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

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based on work in collaboration with

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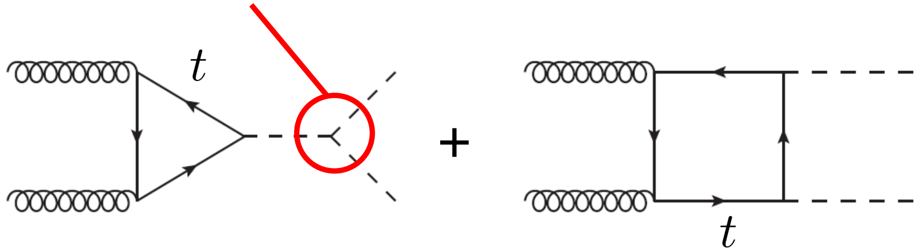
arXiv:1206.7120

Introduction: why is *gg* → *hh* interesting?

- Gluon fusion $gg \to h,\, hh$ 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).

SM



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

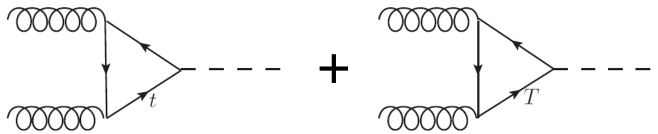
- Experimentally very challenging signal for $m_h = 125\,\mathrm{GeV}$:
  best final state $hh \to \gamma\gamma b\bar{b}$, ***at least O(100) fb^{-1} at LHC14 needed*** to probe it in BSM with enhanced cross section (in the SM, even larger luminosity).

Baur et al., hep-ph/0310056
Contino et al., 1205.5444

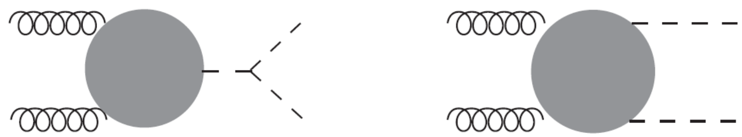
Sensitivity to fermionic resonances

Single production: gg → h

- Well-known result: in many composite models (both with and without collective breaking) the single production cross section $\sigma(gg \to h)$ 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 %.

