THE GLOBAL HIGGS AS A SIGNAL FOR COMPOSITENESS AT THE LHC

Gero von Gersdorff
São Paulo, 13/10/2016

Based on work with E. Pontón, R. Rosenfeld and S. Fichet
INTRODUCTION
INTRODUCTION
Higgs has been found!

Electroweak Symmetry Breaking is far from understood!
EW scale quadratically sensitive to any New Physics threshold
Introduction

- Higgs has been found!
- Electroweak Symmetry Breaking is far from understood!
  EW scale quadratically sensitive to any New Physics threshold

SUSY
Higgs has been found!

Electroweak Symmetry Breaking is far from understood!
EW scale quadratically sensitive to any New Physics threshold
Introduction

- Higgs has been found!
- Electroweak Symmetry Breaking is far from understood!
  EW scale quadratically sensitive to any New Physics threshold

SUSY  Extra Dim's  Composite
• Higgs has been found!
• Electroweak Symmetry Breaking is far from understood!
  EW scale quadratically sensitive to any New Physics threshold
The Composite Higgs

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

Georgi + Kaplan ‘84
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
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:
  - $\text{SU}(3) \rightarrow \text{SU}(2)_L \times \text{U}(1)$
  - $\text{SO}(5) \rightarrow \text{SU}(2)_L \times \text{SU}(2)_R$ Custodial Symmetry!

- The Higgs quartic coupling is one-loop suppressed

$$m_{res} = g_* f \quad m_h = \frac{g^2_* v}{4\pi}$$

- $v = 246$ GeV
- $m_h = 125$ GeV
- $m_{res}$
The Composite Higgs

- If the Higgs is a “meson”, why don’t we see the higher excitations? (why $m_{res} \gg m_h$? “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!

- The Higgs quartic coupling is one-loop suppressed

$$m_{res} = g^* f \quad m_h = \frac{g^*}{4\pi} v$$

- From Higgs couplings: $f > 800$ GeV

$\begin{align*}
    f & \quad m_{res} \quad m_h \\
    v = 246 \text{ GeV} & \quad m_h = 125 \text{ GeV}
\end{align*}$

Georgi + Kaplan '84
The Composite Higgs

- If the Higgs is a “meson”, why don’t we see the higher excitations? (why $m_{res} \gg m_h$? “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!

- The Higgs quartic coupling is one-loop suppressed
  $$m_{res} = g_* f \quad m_h = \frac{g_*^2}{4\pi} v$$

- From Higgs couplings: $f > 800$ GeV

Graph:
- $m_{res}$
- $f$
- $v = 246$ GeV
- $m_h = 125$ GeV

Georgi + Kaplan '84
A Global Higgs?

- Most approaches to the Composite Higgs work in EFT: Describe breaking of SO(5) in non-linear way
- Includes the 4 Goldstones, + various spin-1 resonances!
A **Global Higgs?**

- Most approaches to the Composite Higgs work in EFT: Describe breaking of SO(5) in non-linear way
- Includes the 4 Goldstones, + various spin-1 resonances!

- In analogy to the SM Higgs mechanism:
  - Is there a particle associated with the excitation of the broken vacuum?
  - **A Global Higgs?**
UV completions of CH models are strongly coupled
- 4-fermion theories contain a light scalar near criticality!
- QCD features meson with the right properties, the $\sigma$ (but heavy and broad)
- QCD with large $N_f$ shows restoration of chiral symmetry (the $\sigma$ should become lighter as $N_f$ increases...
UV completions of CH models are strongly coupled
- 4-fermion theories contain a light scalar near criticality!
- QCD features meson with the right properties, the $\sigma$ (but heavy and broad)
- QCD with large $N_f$ shows restoration of chiral symmetry (the $\sigma$ should become lighter as $N_f$ increases…)

Observation 1: It is rather easy (and predictive) to include the Global Higgs in the low-energy theory
A Global Higgs?

- UV completions of CH models are strongly coupled
  - 4-fermion theories contain a light scalar near criticality!
  - QCD features meson with the right properties, the $\sigma$ (but heavy and broad)
  - QCD with large $N_f$ shows restoration of chiral symmetry (the $\sigma$ should become lighter as $N_f$ increases…)

Observation 1: It is rather easy (and predictive) to include the Global Higgs in the low-energy theory

Observation 2: It is an experimental question if such a particle exists!
INTRODUCING THE GLOBAL HIGGS
The non-linear IR theory contains the Goldstones and possible spin-1 resonances.

