Double Higgs production via gluon fusion ($gg \rightarrow hh$) in composite models

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*based on work in collaboration with*

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Introduction: why is \( gg \rightarrow hh \) interesting?

- Gluon fusion \( gg \rightarrow h, hh \) is the dominant mechanism for Higgs production at LHC.
- In the SM, amplitudes mediated by top loops.

Measurement of Higgs self-coupling, long history of studies (still ongoing).

- In Composite Higgs models, two effects arise: modifications of top couplings, and new fermionic resonances enter in loops.

- Experimentally very challenging signal for \( m_h = 125 \text{ GeV} \):
  best final state \( hh \rightarrow \gamma\gamma b\bar{b} \), **at least \( O(100) \text{ fb}^{-1} \) at LHC14 needed** to probe it in BSM with enhanced cross section (in the SM, even larger luminosity).
Sensitivity to fermionic resonances

**Single production:** $gg \rightarrow h$

- Well-known result: in many composite models (both with and without collective breaking) the single production cross section $\sigma(gg \rightarrow h)$ only depends on the overall scale of the strong sector $f$, and **not on the masses of resonances**.
- Nontrivial result (not true e.g. in SUSY!), follows from a cancellation between correction to top Yukawa and loops of resonances
- Result exactly true in the “Higgs low-energy theorem” approximation $\leftrightarrow m_h \ll m_t, T$

Corrections to this approximation are very small, at most few %.

**Double production:** $gg \rightarrow hh$

- Low-energy theorem gives same answer: no sensitivity to masses of resonances.
- But expect the approximation to be less accurate: expansion in $\sim \hat{s}/(4m_t^2)$ is safe for single production, $\hat{s} = m_h^2$
  but doubtful for double production, $\hat{s} \geq 4m_h^2$
\textbf{gg} \rightarrow \textit{hh} including resonances

• Expect large corrections to the LET: in the SM accurate at \sim 20\%, in BSM could get worse! motivates a full computation of \( \sigma(gg \rightarrow hh) \), including all resonances in loops

• Also, masses of resonances are related to the Higgs mass (Higgs potential generated at loop level) \implies \text{upper bound} \quad m_T \lesssim 700 \text{ GeV} \left( \frac{f}{500 \text{ GeV}} \right) \left( \frac{m_h}{125 \text{ GeV}} \right)

So some resonances must be light, their effects in loops expected to be relevant!

see e.g. Pomarol and Riva, 1205.6434

• Choose a specific model, MCHM5. Minimal model but \textbf{realistic}: discuss constraints from electroweak data and from LHC searches for vector-like fermions.

A compositeness scale as low as \( f = 500 \text{ GeV} \) is allowed (\sim 20\% fine-tuning).

\textit{gg} \rightarrow \textit{hh} cross section known to be \textbf{largely enhanced} compared to SM (around a factor 3 for \( f = 500 \text{ GeV} \)) from previous studies without resonances.
Results

Points are exact cross section:
- All points pass EWPT at 99% CL
- Color code depending on point surviving (or not) LHC&Tevatron searches for heavy fermions

Dashed line is low-energy theorem result

• LET fares worse than in the SM: severe underestimate of cross section, corrections up to 50%
• We find a **sizable sensitivity to the masses of resonances**, cross section is *less enhanced* for very light top partner
• Rough estimate of experimental sensitivity: $O(10)$ events after all cuts and efficiencies at LHC14 with 300 fb$^{-1}$, in $hh \rightarrow \gamma\gamma b\bar{b}$ final state (1 $b$-tag)
Backup
Higgs couplings to gluons via the low-energy theorem

• Heavy colored particle getting some of its mass from EWSB, \( m(H) \)

• For \( m_h \ll m \), can integrate the particle out and write effective Lagrangian:
  leading term in \( 1/m \) will read \( F(H)G^{\alpha}_{\mu\nu}G^{\mu\nu\alpha} \).

