Physics of the Interplay Between the Top Quark and
the Higgs Boson

Mikael Chala and José Santiago
CAFPE and Departamento de Física Teórica y del Cosmos,
University of Granada, 18071, Granada, Spain
E-mail: miki@ugr.es, jsantiago@ugr.es

Abstract. We discuss some aspects of the interplay between the top quark and the Higgs
boson at the LHC. First we describe what indirect information on the top Yukawa coupling can
be extracted from measurements in the Higgs sector. We then show that the study of processes
involving $Ht\bar{t}$ and $Hb\bar{b}$ final states can give us information on the spectrum in models of strong
electroweak symmetry breaking. In particular, we introduce a novel analysis of the $Hb\bar{b} \to bb\bar{b}\bar{b}$
channel with an excellent discovery potential at the LHC.

1. Introduction
With the discovery of the Higgs boson at the LHC, the quest to understand the mechanism of
electroweak symmetry breaking (EWSB) has finally started. The top quark has an undeniable
leading role in the physics of the Higgs boson, as it dominates, in the Standard Model (SM),
the main production mechanism ($gg \to H$) and contributes in an important way to one of the
most relevant decay channels ($H \to \gamma\gamma$). Hence, experimental tests of the Higgs sector can
give us precious information on aspects of the top quark, like its Yukawa coupling or on the
possible existence of top partners or even new vector resonances. At the same time the LHC
is a top factory and many of the top quark properties will be measured to an unprecedented
accuracy. Searches of processes involving the top quark or some of its possible partners can in
turn give us non-trivial information on the sector of EWSB. In these proceedings we will discuss
some aspects of this interplay between the top quark and the Higgs boson. In Section 2 we will
describe what indirect information on the top quark Yukawa coupling we can infer from current
results on Higgs searches and how that information might be combined with other searches to
obtain a coherent picture of the EWSB sector. In Section 3 we show how searches involving the
production of $Ht\bar{t}$ and $Hb\bar{b}$ can give us information on the spectrum in models of strong EWSB.
In these models, new vector-like quarks can be singly produced in association with a SM quark,
mediated by a color octet resonance. Subsequent decays of the heavy quark can result in $Ht\bar{t}$
and $Hb\bar{b}$ final states. We show that these channels can be measured at the LHC for a large region
of parameter space. In particular we introduce a novel analysis of the $Hb\bar{b} \to bb\bar{b}\bar{b}$ channel that
takes full advantage of the distinctive kinematics of the process, leading to an excellent reach
potential at the LHC. We finally conclude in Section 4.
2. What is the Higgs telling about the top?
Now that the discovery of a Higgs-like boson has been settled all the efforts are directed towards measuring its main properties. Even though the errors are still large, a coherent picture is starting to emerge from the combination of all the different channels [1, 2]. The experimental data point to a new boson of mass $m_H \approx 126$ GeV with production and decay compatible with those of the standard model Higgs in all channels with the possible exception of the $H \rightarrow \gamma\gamma$ decay, which seems to be consistently larger than the SM one (but still compatible with it at the two standard deviation level).  

The $H \rightarrow \gamma\gamma$ decay is unique for two reasons. First, it occurs at the loop level in the SM, being a priori particularly sensitive to new physics. Second, this decay arises from interfering contributions with the top and the $W$ boson running in the loop and it is therefore sensitive not only to the absolute value of the top Yukawa coupling but also to its sign. It turns out that although it is still possible to explain the data with new particles contributing at the loop level, it would not be easy to accommodate the current enhancement without modifying the production cross section through gluon fusion and without destabilizing the vacuum (see for instance [3]). If we assume instead that there is no significant contribution to the Higgs production and decay from new particles and the only effect is a possible modification of the couplings of the SM particles to the Higgs we find that apart from a region with SM-like couplings there is a second possible explanation to the current data. In this region the couplings of the gauge boson to the Higgs are slightly reduced whereas the top Yukawa coupling has the opposite sign than in the SM [4]. The “wrong sign” top Yukawa coupling turns the destructive interference in the $H \rightarrow \gamma\gamma$ decay into a constructive one thus explaining the observed enhancement.

Most physical processes are sensitive to the absolute value of the top Yukawa and not to its sign so it is not easy to test the hypothesis of a wrong sign Yukawa coupling. One possibility, recently proposed in [5], is to use $t$-channel single top production in association with a Higgs boson. This is a tree level process in which there is interference between diagrams involving the top Yukawa and a $W$, making it also sensitive to the sign of the top Yukawa coupling relative to the $WWH$ coupling. The process is very small in the SM due to an almost perfect destructive interference. With the wrong sign top Yukawa coupling however it becomes observable at the LHC and it is therefore a potentially crucial test of this explanation of current Higgs data. It should be noted however that the information on the top Yukawa coupling is obtained from a loop process in one case and from a tree level process in the other. These two Yukawa couplings are in general different as new physics can affect differently the tree and loop processes. Therefore care should be exercised when interpreting the results of these searches.