\[ \mathcal{L}_{\text{bos}} = \frac{1}{2} (\nabla_\mu \mathcal{H})^2 + \frac{1}{4} f_\rho^2 \left( A^A_\mu - i [U_5^\dagger D_\mu U_5]^A \right)^2 - \frac{1}{4g_\rho^2} (F^A_{\mu\nu})^2 - \frac{1}{4g_0^2} (w^a_{\mu\nu})^2 - \frac{1}{4g_0'^2} (b_{\mu\nu})^2, \]

\[ U_5 = \exp(ih^{\hat{a}}T^{\hat{a}}/f) \quad \nabla = \partial - iA^{\hat{a}}T^{\hat{a}} \quad \mathcal{H} = f\hat{e}_5 \]
The non-linear IR theory contains the Goldstones and possible spin-1 resonances.

\[ \mathcal{L}_{\text{bos}} = \frac{1}{2} (\nabla_\mu \mathcal{H})^2 + \frac{1}{4} f_\rho^2 \left( A_\mu^A - i[U_5^A D_\mu U_5] A^A \right)^2 - \frac{1}{4 g_\rho^2} (\mathcal{F}_{\mu\nu}^A)^2 - \frac{1}{4 g_0^2} (w_{\mu\nu}^A)^2 - \frac{1}{4 g_0^2} (b_{\mu\nu})^2, \]

\[ U_5 = \exp(ih^{\hat{a}} T^{\hat{a}} / f) \quad \nabla = \partial - iA^{\hat{a}} T^{\hat{a}} \quad \mathcal{H} = \hat{f} \hat{e}_5 \]
The non-linear IR theory contains the Goldstones and possible spin-1 resonances.

\[
\mathcal{L}_{\text{bos}} = \frac{1}{2} (\nabla_\mu \mathcal{H})^2 + \frac{1}{4} f_\rho^2 \left( \mathcal{A}_{\mu}^A - i[U_5^\dagger D_\mu U_5]^A \right)^2 \\
- \frac{1}{4g_\rho^2} (\mathcal{F}_{\mu\nu}^A)^2 - \frac{1}{4g_0^2} (w_{\mu\nu}^a)^2 - \frac{1}{4g_0'^2} (b_{\mu\nu})^2, \]

\[
U_5 = \exp(i h^{\hat{a}} T^{\hat{a}} / f) \quad \nabla = \partial - i A^{\hat{a}} T^{\hat{a}} \quad \mathcal{H} = f \hat{e}_5
\]
The non-linear IR theory contains the Goldstones and possible spin-1 resonances

\[ \mathcal{L}_{\text{bos}} = \frac{1}{2} (\nabla_\mu \mathcal{H})^2 + \frac{1}{4} f_\rho^2 \left( \mathcal{A}_\mu^A - i [U_5^\dagger D_\mu U_5]^A \right)^2 - \frac{1}{4 g_\rho^2} (\mathcal{F}_{\mu\nu}^A)^2 - \frac{1}{4 g_0^2} (w_{\mu\nu}^a)^2 - \frac{1}{4 g_0^2} (b_{\mu\nu})^2, \]

\[ U_5 = \exp (i h^\dagger T^\dagger / f) \quad \nabla = \partial - i A^\dagger T^\dagger \quad \mathcal{H} = f \hat{e}_5 \]
Global Higgs Bosonic Couplings

- The non-linear IR theory contains the Goldstones and possible spin-1 resonances

\[ \mathcal{L}_{\text{bos}} = \frac{1}{2} (\nabla_\mu \mathcal{H})^2 + \frac{1}{4} f_\rho^2 \left( A_\mu^A - i[U_5^\dagger D_\mu U_5]^A \right)^2 - \frac{1}{4g_\rho^2} (\mathcal{F}_{\mu\nu}^A)^2 - \frac{1}{4g_0^2} (w_{\mu\nu}^a)^2 - \frac{1}{4g_0'^2} (b_{\mu\nu})^2, \]

\[ U_5 = \exp (ih^{\hat{a}} T^{\hat{a}} / f) \quad \nabla = \partial - iA^{\hat{a}} T^{\hat{a}} \quad \mathcal{H} = f \hat{e}_5 \]
The non-linear IR theory contains the Goldstones and possible spin-1 resonances.

\[ \mathcal{L}_{\text{bos}} = \frac{1}{2} (\nabla_\mu \mathcal{H})^2 - V(\mathcal{H}) + \frac{1}{4} f_\rho^2 \left( A_\mu^A - i [U_5^\dagger D_\mu U_5]^A \right)^2 
- \frac{1}{4 g_\rho^2} (F_{\mu\nu}^A)^2 - \frac{1}{4 g_0^2} (w_{\mu\nu}^a)^2 - \frac{1}{4 g_0'^2} (b_{\mu\nu})^2, \]

\[ U_5 = \exp(i h \hat{a} T^\hat{a} / f) \quad \nabla = \partial - i A^{\hat{a}} T^\hat{a} \quad \mathcal{H} = (\hat{f} + \phi) \hat{e}_5 \]
It is equivalent to simple 2-site model, with the breaking on site 2 realized linearly.
Global Higgs Bosonic Couplings

- It is equivalent to simple 2-site model, with the breaking on site 2 realized linearly.