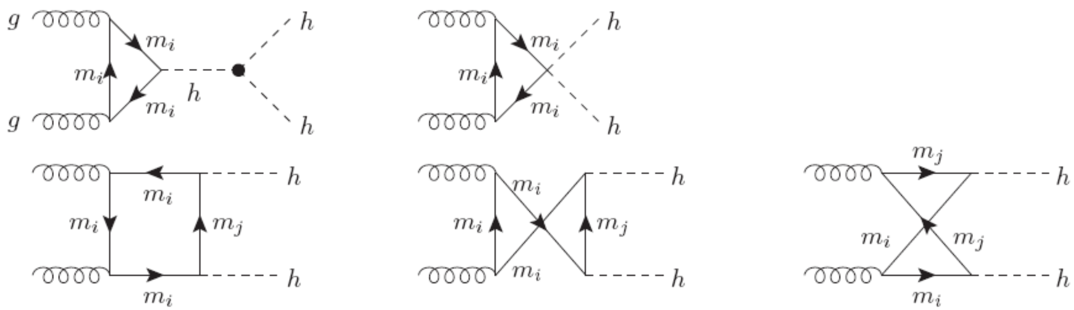


Double production: gg → hh

- 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, $\hat{s} \geq 4m_h^2$

gg → *hh* including resonances

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

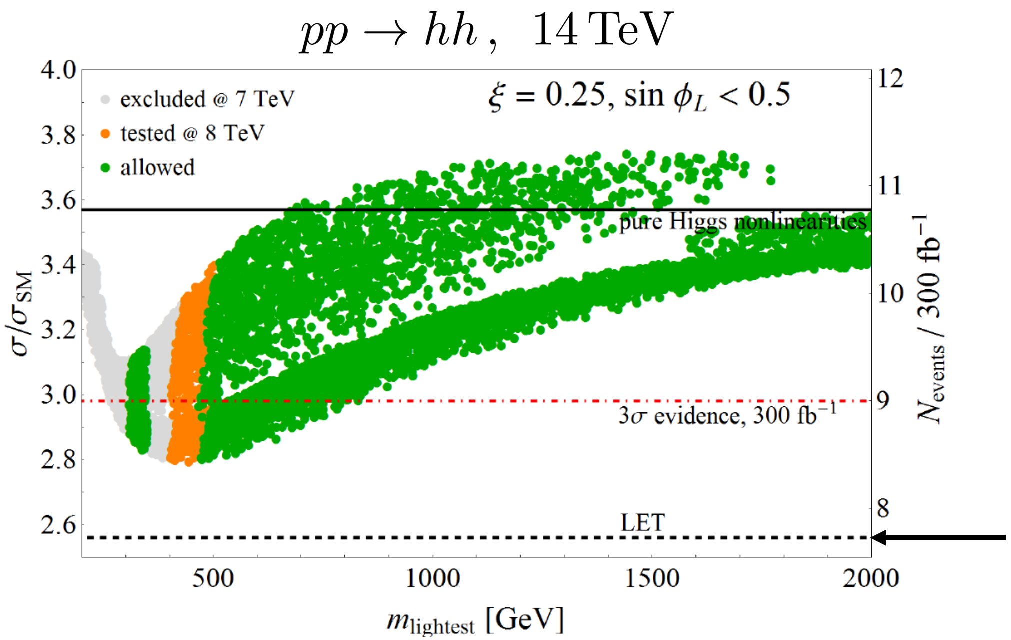


- Also, masses of resonances are related to the Higgs mass (Higgs potential generated at loop level) ➡ upper bound $m_T \lesssim 700\,\mathrm{GeV}\left(\frac{f}{500\,\mathrm{GeV}}\right)\left(\frac{m_h}{125\,\mathrm{GeV}}\right)$
So **some resonances must be light**, their effects in loops expected to be relevant!

see e.g. Pomarol and Riva, 1205.6434

- Choose a specific model, MCHM5. Minimal model but **realistic**: discuss constraints from electroweak data and from LHC searches for vector-like fermions.
A compositeness scale as low as $f = 500\,\mathrm{GeV}$ is allowed (~20% fine-tuning).
$gg \to hh$ cross section known to be **largely enhanced** compared to SM (around a factor 3 for $f = 500\,\mathrm{GeV}$) 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 $hh \to \gamma\gamma b\bar{b}$ final state (1 *b*-tag)

Backup

Higgs couplings to gluons via the low-energy theorem

Ellis et al., NPB 1976
Shifman et al., SJNP 1979

- 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 $F(H) G^a_{\mu\nu} G^{\mu\nu\, a}$.
- Fix the function $F(H)$: treat H as background field, then $m(H)$ is a threshold for the running of QCD gauge coupling

$$\mathcal{L}_{eff} = -\frac{1}{4 g^2_{eff}(\mu, H)} G^a_{\mu\nu} G^{a\,\mu\nu}\,, \qquad \frac{1}{g^2_{eff}(\mu, H)} = \frac{1}{g^2_s(\Lambda)} - \frac{b_{UV}}{8\pi^2} \log\frac{\Lambda}{\mu} - \delta b\, \frac{1}{8\pi^2} \log\frac{m(H)}{\mu}$$

- For Dirac fermions $\delta b = 2/3$ $\Rightarrow$ $\mathcal{L}_{eff} = \sum_f \frac{g_s^2}{96\pi^2} G^a_{\mu\nu} G^{a\,\mu\nu} \log m_f^2(H)$

field-dependent mass of fermion *f*

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

$$\mathcal{L}_{h^n gg} = \frac{g_s^2}{96\pi^2} G^a_{\mu\nu} G^{a\,\mu\nu} \left[A_1 h + \tfrac{1}{2} A_2 h^2 + \ldots \right]$$