3. New Higgs Production Mechanisms in Composite Higgs Models
We have seen in the previous section how Higgs searches can give us information on some properties of the top quark like its Yukawa coupling. In this section we will see how searches involving the production of $Htt$ and $Hbb$ can give us information on the spectrum of new particles in models of strong EWSB. Many models of strong EWSB include in their spectrum light top partners (new vector-like quarks that mix strongly with the top and/or bottom quarks) together with massive color-octet vector resonances, that we will call heavy gluons. In some regions of parameter space the leading production mechanism of these top partners is single production mediated by the exchange of the heavy gluons. If the top partners have electric charge $2/3$ or $-1/3$ they can result in $Htt$ and $Hbb$ final states, respectively. The corresponding process is shown in Fig. 1. In the following we discuss how to use these channels to search for the top partners and even for the heavy gluons in these models of strong EWSB. In our studies we have

---

1 Currently ATLAS also observes an incompatibility between the mass of the new boson as measured in the $ZZ^*$ and $\gamma\gamma$ channels at the level of almost three standard deviations.
used a simplified version of the minimal composite Higgs model [6] as described in [7, 8] (see also [9]). The most relevant parameter that we will consider is the degree of compositeness of the top or bottom quarks, denoted by \( \sin(\phi_t R) \) and \( \sin(\phi_b R) \), respectively. The \( Ht\bar{t} \) and \( Hb\bar{b} \) production cross sections, for \( \sin(\phi_t R) = \sin(\phi_b R) = 0.6 \), are reproduced in Fig. 2 at the LHC for \( \sqrt{s} = 8 \) and 14 TeV. We have simulated our signal and backgrounds using MADGRAPH V4.5.0 [10] and ALPGEN V.2.13 [11], respectively. We have then passed the events through PYTHIA 6.4 [12] for hadronization and showering and DELPHES V1.9 [13] for detector simulation. Further details on the implementation of the model and the simulations can be found in reference [8].

3.1. \( Ht\bar{t} \) Channel

We consider the process shown in Fig. 1 with \( Q = T \) and \( q = t \) and the leading \( H \to bb \) decay channel of the Higgs and a semileptonic decay of the \( t\bar{t} \) system. The specific process is

\[
pp \to G \to T\bar{t} + Tt \to Ht\bar{t} \to 4b + 2j + \not{E}_T. \tag{1}
\]

A detailed analysis of this channel has been performed in Ref. [8] where all the relevant details can be found. Here we will just summarize the main results for the LHC running at a center of mass energy \( \sqrt{s} = 14 \) TeV. The heavy gluon masses that can be probed at this energy are large enough to make all the decay products quite hard. Also \( T \) is typically heavy so that the use of boosted techniques proved useful in these searches.

In order to take maximum advantages of the particular features of the signal we have implemented the following set of cuts

- At least 3 jets, with a minimum of 2 b tags.
- At least 1 isolated charged lepton.
- The two jets with the largest invariant masses, \( j_{1,2} \), are required to have invariant masses close to the top and Higgs mass, respectively, \( |m_{j_1} - m_t| \leq 40 \text{ GeV} \) and \( |m_{j_2} - m_H| \leq 40 \text{ GeV} \).
- A cut on \( S_T \) (the scalar sum of the \( p_T \) of the three hardest jets, the charged lepton and the missing transverse energy) that depends on the test \( M_G \) we are considering

\[
S_T > 1.2, 1.5, 1.7, 2 \text{ TeV for } M_G = 2, 2.5, 3, \geq 3.5 \text{ TeV}. \tag{2}
\]

We have considered all the relevant backgrounds in our analysis. The most important ones turn out to be \( t\bar{t} \) and \( t\bar{t}b\bar{b} \). The result of this analysis is summarized in Fig. 3 in which we show the
Sensitivity \sin(\phi_{tR})

3.0 TeV
3.5 TeV
4.0 TeV
4.5 TeV
5.0 TeV

10
0.4 0.5 0.6 0.7 0.8 0.9

Figure 3. Sensitivity obtained in the $Ht\bar{t}$ channel for different values of the heavy gluon mass as a function of $\sin(\phi_{tR})$ after an integrated luminosity of 100 fb$^{-1}$.

3.2. $Hb\bar{b}$ Channel

We now turn our attention to the case $Q = B$ and $q = b$. We will show that contrary to naive expectations, the $H \rightarrow b\bar{b}$ decay channel, resulting in a four $b$ quark final state, can be quite competitive, allowing for the reconstruction not only of the heavy quark but also of the heavy gluon. The process we are interested in is

$$pp \rightarrow G \rightarrow B\bar{b} + \bar{B}b \rightarrow Hb\bar{b} \rightarrow 4b.$$ (3)