- A simple $\text{SO}(5) \rightarrow \text{SO}(4)$ linear sigma model is obtained in the limit $f_\rho \rightarrow \infty$.

- Four-fermion theories (á la NJL) yield precisely this Lagrangian.
Global Higgs Bosonic Couplings

- It is equivalent to simple 2-site model, with the breaking on site 2 realized linearly.

- A simple $\text{SO}(5) \to \text{SO}(4)$ linear sigma model is obtained in the limit $f_\rho \to \infty$.

- Four-fermion theories (à la NJL) yield precisely this Lagrangian.

- The upshot of this minimal construction:

  $$\mathcal{L}_{\phi hh} = \frac{f^2}{f^3} \phi (D_\mu h^a)^2$$

  $$f^{-2} = \hat{f}^{-2} + f_\rho^{-2}$$
Partial Compositeness: A often-employed framework to explain hierarchical fermion masses

\[ \mathcal{L} = m_{i j}^u \bar{U}_i U_j + m_{i j}^q \bar{Q}_i Q_j + \xi_{i j} \bar{Q}_i U_i \Phi + \epsilon_i^u \bar{u}_R^i U_i + \epsilon_i^q \bar{q}_L^i Q_i \]

- Quark partners \(Q_i, U_i\) (and \(D_i\)) are vector-like
- Yukawa couplings can be \(O(1) \rightarrow \text{"anarchy"} \)
- Mixing parameters can be naturally small
- \(\Phi = \exp(i h \cdot T/f) \mathcal{H}\) contains Goldstones + Global Higgs
Global Higgs Fermionic Couplings

Possible Fermion Representations:

<table>
<thead>
<tr>
<th>$SO(5) \times U(1)_X$</th>
<th>$SO(4) \times U(1)_X$</th>
<th>$SU(2)_L \times U(1)_Y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{1}{3}$</td>
<td>$\frac{2}{3}$</td>
<td>$\frac{2}{3}$</td>
</tr>
<tr>
<td>$\frac{2}{3}$</td>
<td>$\frac{1}{3} + \frac{2}{3}$</td>
<td>$\frac{2}{3} + (\frac{2}{6} + \frac{2}{6})$</td>
</tr>
<tr>
<td>$\frac{1}{3}$</td>
<td>$\frac{1}{3} + \frac{1}{3}$</td>
<td>$\frac{1}{3} + (\frac{5}{6} + \frac{2}{6})$</td>
</tr>
<tr>
<td>$\frac{5}{3}$</td>
<td>$\frac{1}{3} + \frac{4}{3}$</td>
<td>$\frac{1}{3} + (\frac{3}{2} + \frac{2}{2})$</td>
</tr>
<tr>
<td>$\frac{2}{3}$</td>
<td>$\frac{2}{3} + \frac{6}{3}$</td>
<td>$(\frac{2}{6} + \frac{2}{6}) + (\frac{1}{3} + \frac{2}{3} + \frac{5}{3} + \frac{3}{3})$</td>
</tr>
<tr>
<td>$\frac{2}{3}$</td>
<td>$\frac{1}{3} + \frac{4}{3} + \frac{9}{3}$</td>
<td>$\frac{2}{3} + (\frac{2}{6} + \frac{7}{6}) + (\frac{3}{3} + \frac{3}{3} + \frac{3}{3})$</td>
</tr>
</tbody>
</table>
### Global Higgs Fermionic Couplings