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

heavy fermion mass matrix

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**

Falkowski, 0711.0828
Low and Vichi, 1010.2753

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

Azatov and Galloway, 1110.5646

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

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

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

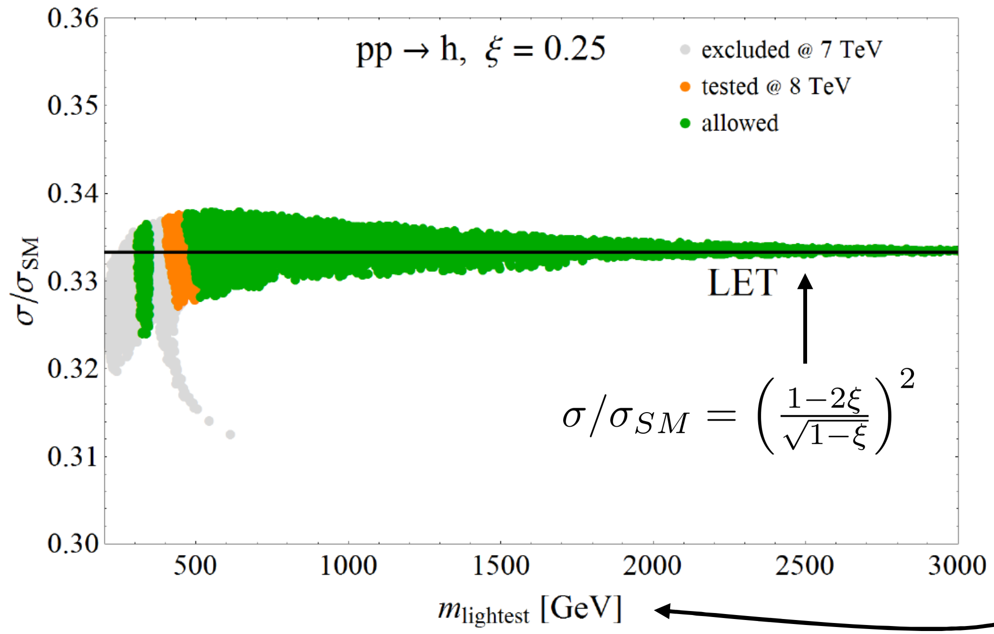
$$\det \mathcal{M}^\dagger(H)\mathcal{M}(H) = \sin^2(2H/f) \times P(y, M_0, f, \ldots)$$

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

$\longleftrightarrow$ 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:



Note the sizable suppression compared to the SM!

…but BRs enhanced

mass of lightest new fermion

- 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

Agashe et al., hep-ph/0412089

- Higgs as a pseudo-Goldstone boson of spontaneous symmetry breaking $\mathcal{G}/\mathcal{H}$

  ⇒ explain "Little Hierarchy" between EW scale and scale of new strong sector.

- Minimal choice containing custodial symmetry (needed to protect ρ 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

$$\Sigma = \Sigma_0 e^{\Pi/f}\,, \qquad \Pi = -i\sqrt{2}\,T^{\hat{a}} h^{\hat{a}}\,, \qquad \Sigma_0 = (\,0\,,\,0\,,\,0\,,\,0\,,\,1\,)$$

$$\Sigma = \frac{\sin(h/f)}{h}\big(h_1, \quad h_2, \quad h_3, \quad h_4, \quad h\,\mathrm{cotan}(h/f)\big)\;, \qquad h = \sqrt{\textstyle\sum_{\hat{a}} h_{\hat{a}}^2}$$

and the two-derivative Lagrangian is $\mathcal{L} = \frac{f^2}{2}(D_\mu\Sigma)(D^\mu\Sigma)^T$

$$\left(D_\mu\Sigma = \partial_\mu\Sigma + ig\,W_\mu^a \Sigma T_L^a + ig'\,B_\mu \Sigma T_R^3\right)$$

- Can write in unitary gauge

$$\Sigma = \big(0, \quad 0, \quad \sin(H/f), \quad 0, \quad \cos(H/f)\big)$$

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

Partial compositeness Lagrangian

- Composite multiplet can be written as:

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

$$\psi = \frac{1}{\sqrt{2}} \begin{pmatrix} B - X^{5/3} \\ -i(B + X^{5/3}) \\ T + X^{2/3} \\ i(T - X^{2/3}) \\ \sqrt{2}\tilde{T} \end{pmatrix}$$

$$\mathbf{5} \sim (\mathbf{2},\mathbf{2}) \oplus (\mathbf{1},\mathbf{1})$$

$$\tilde{T}$$

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

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:

$$\begin{aligned} \mathcal{L}_f &= i\bar{q}_L \not{D} q_L + i\bar{t}_R \not{D} t_R + i\bar{b}_R \not{D} b_R + i\overline{\psi}_L \not{D} \psi_L + i\overline{\psi}_R \not{D} \psi_R \\ &\quad - y f (\overline{\psi}_L \Sigma^T)(\Sigma \psi_R) - M_0 \bar{\psi}_L \psi_R + \text{h.c.} \\ &\quad - \Delta_L \bar{q}_L Q_R - \Delta_R \overline{\tilde{T}}_L t_R + \text{h.c.} \end{aligned}$$

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 $\mathbf{5}_{-1/3}$)