In order to reduce the background to manageable levels we need to require all four $b$-quarks to be measured, well isolated and also all four of them to be quite hard. Once these cuts are imposed and the signal and background cross sections are comparable, we can take advantage of the particular kinematics of the signal in which the two $b$-jets coming from the decay of the Higgs are typically softer than the other two. Thus the requirement that the two softest $b$-jets reconstruct the Higgs mass is a good extra discriminator. Finally, we can reconstruct the $B$ quark using the reconstructed Higgs together with the hardest $b$-jet and $G$ using the invariant mass of all four $b$-jets. We use the latter invariant mass as a final discriminating variable. The proposed cuts are

- 4 $b$-tagged jets with $\Delta R(bb) > 0.7$ and $p_T(b) > 50$ GeV
- No isolated leptons
- $p_T(b_h) > 300$ GeV for the hardest $b$-jet
- $|M_{bl_4} - M_H| < 30$ GeV, where $b_{3,4}$ are the two softest $b$-jets
- $M_G - 1000$ GeV $< M_{4b} < M_G + 500$ GeV.

Our results are summarized in Fig. 4 in which we show the sensitivity that can be reached with 100 fb$^{-1}$ for different values of $M_G$ as a function of $\sin(\phi_{bH})$. Further details of the study will be presented elsewhere [14]. A sample of the reconstruction power for the heavy quark and the heavy gluon is shown in Fig. 5 for the particular case of $M_B = 1.25$ TeV and $M_G = 2.5$ TeV.
Figure 5. Reconstruction of the heavy quark (left) and the heavy gluon (right) with $m_B = 1250$ GeV and $m_G = 2500$ GeV with an integrated luminosity of 100 fb$^{-1}$. The dotted, dashed and solid lines correspond to the background, signal and sum of both, respectively.

4. Conclusions
We have discussed how searches involving the Higgs boson can give us valuable information on the top quark and other particles beyond the SM related to the top quark. Current experimental data on the Higgs boson might be pointing to a large correction to the top Yukawa coupling, effectively reversing its sign. This possibility might be tested through single top production in association with a Higgs boson although further studies are required before considering the results of such searches conclusive. We have also shown how searches involving the production of $Ht\bar{t}$ and $Hb\bar{b}$ can give us information on the spectrum of new particles in models of strong EWSB. In particular, they can be used to search for top partners, new vector-like quarks that mix strongly with the top and/or bottom quarks.

Acknowledgments
We would like to thank N. F. Castro and J. P. Araque for the useful discussions. This work has been supported by MICINN projects FPA2006-05294 and FPA2010-17915, through the FPU programme and by Junta de Andalucía projects FQM 101, FQM 03048 and FQM 6552.

References
[1] CMS Collaboration, CMS-PAS-HIG-12-045; ATLAS Collaboration, ATLAS-CONF-2012-170.
[2] Tevatron New Physics Higgs Working Group and CDF and D0 Collaborations, arXiv:1207.0449.
[3] M. Carena, I. Low and C. E. M. Wagner, JHEP 1208 (2012) 060 [arXiv:1206.1082]; N. Arkani-Hamed, K. Blum, R. T. D’Agnolo and J. Fan, JHEP 1301 (2013) 149 [arXiv:1207.4482]; M. Reece, arXiv:1208.1765.
[4] A. Azatov, R. Contino and J. Galloway, JHEP 1204 (2012) 127 [arXiv:1202.3415]; P. P. Giardino, K. Kannike, M. Raidal and A. Strumia, Phys. Lett. B 718 (2012) 469 [arXiv:1207.1347]; J. R. Espinosa, C. Grojean, M. Muhlleitner and M. Trott, JHEP 1212, 045 (2012) [arXiv:1207.1717]; D. Carni, A. Falkowski, E. Kuilk, T. Volansky and J. Zupan, JHEP 1210 (2012) 196 [arXiv:1207.1718].
[5] M. Farina, C. Grojean, F. Maltoni, E. Salvioni and A. Thamm, arXiv:1211.3736.
[6] K. Agashe, R. Contino and A. Pomarol, Nucl. Phys. B 719 (2005) 165 [hep-ph/0412089].
[7] C. Bini, R. Contino and N. Vignaroli, JHEP 1201 (2012) 157 [arXiv:1110.6058].
[8] A. Carmona, M. Chala and J. Santiago, JHEP 1207 (2012) 049 [arXiv:1205.2378].
[9] R. Barcelo, A. Carmona, M. Chala, M. Masip, J. Santiago, Nucl. Phys. B 857 (2012) 172 [arXiv:1110.5914].
[10] J. Alwall, P. Demin, S. de Visscher, R. Frederix, M. Herquet, F. Maltoni, T. Plehn and D. L. Rainwater et al., JHEP 0709 (2007) 028 [arXiv:0706.2334].
[11] M. L. Mangano, M. Moretti, F. Piccinini, R. Pittau and A. D. Polosa, JHEP 0307 (2003) 001 [hep-ph/0206293].
[12] T. Sjostrand, S. Mrenna and P. Z. Skands, JHEP 0605 (2006) 026 [hep-ph/0603175].
[13] S. Ovyn, X. Roudy and V. Lemaitre, arXiv:0903.2225.
[14] M. Chala and J. Santiago, in preparation.