#### Possible Fermion Representations:

<table>
<thead>
<tr>
<th>$SO(5) \times U(1)_X$</th>
<th>$SO(4) \times U(1)_X$</th>
<th>$SU(2)_L \times U(1)_Y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{1}{3}$</td>
<td>$\frac{1}{2}$</td>
<td>$\frac{1}{2}$</td>
</tr>
<tr>
<td>$\frac{5}{3}$</td>
<td>$\frac{1}{2} + \frac{4}{3}$</td>
<td>$\frac{1}{2} + \left(\frac{2}{3} \frac{1}{6} + \frac{2}{7} \frac{1}{6}\right)$</td>
</tr>
<tr>
<td>$\frac{5}{3}$</td>
<td>$\frac{1}{3} + \frac{4}{3}$</td>
<td>$\frac{1}{3} + \left(\frac{2}{3} \frac{5}{6} + \frac{2}{3} \frac{1}{6}\right)$</td>
</tr>
<tr>
<td>$\frac{5}{3}$</td>
<td>$\frac{1}{3} + \frac{4}{3}$</td>
<td>$\frac{1}{3} + \left(\frac{2}{3} \frac{3}{2} + \frac{2}{3} \frac{1}{2}\right)$</td>
</tr>
<tr>
<td>$\frac{10}{3}$</td>
<td>$\frac{4}{3} + \frac{6}{3}$</td>
<td>$\left(\frac{2}{3} \frac{1}{6} + \frac{2}{7} \frac{1}{6}\right) + \left(\frac{1}{3} \frac{1}{3} + \frac{2}{3} \frac{1}{3} + \frac{5}{3} \frac{1}{3} + \frac{3}{3} \frac{1}{3}\right)$</td>
</tr>
<tr>
<td>$\frac{14}{3}$</td>
<td>$\frac{1}{3} + \frac{4}{3} + \frac{9}{3}$</td>
<td>$\frac{1}{3} + \left(\frac{2}{3} \frac{1}{6} + \frac{2}{7} \frac{1}{6}\right) + \left(\frac{3}{3} \frac{1}{3} + \frac{3}{3} \frac{2}{3} + \frac{3}{3} \frac{3}{3}\right)$</td>
</tr>
</tbody>
</table>

**SM-like** + **Exotic**
### Possible Fermion Representations:

<table>
<thead>
<tr>
<th>$SO(5) \times U(1)_X$</th>
<th>$SO(4) \times U(1)_X$</th>
<th>$SU(2)_L \times U(1)_Y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{1}{3}$</td>
<td>$\frac{1}{3}$</td>
<td>$\frac{1}{3}$</td>
</tr>
<tr>
<td>$\frac{5}{3}$</td>
<td>$\frac{1}{3} + \frac{4}{3}$</td>
<td>$\frac{1}{3} + (\frac{2}{6} + \frac{7}{6})$</td>
</tr>
<tr>
<td>$\frac{5}{6}$</td>
<td>$\frac{1}{3} + \frac{4}{3}$</td>
<td>$\frac{1}{3} + (\frac{2}{6} + \frac{5}{6} + \frac{2}{6})$</td>
</tr>
<tr>
<td>$\frac{5}{1}$</td>
<td>$1 + 4$</td>
<td>$1 + (\frac{2}{3} + \frac{2}{3})$</td>
</tr>
<tr>
<td>$\frac{10}{6}$</td>
<td>$\frac{4}{3} + \frac{6}{3}$</td>
<td>$(\frac{2}{6} + \frac{7}{6}) + (\frac{1}{3} + \frac{2}{3} + \frac{5}{3} + \frac{3}{3})$</td>
</tr>
<tr>
<td>$\frac{14}{3}$</td>
<td>$\frac{4}{3} + \frac{9}{3}$</td>
<td>$\frac{1}{2} + (\frac{2}{6} + \frac{7}{6}) + (\frac{3}{3} + \frac{2}{3} + \frac{3}{3})$</td>
</tr>
</tbody>
</table>

- **SM-like**
- **Exotic**

- New vector-like matter that can potentially be observed at LHC (top partners mainly)
GLOBAL HIGGS FERMIONIC COUPLINGS

- Couplings determined in part by group theory
- Realistic fermion sectors predict various SO(4) irreps $\phi\psi\psi$
**Global Higgs Fermionic Couplings**

- Couplings determined in part by group theory
- Realistic fermion sectors predict various SO(4) irreps

### SO(5) Yukawas

**GH embedded in fundamental \( \Phi \) of SO(5)**

<table>
<thead>
<tr>
<th>proto-Yukawa</th>
<th>( F \Phi S' )</th>
<th>( FA' \Phi )</th>
<th>( FB' \Phi )</th>
<th>( F \Psi F' )</th>
<th>( \tilde{S} \text{tr} \Psi B' )</th>
<th>( \text{tr} \tilde{A} \Psi A' )</th>
<th>( \text{tr} \tilde{B} \Psi B' )</th>
<th>( \text{tr} \tilde{B} \Psi A' )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \phi \bar{ss}' )</td>
<td>1</td>
<td>–</td>
<td>( \frac{2}{\sqrt{5}} )</td>
<td>( \frac{2}{\sqrt{5}} )</td>
<td>1</td>
<td>–</td>
<td>( \frac{3}{2\sqrt{5}} )</td>
<td>–</td>
</tr>
<tr>
<td>( \phi \bar{ff}' )</td>
<td>–</td>
<td>( \frac{1}{\sqrt{2}} )</td>
<td>( \frac{1}{\sqrt{2}} )</td>
<td>( \frac{1}{2\sqrt{5}} )</td>
<td>–</td>
<td>( \frac{3}{4\sqrt{5}} )</td>
<td>( \frac{3}{4\sqrt{5}} )</td>
<td>( \frac{\sqrt{5}}{4} )</td>
</tr>
<tr>
<td>( \phi \bar{aa}' )</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>( \frac{1}{2\sqrt{5}} )</td>
<td>–</td>
</tr>
<tr>
<td>( \phi \bar{bb}' )</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>( \frac{1}{2\sqrt{5}} )</td>
<td>–</td>
</tr>
</tbody>
</table>
Global Higgs Fermionic Couplings