Fermion masses

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

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

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

- **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

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

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

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

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

$$\xi \equiv v^2/f^2, \quad \phi_L, \quad \phi_R, \quad R = (M_0 + yf)/M_0$$

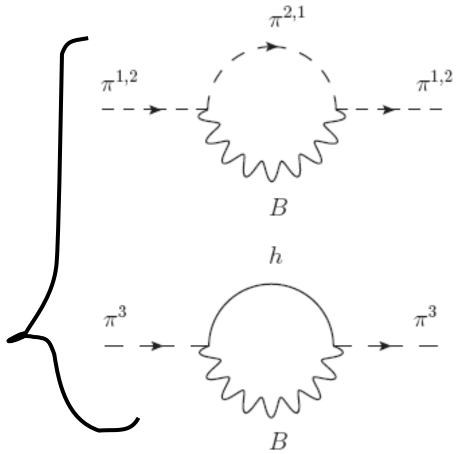
Electroweak precision tests

Three beyond-SM contributions to ϵ_i, ϵ_b parameters:

- Modified coupling of the Higgs to gauge bosons

➡ log divergence in $\epsilon_{1,3} \sim T, S$

$$\Delta\epsilon_3^{\rm IR} = \frac{\alpha(M_Z)}{48\pi \sin^2\theta_W}\xi \log\left(\frac{m_\rho^2}{m_h^2}\right), \qquad \Delta\epsilon_1^{\rm IR} = -\frac{3\,\alpha(M_Z)}{16\pi \cos^2\theta_W}\xi \log\left(\frac{m_\rho^2}{m_h^2}\right)$$



Barbieri et al., 0706.0432

- UV contribution to S from tree-level exchange of spin-1 resonances

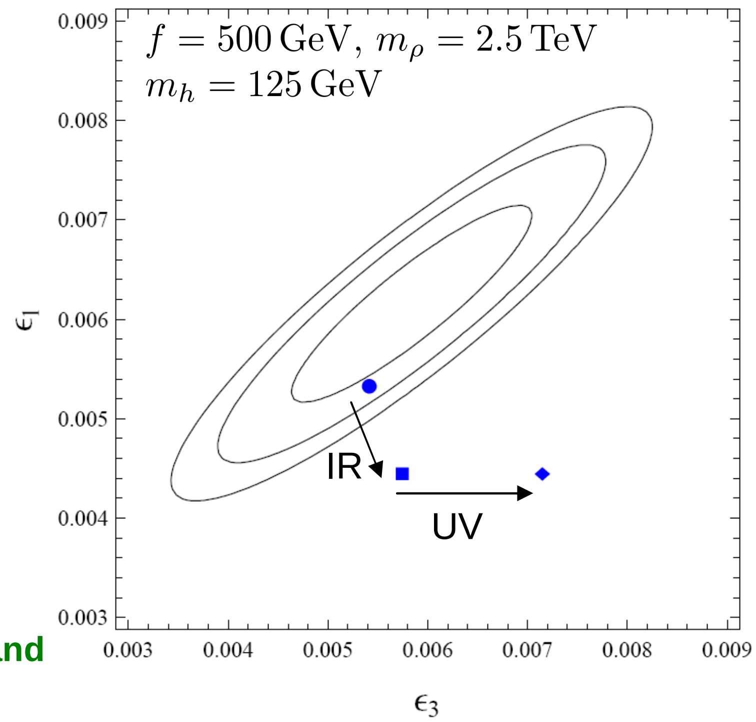
$$\Delta\epsilon_3^{\rm UV} = \frac{m_W^2}{m_\rho^2}\left(1 + \frac{m_\rho^2}{m_a^2}\right) \simeq 1.36\frac{m_W^2}{m_\rho^2}$$

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

➡ non-trivial interplay!

Gillioz, 0806.3450
Anastasiou, Furlan and Santiago, 0901.2117



Electroweak precision tests (2)

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

For largish ξ , **two regions** satisfying the constraints are found:

1) Singlet $\tilde{T}$ lighter than rest of the spectrum: it contributes positively to T and to ϵ_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 $X = (X^{5/3}, X^{2/3})$ is light. Intricated interplay of contributions to EW parameters.