• Fix the function \( F(H) \): treat \( H \) as background field, then \( m(H) \) is a threshold for the running of QCD gauge coupling

\[
\mathcal{L}_{\text{eff}} = -\frac{1}{4g_{\text{eff}}^2(\mu, H)}G^{\alpha}_{\mu\nu}G^{\alpha\mu\nu}, \quad \frac{1}{g_{\text{eff}}^2(\mu, H)} = \frac{1}{g_s^2(\Lambda)} - \frac{b_{UV}}{8\pi^2} \log \frac{\Lambda}{\mu} - \delta b \frac{1}{8\pi^2} \log \frac{m(H)}{\mu}
\]

• For Dirac fermions \( \delta b = 2/3 \) \( \rightarrow \) \( \mathcal{L}_{\text{eff}} = \sum_f \frac{g_s^2}{96\pi^2}G^{\alpha}_{\mu\nu}G^{\alpha\mu\nu} \log m_f^2(H) \)

and expanding get (\( H = \langle H \rangle + h \))

\[
\mathcal{L}_{hh^g} = \frac{g_s^2}{96\pi^2}G^{\alpha}_{\mu\nu}G^{\alpha\mu\nu} \left[ A_1 h + \frac{1}{2} A_2 h^2 + \ldots \right]
\]

\[
A_n \equiv \left( \frac{\partial^n}{\partial H^n} \log \det \mathcal{M}^\dagger(H)\mathcal{M}(H) \right)_{\langle H \rangle}
\]

Ellis et al., NPB 1976
Shifman et al., SJNP 1979
**hgg coupling in specific models**

• In many popular models (both composite and Little Higgs), the gluon fusion cross section depends only on $\xi \equiv v^2 / f^2$, and is **independent of the couplings and masses of the heavy fermions**

• Remarkable result (not true in other cases, e.g. SUSY), it happens because the determinant of fermion mass matrix has the form

$$\det \mathcal{M}^\dagger(H) \mathcal{M}(H) = F(H/f) \times P(\lambda_i, M_i, f)$$

so taking $\frac{\partial}{\partial H} \log [F(H/f) \times P]$ the dependence on $P$ cancels!

• Example: $SO(5)/SO(4)$ with composite fermions in a 5 (fundamental)

$$\det \mathcal{M}^\dagger(H) \mathcal{M}(H) = \sin^2 (2H/f) \times P(y, M_0, f, \ldots)$$

• Independence of spectrum is exactly true in the infinite fermion mass approximation

  low-energy theorem. *Corrections due to higher orders in $1/m_f$ ?*
Finite mass corrections: a full computation

• Take specific model: $SO(5)/SO(4)$ with 1 multiplet of composite fermions in fundamental representation

• Top sector has 4 states: top + 3 partners

• Full numerical result, including all fermions and mass dependence:

\[
\sigma/\sigma_{SM} = \left(\frac{1-2\xi}{\sqrt{1-\xi}}\right)^2
\]

\[
pp \to h, \; \xi = 0.25
\]

Note the sizable suppression compared to the SM!

…but BRs enhanced

• Corrections to LET very small as estimated: $\delta \sigma/\sigma_{SM} \sim (0.06 \xi) \sim 0.015$

• For single production, low-energy theorem gives excellent approximation, for any spectrum of extra fermions.
Minimal composite Higgs model

- Higgs as a pseudo-Goldstone boson of spontaneous symmetry breaking \( g/H \)
  explain “Little Hierarchy” between EW scale and scale of new strong sector.

- Minimal choice containing custodial symmetry (needed to protect \( \rho \) parameter) is \( SO(5)/SO(4) \), giving four GBs in a 4 of \( SO(4) \sim SU(2)_L \times SU(2)_R \)

- Goldstones are described in terms of the field

\[
\Sigma = \Sigma_0 e^{\Pi/f}, \quad \Pi = -i\sqrt{2} T^a h^a, \quad \Sigma_0 = (0, 0, 0, 0, 1)
\]

\[
\Sigma = \frac{\sin(h/f)}{h} (h_1, h_2, h_3, h_4, h \cotan(h/f)), \quad h = \sqrt{\sum_a h^2_a}
\]

and the two-derivative Lagrangian is

\[
\mathcal{L} = \frac{f^2}{2} (D_\mu \Sigma)(D^\mu \Sigma)^T
\]

\[
(D_\mu \Sigma = \partial_\mu \Sigma + ig W^a_\mu \Sigma T^a_L + ig' B_\mu \Sigma T^3_R)
\]

- Can write in unitary gauge

\[
\Sigma = (0, 0, \sin(H/f), 0, \cos(H/f))
\]

where \( H \) is the Higgs field (with \( \langle H \rangle \neq 0 \)).