- Couplings determined in part by group theory
- Realistic fermion sectors predict various SO(4) irreps

SO(5) Yukawas

$GH$ embedded in fundamental $\Phi$
$GH$ embedded in symmetric $\Psi$

$\begin{array}{c|cccc|cccc|c}
\text{proto-Yukawa} & \tilde{F} \Phi S' & \tilde{F} A' \Phi & \tilde{F} B' \Phi & \tilde{F} \Psi F' & \bar{S} \text{tr} \Psi B' & \text{tr} \bar{A} \Psi A' & \text{tr} \bar{B} \Psi B' & \text{tr} \bar{B} \Psi A' \\
\hline
\phi ss' & 1 & - & \frac{2}{\sqrt{5}} & \frac{2}{\sqrt{5}} & 1 & - & \frac{3}{2\sqrt{5}} & - \\
\phi ff' & - & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{2\sqrt{5}} & - & \frac{3}{4\sqrt{5}} & \frac{3}{4\sqrt{5}} & \frac{\sqrt{5}}{4} \\
\phi aa' & - & - & - & - & - & \frac{1}{2\sqrt{5}} & - & - \\
\phi bb' & - & - & - & - & - & \frac{1}{2\sqrt{5}} & - & - \\
\end{array}$

SO(4) Yukawas

- $\phi ss'$ 1-1
- $\phi ff'$ 4-4
- $\phi aa'$ 6-6
- $\phi bb'$ 9-9
Loops of new fermions couple GH to gluons (and photons / weak bosons)
Loops of new fermions couple GH to gluons (and photons / weak bosons)

\[ \phi \ G_{\mu\nu}G^{\mu\nu} \]

Many SO(4) irreps

- Large Multiplicity can potentially enhance these couplings.
- In a large part of parameter space, these couplings do not depend on details of fermionic sector (only multiplicities)
Loops of new fermions couple GH to gluons (and photons / weak bosons)

\[ \phi \, G_{\mu\nu}G^{\mu\nu} \]

Many SO(4) irreps

Large Multiplicity can potentially enhance these couplings.

In a *large part of parameter space*, these couplings do not depend on details of fermionic sector (only multiplicities)

(when symmetry breaking contributions to fermion masses can be treated perturbatively)
Benchmark Models

Defined by SO(5) representations of fermion partners

- $\text{MCMH}_{5-1-10} \; Q_i, U_i, D_i = (5, 1, 10)$
  - Yukawa Anarchy
- $\text{MCMH}_{5-1-10} \; Q_i, U_i, D_i = (5, 14, 10)$
  - High Multiplicity
- $\text{MCMH}_{5-1-10} \; Q_i, U_i, D_i = (14, 14, 10)$
- $\text{MCMH}_{5-1} \; Q_3, U_3 = (5, 1)$
  - Hierarchical, low multiplicity
**Benchmark Models**

Defined by SO(5) representations of fermion partners

<table>
<thead>
<tr>
<th>Model</th>
<th>Q, U, D</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCMH(_{5-1-10})</td>
<td>(5, 1, 10)</td>
<td>Yukawa Anarchy</td>
</tr>
<tr>
<td>MCMH(_{5-1-10})</td>
<td>(5, 14, 10)</td>
<td>High Multiplicity</td>
</tr>
<tr>
<td>MCMH(_{5-1-10})</td>
<td>(14, 14, 10)</td>
<td></td>
</tr>
<tr>
<td>MCMH(_{5-1})</td>
<td>(5, 1)</td>
<td>Hierarchical, low multiplicity</td>
</tr>
</tbody>
</table>

After fixing the Yukawas, get loop induced couplings:

<table>
<thead>
<tr>
<th>Model</th>
<th>(c_{gg})</th>
<th>(c_{\gamma\gamma})</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCMH(_{5-1-10})</td>
<td>0.013</td>
<td>0.0054</td>
</tr>
<tr>
<td>MCMH(_{5-1-10})</td>
<td>0.014</td>
<td>0.0063</td>
</tr>
<tr>
<td>MCMH(_{5-1-10})</td>
<td>0.011</td>
<td>0.0060</td>
</tr>
<tr>
<td>MCMH(_{5-10})</td>
<td>0.010</td>
<td>0.0021</td>
</tr>
</tbody>
</table>

\[ c_{xx} \frac{f}{M_{\text{ferm}}^2} \phi F_{\mu\nu}^2 \]
E∗imate of Couplings

- Large multiplicities also affect the running of the Yukawa coupling

\[ \mu \frac{d}{d\mu} \xi^2_{\text{eff}} = \frac{\xi^4_{\text{eff}}}{16\pi^2} \]

