S_L \end{pmatrix} \right) + i\bar{S}_R\mathcal{D}S_R + \frac{1}{2}(\nabla_\mu \mathcal{H})^2 - \frac{1}{4} \lambda \left( \mathcal{H}^2 - \hat{f}^2 \right)^2 - \xi \mathcal{H} \bar{S}S \\
+ \frac{1}{4} f_\rho^2 \left( A^A_\mu - i[U_5^\dagger D^SM U_5]^A \right)^2 + \frac{1}{4} f_X^2 \left( A^X_\mu - iU_1^\dagger D^SM U_1 \right)^2 \\
- \frac{1}{4 g^2_\rho} (F^V_{\mu\nu})^2 - \frac{1}{4 g^2_X} (F^X_{\mu\nu})^2 - \frac{1}{4 g^2_0} (w^a_{\mu\nu})^2 - \frac{1}{4 g^2_0} (b_{\mu\nu})^2 ,
\]
A Renormalizable UV Model

Consider a $SU(N_c) \times SU(N_c)$ gauge theory, spontaneously broken to the diagonal (as in top-color models)

Field content: SM quarks and any new vector-like states charged under first $SU(N_c)$, hence no anomalies. Diagonal unbroken subgroup identified with QCD $N_c = 3$

• Focus on $F^i_L(i = 1, \ldots 5)$ and $S_R$ of the main part of the talk.
• Add a (neutral) real scalar $\Xi^i(i = 1, \ldots 5)$ with mass of the same order as the broken gauge bosons (this scalar may itself be a composite state)

In unitary gauge:

$$\mathcal{L}_{UV} \supset -\frac{1}{2} M^2_{\Xi} \Xi^2 + y (\bar{S}_R \Xi^i F^i_L + \text{h.c.}) + \frac{1}{2} M^2_{G} G^{\mu\nu} G_{\mu\nu} + \frac{1}{2} \tilde{g} G^A_{\mu} (\bar{S}_R \gamma^\mu \lambda^A S_R + F^i_L, i \gamma^\mu \lambda^A F^i_L)$$

Integrating out the heavy fields:

$$\mathcal{L} \supset \frac{y^2}{2 M^2_{\Xi}} (\bar{S}_R F^i_L + \text{h.c.})^2 - \frac{\tilde{g}^2}{8 M^2_{G}} (\bar{S}_R \gamma^\mu \lambda^A S_R + F^i_L, i \gamma^\mu \lambda^A F^i_L)^2$$
A Renormalizable UV Model

\[ L \supset \frac{y^2}{2M^2_Z} (\bar{S}_R F^i_L + \text{h.c.})^2 - \frac{\hat{g}^2}{8M^2_G} (\bar{S}_R \gamma^\mu \lambda^A S_R + \bar{F}_{L,i} \gamma^\mu \lambda^A F_L^i)^2 \]

After Fierz rearrangement, this leads to the "scalar channel" 4-fermion int’ls, with

\[ G_S' = \frac{\hat{g}^2}{2M^2_G} + \frac{y^2}{M^2_Z}, \quad G_S' = \frac{\hat{g}^2}{2M^2_G} \]

One naturally obtains \( G_S' > G'_S \): one super-critical, the other sub-critical.

At the same time, one finds the required "vector channel" 4-fermion interactions