Single top and Higgs associated production as a probe of the $Ht\bar{t}$ coupling sign at the LHC

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ABSTRACT

The LHC sensitivity to an anomalous Higgs coupling to the top quark in the Higgs-top associated production is analyzed. Thanks to the strong destructive interference in the $t$-channel for standard model couplings, this process can be very sensitive to both the magnitude and the sign of a nonstandard top-Higgs coupling. We analyze cross sections and the main irreducible backgrounds for the $H \rightarrow \gamma\gamma$ decay channel. Sensitivities to an anomalous sign for the top Yukawa coupling are found to be large. In particular, at $\sqrt{s} = 14$ TeV, assuming a universal rescaling in the Yukawa sector, a parton-level analysis with realistic selection cuts gives a signal-to-background ratio $S/B \sim 5$, for $-1.5 \lesssim Y_t/Y_{t}^{SM} \lesssim 0$. A number of events $S \simeq 10$ (with corresponding significances $\sim 3 \sigma$) are expected for 60 fb$^{-1}$, to be compared with the standard-model expectation $S \sim 0.3$.

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1 Introduction

After many years of challenging experimental searches, a signal consistent with a Higgs-boson has finally been consolidated at the LHC, with production rates compatible with the standard model (SM) predictions \[1, 2\]. We are now entering a new phase in Higgs boson physics, where (apart from looking for possible further Higgs physical states) the actual properties of this new particle will be determined by measuring its couplings to the other known particles with ever increasing precision. The Higgs couplings to heavy vector bosons were indirectly detected through electroweak precision tests even before an Higgs signal direct observation \[3\]. On the other hand, in order to constrain the Yukawa sector, which describes the Higgs couplings to fermions, we have to rely on the Higgs direct-observation profile. Indeed, electroweak precision tests are not yet sensitive at a measurable level to Yukawa coupling effects, which enter only at 2-loop level \[4\]. There is now a first direct determination of the $H \rightarrow b\bar{b}$ decay recently claimed at Tevatron \[5\], while the LHC will likely be sensitive at the 2 $\sigma$ level to both the $Hb\bar{b}$ and $H\tau\tau$ SM couplings with the statistics accumulated by the end of 2012 \[6\]. Nevertheless, by making proper theoretical assumptions, one can already constrain at the LHC the actual characteristics of the Yukawa sector of a Higgs boson \[7\]. For instance, by assuming a universal scale factor $C_f$ for the Higgs Yukawa couplings to all fermion species $f$

$$Y_f = C_f Y_f^{SM}, \quad (1)$$

(where $Y_f^{SM} = m_f/v$ is the SM Yukawa coupling and $v = \langle H \rangle$ is the vacuum expectation value of the Higgs field) and a further scale factor describing the $HVV$ (where $V = W, Z$) couplings

$$g_{HVV} = C_V g_{HVV}^{SM}, \quad (2)$$

present data already constrains the fermion Yukawa couplings $Y_f$ to be inside two regions of values of opposite signs \[8, 9\]. In particular, if no new physical degrees of freedom is present, the ATLAS fit pinpoints at 95% C.L. the intervals [-1.5, -0.5] and [0.5, 1.7] for the scale factor $C_f$, and the interval [0.7, 1.4] for the $W/Z$ scale factor $C_V$ (where $C_{f,V} = 1$ in the SM) \[10\]. On the other hand, the CMS fit restricts the analysis to positive values of the Yukawa couplings, and finds $C_f$ and $C_V$ in the intervals [0.3, 1.0] and [0.7, 1.2], respectively, at 95% C.L.\[11\].

One should keep in mind that an opposite sign in the Yukawa couplings with respect to the SM prediction would have a dramatic impact on the EW breaking mechanism, even if its magnitude were close to 1. This is because the relative sign of the Higgs coupling to fermions and gauge vector bosons is crucial for recovering the unitarity and renormalizability of the theory \[12\]. Therefore, a negative sign in the Yukawa coupling would be an evidence of new physics that could manifest itself in many different ways. Starting from the appearance of new Higgs bosons or weakly interacting resonances in the spectrum, in case one wants to recover perturbative unitarity, up to a new strongly interacting regime of weak gauge bosons with fermions above the TeV scale. Furthermore, flipping the sign of the $ttH$ coupling may lead to catastrophic vacuum instabilities \[13\].

\[2\]Note that ATLAS and CMS obtain the 95%C.L. $C_f$ and $C_V$ intervals with different marginalization procedures.
The only fermion species that sensibly contribute to the above LHC fits are the top quark (that enters in the loop of the main Higgs production mechanism \( gg \rightarrow H \), and contributes with maximal weight to the fits), the \( b \) quark and the \( \tau \) lepton, under the hypothesis \( C_t = C_b = C_\tau \).