- Perturbativity limits on Yukawa (model dependent)
  - For anarchic models: \( \xi < 0.4 \ldots 0.5 \)
  - (For hierarchic model: \( \xi < 1.2 \))

\[ \xi^2_{\text{eff}} = N_{\text{eff}} \xi^2 \]

model-dependent
eff. multiplicity

SO(5) Yukawa
ESTIMATE OF COUPLINGS

- Large multiplicities also affect the running of the Yukawa coupling

\[ \mu \frac{d}{d\mu} \xi_{\text{eff}}^2 = \frac{\xi_{\text{eff}}^4}{16\pi^2} \]

- Perturbativity limits on Yukawa (model dependent)
  - For anarchic models: \( \xi < 0.4 \ldots 0.5 \)
  - (For hierarchic model: \( \xi < 1.2 \))

- The quartic self-coupling \( \lambda \phi^4 \)
  - Similarly to light/heavy SM Higgs
    - Upper bound from Landau pole: \( \lambda < 2.5-2.6 \) \( (\lambda < 3.9) \)
    - Lower bound from stability: \( \lambda > 0.1-0.2 \) \( (\lambda > 2.3) \)
**Parameter Space**

- $\xi$: Yukawa coupling $\rightarrow$ fix to NDA value
- $f$: *Global Higgs* decay constant
  - Higgs couplings $f \leq 800$ GeV
  - Fine tuning: want $f$ small!
PARAMETER SPACE

- $\xi$: Yukawa coupling $\rightarrow$ fix to NDA value
- $f$: Global Higgs decay constant
  - Higgs couplings $f \leq 800$ GeV $\rightarrow$ fix $f = 800$ GeV
  - Fine tuning: want $f$ small!
Parameter Space

- $\xi$: Yukawa coupling $\rightarrow$ fix to NDA value
- $f$: Global Higgs decay constant
  - Higgs couplings $f \lesssim 800 \text{ GeV}$ $\rightarrow$ fix $f = 800 \text{ GeV}$
  - Fine tuning: want $f$ small!

- $\hat{f}$: Global Higgs vacuum exp. value
- $\lambda$: Global Higgs self coupling
- $M_{\text{ferm}}$: Fermion mass scale
**PARAMETER SPACE**

- $\xi$: Yukawa coupling $\rightarrow$ fix to NDA value
- $f$: *Global Higgs* decay constant
  - Higgs couplings $f \lesssim 800$ GeV $\rightarrow$ fix $f = 800$ GeV
  - Fine tuning: want $f$ small!

- $m_{\phi}$: *Global Higgs* vev mass
- $\lambda$: *Global Higgs* self coupling
- $M_{\text{ferm}}$: Fermion mass scale
**Parameter Space**

- $\xi$: Yukawa coupling $\rightarrow$ fix to NDA value
- $f$: *Global Higgs* decay constant
- Higgs couplings $f \lesssim 800$ GeV $\rightarrow$ fix $f = 800$ GeV
- Fine tuning: want $f$ small!

- $m_\phi$: *Global Higgs* vev mass
- $\lambda$: *Global Higgs* self coupling
- $M_{\text{ferm}}$: Fermion mass scale

- Caveat: For small vectorlike masses, pheno depends on details of the fermion sector!
The Width of the Global Higgs

- If decays into fermions are closed, decays predominantly into EW gauge bosons and tops → Narrow Resonance
The Width of the Global Higgs

- If decays into fermions are closed, decays predominantly into EW gauge bosons and tops $\rightarrow$ Narrow Resonance

- If decays into fermions are open $\rightarrow$ Broad Resonance
  
  Width/Mass $\sim 0.5...0.9$
Decays into Ew Bosons and Tops

\[ \Gamma_{\phi \rightarrow EW} \sim \frac{f^4 m_{\phi}^2}{\hat{f}^6} \sim \frac{\lambda^3 f^4}{m_{\phi}^3} \]

\[ \Gamma_{\phi \rightarrow t\bar{t}} \sim \frac{m_t^2 m_{\phi}}{\hat{f}^2} \sim \frac{m_t^2 \lambda}{m_{\phi}} \]

Figure 1. Regions in the \( m_{\phi} \)–\( \lambda \)-plane where the global Higgs decays dominantly into NGBs or \( t\bar{t} \) pairs, assuming that all fermion resonances are heavier than the global Higgs. We take \( \hat{f} = 800 \) GeV. The shaded region below the \( \hat{f} = 3f \) line requires a large hierarchy between \( \hat{f} \) and \( f \), and may not be realized in typical strongly coupled scenarios. We also show a current bound adapted from the ATLAS heavy Higgs search of Ref. [8], which shows that the global Higgs must be heavier than about 750 GeV.
LHC PHENOMENOLOGY OF THE
GLOBAL HIGGS
LHC Production

- Production modes similar to SM Higgs (Gluon fusion/Vector Boson Fusion)

Figure 2. Global Higgs production rates via gluon fusion (left) and vector-boson fusion (right), as a function of the global Higgs mass. Red and purple lines correspond to $M = m$ and $M = 2m$, respectively. Plain, dashed and dotted lines correspond to $\gamma = 0.2, 1, 3$, respectively.