light Q = 5/3 state $\Rightarrow$ strong bounds from LHC, see later

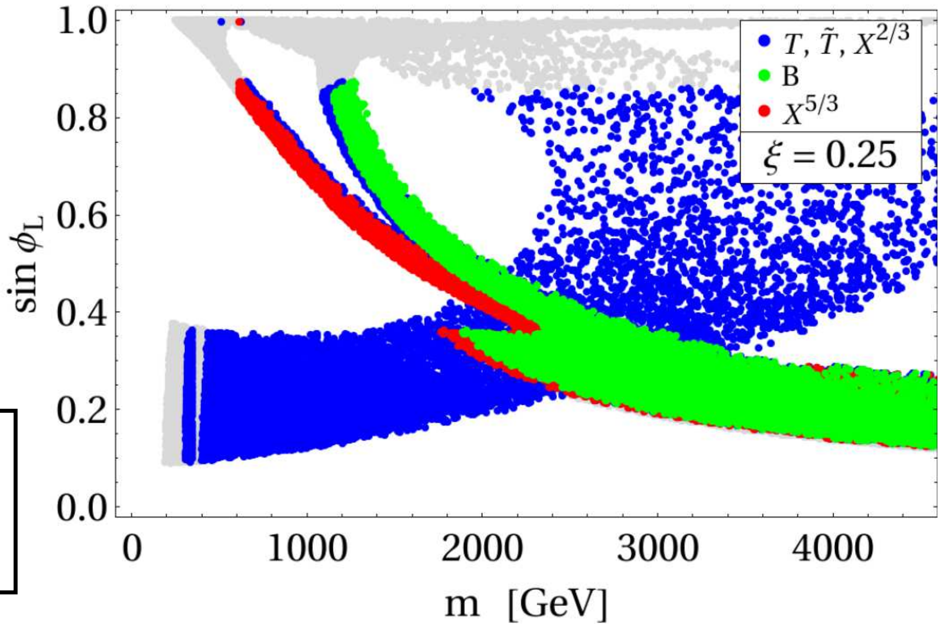
- *Note that a light Higgs requires at least one light fermionic resonance:*

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

see for example

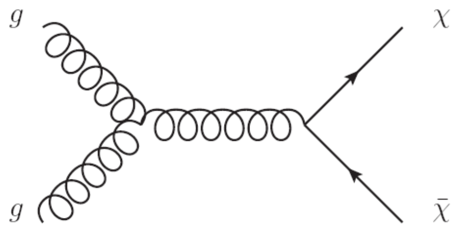
Pomarol and Riva, 1205.6434

blue	Q = 2/3
red	Q = 5/3
green	Q = -1/3



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



$$\left.\begin{aligned} &\mathrm{BR}(\tilde{T} \to Wb) = \frac{1}{2}\,, \qquad \mathrm{BR}(\tilde{T} \to Zt) = \mathrm{BR}(\tilde{T} \to ht) = \frac{1}{4}\,; \\ &\mathrm{BR}(X^{2/3} \to Zt) = \mathrm{BR}(X^{2/3} \to ht) = \frac{1}{2}\,, \qquad \mathrm{BR}(X^{5/3} \to Wt) = 1 \end{aligned}\right\}$$

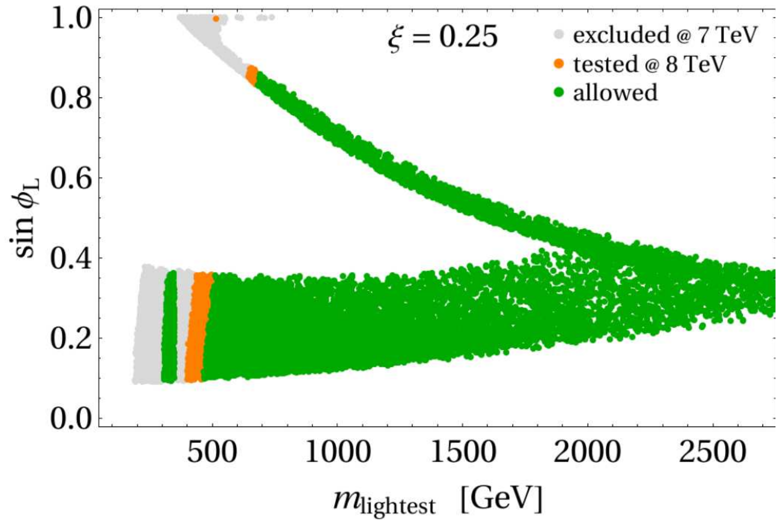
from Yukawas, using Goldstone equivalence theorem

- 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 BR = 1 into tW ⇒ $m_{5/3} > 600\,\mathrm{GeV}$