The two non-degenerate opposite-sign intervals for the top-Yukawa coupling arise from the \( SM \) (destructive) interference between the \( W \) vector-boson loop and the top-quark loop in the \( H \rightarrow \gamma\gamma \) amplitude. Indeed, the present moderate enhancement observed in the \( H \rightarrow \gamma\gamma \) rate with respect to the \( SM \) predictions (see e.g. [14, 15], and references therein) could be related to a decreased top-Yukawa coupling, or even to a change in the relative sign of the \( W \)-Higgs and top-Higgs couplings. The latter could considerably enhance the \( H \rightarrow \gamma\gamma \) branching ratio, without affecting the \( gg \rightarrow H \) production rate.

A strictly fermiophobic Higgs interpretation, where \( C_f = 0 \), and \( C_V = 1 \), has been excluded by the LHC for the observed resonance. One should however keep in mind that, in realistic fermiophobic models, non-vanishing Yukawa couplings are generated at least at the radiative level by the chiral symmetry breaking induced by the non-vanishing fermion masses. Note that, in effective fermiophobic models, a radiatively generated top Yukawa coupling tends to have an opposite sign with respect to its \( SM \) value [4].

In this paper, we address the problem of the determination of the relative sign of the \( ttH \) and \( WWH \) couplings through the study of the Higgs production in association with a single top quark at the LHC. While the magnitude of the top and \( W \) couplings can be directly measured, respectively, through the Higgs boson production in association with a top pair (see [16] for a recent study), and in vector-boson-fusion or \( HW \)-associated production, all these processes are not affected by the top and \( W \) couplings relative sign. The \( t \)-channel for single top and Higgs associated production is, on the other hand, particularly sensitive to the \( Y_t \) and \( g_{HWW} \) relative phase, because of the strong destructive interference in the \( SM \) matrix element of the two Feynman graphs for \( q \bar{b} \rightarrow tq'H \) in Figure 1 [17].

The associated production of a Higgs and a single top quark at the LHC and the SSC (the Superconducting Super Collider) was analyzed in the SM for a light Higgs boson in [18]-[20] (with [18] focusing on the \( H \rightarrow \gamma\gamma \) decay). In [21] (see also [22]), a Higgs decaying into \( bb \) pairs was studied for the same process at the LHC. However, quite negative conclusions were
reached for both the $H \to \gamma\gamma$ and $H \to b\bar{b}$ modes in the SM. The extension to a minimal supersymmetric two Higgs-doublet model slightly improves the expectations. In [22], the $H \to WW^{(*)}, ZZ^{(*)}$ decays were studied for Higgs masses $150 \text{ GeV} < m_H < 200 \text{ GeV}$. Both a SM Higgs and a variable $Y_t$-strength setups (including the possibility of switching the $g_{HVV}^{SM}$ sign) were considered. Good sensitivities in the above $m_H$ range were found for a non-standard relative sign of the Higgs couplings to $W$ and top quarks.

Among the three processes contributing to the associated production of a Higgs and a single top quark process ($t$-channel $q b \to tq'H$, $s$-channel $qq' \to tbH$, and $W$ associated production $gb \to WtH$), here we concentrate on the $t$-channel $qb \to tq'H$. Indeed, as we will explicitly show, for a Higgs boson as light as 125 GeV, the latter has the largest cross section at the LHC, and the highest sensitivity to anomalous $Y_t$ couplings coming from the interference effects of the two Feynman diagrams in Figure 1 [21]. We focus on the two-photon decay $H \to \gamma\gamma$, and study the event rates for the signature corresponding to

$$q b \to tq'H \to t q'\gamma\gamma,$$

by applying realistic selection cuts based on present searches at the LHC. The rate suppression by the branching ratio $(BR)$ for $H \to \gamma\gamma$ is then expected to be compensated by a better signal-to-background event ratio $S/B$. We consider the hadronic $t \to b qq'$ decay, and estimate the corresponding main irreducible backgrounds at parton level, requiring the tagging of a $b$-jet in the final state. Present experimental studies of the $H \to \gamma\gamma$ decay suggest that the contribution of the reducible backgrounds where photons are misidentified is subdominant [23, 24]. We expect a moderate contribution also from misidentified light and $b$ jets (see e.g. [25] as a relevant example).

We show that, while, for $Y_t$ close to its SM value $C_t \sim 1$, the study of the $H \to \gamma\gamma$ decay channel in $pp \to tqH$ requires many hundreds of $fb^{-1}$ of integrated luminosity at 14 TeV, a negative value of the top Yukawa coupling with $C_t \sim -1$ would produce a detectable signal already with a few tens of $fb^{-1}$. A small but detectable number of events (with excellent signal-to-background ratio $S/B$) are expected for $C_t \sim -1$ even at 8 TeV with the integrated luminosity available by the end of 2012.