We see that the total production rate is high enough to motivate a more precise study of the LHC implications of the presence of a global Higgs. In the following, since the VBF process is important only for large $m$, we choose to focus on a $pp + jj + X$ final state, without requiring forward jet tagging.

The LHC signals of the global Higgs can be split into two broad cases:

• Case I: All decays involving fermion resonances are closed. The phenomenology is then largely independent of the details of the heavy fermion sector, and the narrow width approximation applies. We study this case in Sec. 4.

• Case II: Some decays involving fermion resonances are open, and the phenomenology depends strongly on the realization of the fermion sector. Some generic aspects of this case will be discussed in Sec. 5.

4 Global Higgs Discovery Prospects: Decays into SM Particles

In this section we provide an estimate of the LHC sensitivity for detecting the global Higgs at a center-of-mass energy of 13 TeV and with 300 fb$^{-1}$ of integrated luminosity, assuming that all decays involving fermion resonances are kinematically forbidden. We will take $M = m$ for definiteness, and we will therefore present our results in the $m$ plane.

The main decay channels to be investigated, $\gamma \gamma, ZZ, W^+W^-$, were discussed in Fig. 1, which shows the dominant channels in different regions of parameter space. Here we explore them in more detail.
LHC Production

- Production modes similar to SM Higgs (Gluon fusion/Vector Boson Fusion)

Typically GGF > VBF

In some regions of parameter space VBF dominates
LHC Production

- Production modes similar to SM Higgs (Gluon fusion/Vector Boson Fusion)

Typically GGF > VBF
In some regions of parameter space VBF dominates
LHC Discovery Potential

- When decays into fermion partners are closed, most promising discovery channels are diboson and $tt$.
**LHC Discovery Potential**

- When decays into fermion partners are closed, most promising discovery channels are **diboson** and **tt**

**Diboson (WW or ZZ)**

- Largest branchings are hadronic decays of W/Z
- Decay products appear in highly boosted jets (fat jets J)
  \[ pp \rightarrow \phi \rightarrow JJ \]
- Detailed backgrounds adapted from [ATLAS 1506.00962](https://arxiv.org/abs/1506.00962)
When decays into fermion partners are closed, most promising discovery channels are diboson and $tt$

**Diboson ($WW$ or $ZZ$)**
- Largest branchings are hadronic decays of $W/Z$
- Decay products appear in highly boosted jets (fat jets $J$)
  $$pp \to \phi \to JJ$$
- Detailed backgrounds adapted from [ATLAS 1506.00962](https://arxiv.org/abs/1506.00962)

**Tops ($pp \to \phi \to tt$)**
- Tops are highly boosted
- Expected sensitivities in this channel can be extracted from generic bump searches in $m_{tt}$ [ATLAS CONF 2016-014](https://cds.cern.ch/record/2166805)
LHC Discovery Potential

\begin{center}
\begin{tikzpicture}
\begin{axis}[
    xlabel={$m_\phi$ [TeV]},
    ylabel={$\lambda$},
    xmin=0, xmax=5,
    ymin=0, ymax=3,
    xtick={0,1,2,3,5},
    ytick={0.2,0.5,1,1.5,2,3},
    xlabel style={at={(ticklabel* cs:1)},anchor=north east},
    ylabel style={at={(ticklabel* cs:1)},anchor=south east},
    legend style={at={(1,0.5)},anchor=north}
]
\addplot[red,fill=red!30] coordinates {(1,2)(2,1)(3,0.5)(4,0.2)}; 
\addlegendentry{$B_0>3$}
\addplot[gray,fill=gray!30] coordinates {(1,2)(2,1)(3,0.5)(4,0.2)}; 
\addlegendentry{$B_0>12$}
\addplot[yellow,fill=yellow!30] coordinates {(1,2)(2,1)(3,0.5)(4,0.2)}; 
\addlegendentry{$B_0>150$}
\addplot[red,fill=red!50] coordinates {(1,2)(2,1)(3,0.5)(4,0.2)}; 
\addlegendentry{95\% CL}
\addnode{Unphysical}{(f < f)} at (axis cs:1,2);
\addnode{ATLAS 4l run I}{pp$\to\phi$JJ 300 fb$^{-1}$} at (axis cs:1,0.5);
\addnode{pp$\to\phi$t$\bar{t}$ 300 fb$^{-1}$} at (axis cs:1,0.2);
\end{axis}
\end{tikzpicture}
\end{center}