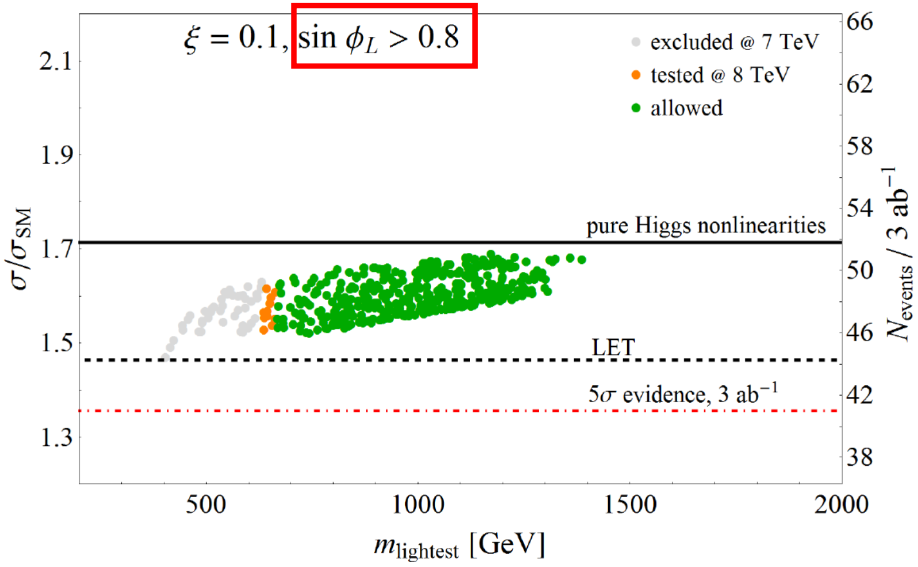
  and thus $\sin\phi_L < 0.8$
- Region of composite t_R less constrained:

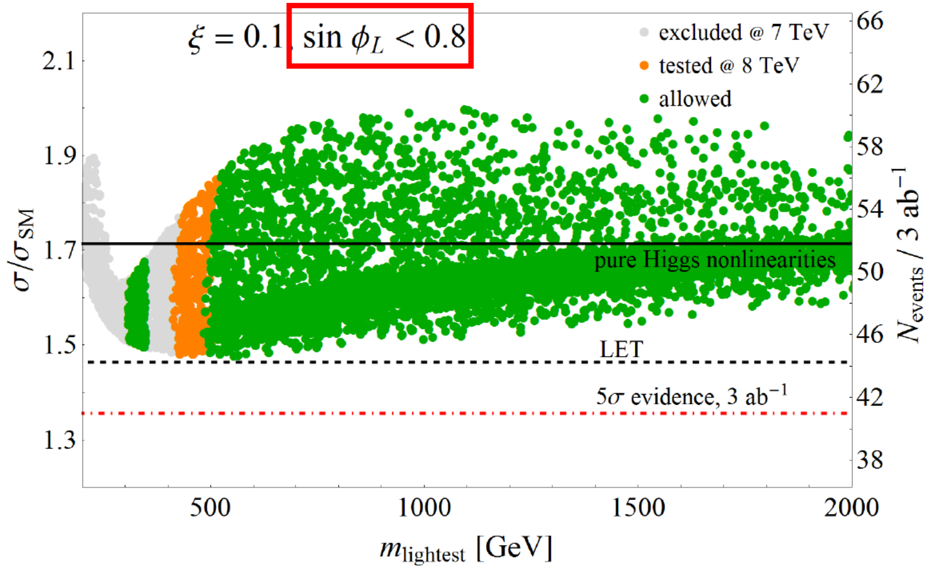
  $\tilde{T}$ is light, strongest bound from $WbWb$ channel ⇒ $m_{\tilde{T}} > 400\,\mathrm{GeV}$



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 $hh \to b\bar{b}\gamma\gamma$
- We follow the analysis of **Baur et al., hep-ph/0310056**

  roughly estimate the number of events at LHC14 by computing

  $\sigma(pp \to hh) \times \mathrm{BR}(hh \to b\bar{b}\gamma\gamma)$ and multiplying times the efficiency of cuts *for the SM*

  ($\epsilon \simeq 7\%$)
- 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: $\mathcal{O}_\gamma = c_\gamma \frac{g'^2}{16\pi^2 f^2}\frac{g^2}{g_\rho^2} H^\dagger H B_{\mu\nu}B^{\mu\nu}$

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

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

and linear term in *h* reads

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

full result for *W* loop

valid for $m_h \ll m_t$.

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

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

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

longitudinal (Goldstones)