Agashe et al., hep-ph/0412089
Partial compositeness Lagrangian

• Composite multiplet can be written as:

\[ 5 \sim (2, 2) \oplus (1, 1) \]

Under \( SU(2)_L \times SU(2)_R \),

\[ Q = \begin{pmatrix} T \\ B \end{pmatrix}, \quad X = \begin{pmatrix} X^{5/3} \\ X^{2/3} \end{pmatrix} \]

peculiar of 5 representation, contains a charge 5/3 fermion

• \( Q \) has the EW quantum numbers of \( q_L \), while \( \tilde{T} \) of \( t_R \)

• Minimal Lagrangian:

\[ \mathcal{L}_f = i \bar{q}_L \dot{q}_L + i \bar{t}_R \dot{t}_R + i \bar{b}_R \dot{b}_R + i \bar{\psi}_L \dot{\psi}_L + i \bar{\psi}_R \dot{\psi}_R - y_f (\bar{\psi}_L \Sigma^T)(\Sigma \psi_R) - M_0 \bar{\psi}_L \psi_R + \text{h.c.} \]

\[ - \Delta_L \bar{q}_L Q_R - \Delta_R \bar{T}_L t_R + \text{h.c.} \]

composite “proto-Yukawa”, \( SO(5) \) invariant

elementary/composite mixings break global symmetry

• Notice that there is no composite with quantum numbers of \( b_R \)

no mass for the bottom is generated (need for ex. a \( 5_{-1/3} \))
Fermion masses

• Diagonalization of masses is simple for $v = 0$ ($\Sigma = \Sigma_0$): rotate

$$
\begin{pmatrix}
q_L \\
Q_L
\end{pmatrix}
\rightarrow
\begin{pmatrix}
\cos \phi_L & \sin \phi_L \\
-\sin \phi_L & \cos \phi_L
\end{pmatrix}
\begin{pmatrix}
q_L \\
Q_L
\end{pmatrix}, \quad \tan \phi_L = \frac{\Delta_L}{M_0}
$$

$$
\begin{pmatrix}
t_R \\
\tilde{T}_R
\end{pmatrix}
\rightarrow
\begin{pmatrix}
\cos \phi_R & \sin \phi_R \\
-\sin \phi_R & \cos \phi_R
\end{pmatrix}
\begin{pmatrix}
t_R \\
\tilde{T}_R
\end{pmatrix}, \quad \tan \phi_R = \frac{\Delta_R}{M_0 + yf}
$$

• SM states are a linear combination of elementary and composite states

$\phi_{L,R}$ parameterize the degree of compositeness of $t_{L,R}$

• In this limit the top is massless, and composites have masses

$$M_Q = \frac{M_0}{c_L}, \quad M_X = M_0, \quad M_{\tilde{T}} = \frac{yf + M_0}{c_R}$$

• Turning on EWSB, top becomes massive via mixing of $t_{L,R}$ with composites:

$$m_t = y \sin \phi_L \sin \phi_R \frac{v}{\sqrt{2}} \left(1 + O(\xi)\right)$$

• After setting the top mass to exp value, model fully described by 4 parameters:

$$\xi \equiv \frac{v^2}{f^2}, \quad \phi_L, \quad \phi_R, \quad R = \frac{(M_0 + yf)}{M_0}$$
Electroweak precision tests

Three beyond-SM contributions to $\epsilon_i, \epsilon_b$ parameters:

- Modified coupling of the Higgs to gauge bosons
  
  \[ \Delta \epsilon_3^{\text{IR}} = \frac{\alpha(M_Z)}{48\pi \sin^2 \theta_W} \xi \log \left( \frac{m^2_\rho}{m^2_h} \right), \quad \Delta \epsilon_1^{\text{IR}} = -\frac{3 \alpha(M_Z)}{16\pi \cos^2 \theta_W} \xi \log \left( \frac{m^2_\rho}{m^2_h} \right) \]

Barbieri et al., 0706.0432

- UV contribution to $S$ from tree-level exchange of spin-1 resonances
  
  \[ \Delta \epsilon_3^{\text{UV}} = \frac{m^2_W}{m^2_\rho} \left( 1 + \frac{m^2_\rho}{m^2_a} \right) \approx 1.36 \frac{m^2_W}{m^2_\rho} \]

- 1-loop contributions to $T$ and $\epsilon_b \sim Z-b_L-\bar{b}_L$

  from heavy fermions

In general need a **positive contribution to $T$** to get back into the ellipse, but at the same time need to control correction to $\epsilon_b$

non-trivial interplay!

Barbieri et al., 0706.0432

Gillioz, 0806.3450

Anastasiou, Furlan and Santiago, 0901.2117
Electroweak precision tests (2)

Perform numerical analysis, allowing $1.5 \text{ TeV} < m_\rho < 4\pi f$

For largish $\xi$, **two regions** satisfying the constraints are found:

1) Singlet $\tilde{T}$ lighter than rest of the spectrum: it contributes positively to $T$ and to $\epsilon_b$. In this region $\sin \phi_L < 0.5$, so $t_R$ has sizable degree of compositeness.