Figure 4. Projected LHC sensitivities to a global Higgs signal with 300 fb$^{-1}$ at 13 TeV. The light blue region is a bound adapted from an ATLAS heavy Higgs search [8]. The light red region is a projected 95\%CL limit from boosted top quark searches, as extrapolated from Ref. [22]. The red, gray, yellow regions show the discovery Bayes factor for the global Higgs in the pp$\to\phi$JJ channel, and correspond respectively to weak, moderate and strong evidence for the signal hypothesis.

Greater for smaller $\lambda$, reflecting the larger gluon fusion production rate, as explained in Sec. 3. We also see that the boosted $t\bar{t}$ channel is less sensitive, with a mass reach of $m_\phi \ll 1.5$ TeV for low $\lambda$. At larger values of $\lambda$ the sensitivity of this search disappears because the BR($p\to t\bar{t}$) becomes suppressed (see Fig. 1).

We emphasize that these sensitivities constitute only rough estimates, based on extrapolations of specific experimental analyses. This work should be viewed as a first step towards a more realistic analysis. Still, it is rather encouraging that these results appear to be competitive with projected searches for top partners (for example, in the recent analysis of Ref. [23], the mass reach for top partners is found to be around 1 TeV assuming 100 fb$^{-1}$). Therefore, there is a concrete possibility that the global Higgs can be the first manifestation of compositeness detectable at the LHC.

5 Top Partners from Global Higgs Decays

In this section we consider the case where the global Higgs can decay into channels involving fermion resonances. Of the large number of resonances present in scenarios of the type described in Sec. 2, one can reasonably expect that a subset of those related to the top sector would be the lightest. This is typically a consequence of the large elementary-composite mixing characterizing the top sector. For definiteness, we will assume that only
DECAYS INTO FERMIONS
Decays into Fermions

- When decays into fermion partners are open
  - some partner(s) are light
  - symmetry breaking contributions to fermion masses no longer subdominant.
  - more model dependence

- Assume only one fermion light (top partner $t'$), $\phi$ production not affected much

- $t'$ searches main experimental strategies in CH pheno
  (current LHC bounds around $m_{t'} > 750$ GeV)
Decays into Fermions

- When decays into fermion partners are open
  - some partner(s) are light
  - symmetry breaking contributions to fermion masses no longer subdominant.
  - more model dependence

- Assume only one fermion light (top partner $t'$), $\phi$ production not affected much

- $t'$ searches main experimental strategies in CH pheno
  (current LHC bounds around $m_{t'} > 750 \text{ GeV}$)

- $t'$ production via Global Higgs is resonant
- mixed decays: $t$ is always highly boosted
  $\phi \rightarrow t't$
- $t'$ significantly lighter than the $\phi$
  $\phi \rightarrow t't'$
  $t'$ will be boosted → fat jet
Decays into Fermions

- Fractions of merged $t'$ decays in function of masses:

![Fraction of merged $t'$ decays in the $m_{t'} - m_{\phi}$ plane for the cases of $t_0 \rightarrow \bar{t} t'$ (left plots) and $t_0 \rightarrow \bar{t} \bar{t}$ (right plots). In the white region, these decays cannot occur on-shell. The plots from top to bottom correspond to the possible $t_0$ decays, $t_0 \rightarrow t \bar{t}$, $t_0 \rightarrow tZ$, and $t_0 \rightarrow bW$. The gray vertical band is a conservative 95% exclusion region from Run I searches. The dashed line is an estimate of the merging region following the calculation of App. B, assuming azimuthal $t_0$ opening angle (see Eq. (B.6)).]{fig}

- $\phi \rightarrow t' \bar{t}' (t' \rightarrow th)$

- $\phi \rightarrow t' \bar{t}$
CONCLUSIONS
CONCLUSIONS

- The excitation of the $\text{SO}(5) \rightarrow \text{SO}(4)$ breaking vacuum (Global Higgs) may be the first hint of a “Higgs as a NGB” scenario.
- Partial compositeness paradigm implies large production cross section in gluon fusion.
- Two scenarios at the LHC:
  - Scenario 1: Decays into fermion partners are closed: detection in diboson (also tt) channel, with sensitivity $\sim 2.5 \text{ TeV}$ after 300 $\text{fb}$ of data
  - Scenario 2: Decays into to partners are open: resonant single/double production of $t'$, with boosted decay products that appear as $t'$ jets, dedicated analysis necessary.