2) Large $\sin \phi_L \rightarrow t_L$ largely composite, doublet $X = \left( X^{5/3}, X^{2/3} \right)$ is light. Intricated interplay of contributions to EW parameters.

*Note that a light Higgs requires at least one light fermionic resonance:*

$$m_Q \lesssim 700 \text{ GeV} \left( \frac{f}{500 \text{ GeV}} \right) \left( \frac{m_h}{125 \text{ GeV}} \right)$$

see for example Pomarol and Riva, 1205.6434

![Diagram showing regions of parameter space](https://example.com/diagram.png)
Bounds from collider searches

- Searches for heavy fermions at Tevatron\&LHC put constraints on the model:
  - pair production via QCD, decay into 3rd gen fermions
  - and Goldstones: leading order BRs
    \[
    \text{BR}(\tilde{T} \to Wb) = \frac{1}{2}, \quad \text{BR}(\tilde{T} \to Zt) = \text{BR}(\tilde{T} \to ht) = \frac{1}{4};
    \]
    \[
    \text{BR}(X^{2/3} \to Zt) = \text{BR}(X^{2/3} \to ht) = \frac{1}{2}, \quad \text{BR}(X^{5/3} \to Wt) = 1
    \]
    from Yukawas, using Goldstone equivalence theorem

- Exp searches in final states \( WbWb, ZtZt, WtWt \)

- Region of composite \( t_L \) (large \( \sin \phi_L \)) is already strongly constrained:
  - \( X^{5/3} \) is light and decays with \( \text{BR} = 1 \) into \( tW \)
  - and thus \( \sin \phi_L < 0.8 \)

- Region of composite \( t_R \) less constrained:
  - \( \tilde{T} \) is light, strongest bound from \( WbWb \)
  - channel \( m_{\tilde{T}} > 400 \text{ GeV} \)

Contino and Servant, 0801.1679
Aguilar-Saavedra, 0907.3155,
Dissertori et al., 1005.4414
Higgs pair production in MCHM5 (2)

- Best final state for Higgs pair production at LHC, for a light Higgs, is $hh \rightarrow b\bar{b}\gamma\gamma$
- We follow the analysis of Baur et al., hep-ph/0310056
  roughly estimate the number of events at LHC14 by computing
  $\sigma(pp \rightarrow hh) \times \text{BR}(hh \rightarrow b\bar{b}\gamma\gamma)$ and multiplying times the efficiency of cuts for the SM ($\epsilon \approx 7\%$)
- QCD K-factor is 1.9; require 1 $b$-tagged jet
- Take background estimate of Baur et al. (likely conservative):
  3σ evidence at LHC for $\xi = 0.25$, 5σ discovery at SuperLHC even for $\xi = 0.1$

*see also* Contino et al., 1205.5444
**$h\gamma\gamma$ coupling**

- Contributions from fermion loops and $W$ loop.

Another SILH operator is relevant:

$$\mathcal{O}_\gamma = c_\gamma \frac{g'_2}{16\pi^2} \frac{g^2}{f^2} H^\dagger H B_{\mu\nu} B^{\mu\nu}$$

- Applying the LET obtain ($m_h \ll m_t, m_W$)

$$\mathcal{L}_{\text{eff}} = \frac{e^2}{16\pi^2} F_{\mu\nu} F^{\mu\nu} \left( \sum_f Q_f^2 \log m_f^2(H) - \frac{7}{4} \log m_W^2(H) \right)$$

and linear term in $h$ reads

$$\mathcal{L}_{h\gamma\gamma} = \frac{e^2}{32\pi^2} F_{\mu\nu} F^{\mu\nu} \frac{h}{v} \left[ \Lambda Q_t^2 \left( \frac{1}{2} \left( \frac{\partial}{\partial \log H} \log \det \mathcal{M}^2(H) \right)_{H=v} - \frac{c_H}{2} \xi \right) 
- J_\gamma \left( 4m_W^2/m_h^2 \right) \left( 1 + \xi \left( \frac{c_r}{4} - \frac{c_H}{2} \right) \right) \right]$$

valid for $m_h \ll m_t$.

Full result for $W$ loop

$$J_\gamma \simeq 8.3 \ (m_h = 125 \text{ GeV})$$

for $m_h \lesssim 2m_W \rightarrow J_\gamma(\infty) = 7 = \frac{22}{3} - \frac{1}{3}$

Transverse, equal to gauge contribution to $SU(2)_L$ beta function

Longitudinal (Goldstones)