The plan of the paper is the following. In Section 2, we define the theoretical framework for the Higgs coupling dependence of the present study. In Section 3, we detail the top Yukawa dependence of the single-top plus Higgs associated production cross sections for the three main production mechanisms. We define the relevant backgrounds and selection cuts for the $t$-channel $pp \to tqH$, in Section 4, where we also present results on signal $(S)$ and background $(B)$ event numbers. In Section 5, we discuss statistical significances of our results, and finally we conclude in Section 6.
2 Coupling parameter setups

In the analysis of the potential of the channel $pp \rightarrow tqH \rightarrow tq\gamma\gamma$ at the LHC, we will focus on the dependence on both magnitude and sign of the $C_t$ scale factor. Nevertheless, our results on the $pp \rightarrow tqH$ cross sections can straightforwardly be extended to a larger framework, where the $W$ coupling factor $C_W$ has a non-standard value. This follows from the $C_W$ and $C_t$ dependence of the relevant production rates for the $qb \rightarrow tq'H$ process:

$$d\sigma = d\sigma(C_W, C_t) = |C_W|^2 d\sigma(1, C_t/C_W).$$

(4)

Hence, the critical parameter for cross sections in the present study is the relative phase of the $C_t$ and $C_W$ scale factors, while a further variation in the $W$ coupling magnitude $|C_W|$ will just affect the production rate normalization. From now on, we will then assume $C_W = C_V = 1$.

Of course, the $C_V$ and $C_f$ setup have an impact not only on the Higgs production cross section but also on the branching ratio $BR_{\gamma\gamma}$ that enters the $pp \rightarrow tq\gamma\gamma$ event rates. In order to make our results as model independent as possible, we will consider two different parameter setups:

- **Universal Yukawa rescaling**, that is assuming just one free parameter $C_f = C_t$ (and $C_V = 1$) both in production and decay amplitudes. $BR_{\gamma\gamma}$ is then a function of $C_t$, which enters both the $H \rightarrow \gamma\gamma$ width and the Higgs total width through $C_f$;

- **$C_t$ and $BR_{\gamma\gamma}$ as independent parameters** (and $C_V = 1$), with $C_t$ affecting only production cross sections, and $BR_{\gamma\gamma}$ describing the overall effect of new physics on the Higgs decay rate.

All the remaining couplings and physical degrees of freedom entering this study will be just the SM ones. The final results for the two setups can be easily related by just rescaling the event rates by the proper $BR_{\gamma\gamma}$ ratio.

3 Signal production rates versus $C_t$

In this section, we study the $pp \rightarrow tqH$ cross section dependence on the $C_t$ scaling factor, assuming $C_V = 1$. From now on, all the numerical cross sections discussed will refer to the hadronic $pp$ collisions, even when the partonic initial state is shown. In order to compute the production rates at leading order, we used the MADGRAPH5 (v1.3.33) software package [26], with the CTEQ6L1 parton distribution functions [27]. We set both the factorization and renormalization scales at the value $Q = \frac{1}{2}(m_H + m_t)$ for the $pp \rightarrow tqH$ signal, where $m_t$ is
the top-quark mass. The other relevant parameters entering our computation are set as follow \cite{1, 2, 28, 29}:

\[
\begin{align*}
    m_H &= 125 \text{ GeV}, & m_t &= 173.2 \text{ GeV}, \\
    M_Z &= 91.188 \text{ GeV}, & M_W &= 80.419 \text{ GeV}, \\
    m_b &= 4.7 \text{ GeV}, & \alpha_S(M_Z) &= 0.118.
\end{align*}
\]

The SM $H \rightarrow \gamma\gamma$ branching ratio $BR_{\gamma\gamma}^{SM}$ was obtained by HDECAY \cite{30}, while the model dependent $BR_{\gamma\gamma}$ versus $C_f$ has been evaluated via the leading-order $H$ partial widths \cite{31}, improved by normalizing the result by a factor $BR_{\gamma\gamma}^{SM}/BR_{\gamma\gamma}^{C_f=1}$ (where $BR_{\gamma\gamma}^{C_f=1}$ is the leading-order evaluation of the SM branching ratio). For reference in the following discussion, the relevant SM cross sections $\sigma$ and $BR_{\gamma\gamma}$ are (summing up cross sections over the two charge-conjugated channels) \cite{3}

\[
\begin{align*}
    \sigma(qb \rightarrow tq'H)^{SM} &\approx 15.2 \text{ fb} & \text{at } \sqrt{s} = 8 \text{ TeV} \quad (6) \\
    \sigma(qb \rightarrow tq'H)^{SM} &\approx 71.8 \text{ fb} & \text{at } \sqrt{s} = 14 \text{ TeV} \quad (7) \\
    BR_{\gamma\gamma}^{SM} &\approx 2.29 \cdot 10^{-3} \quad (8)
\end{align*}
\]

In Figure 2 we plot the $pp \rightarrow tqH$ production cross-section versus $C_t$, for $\sqrt{s} = 8$ TeV and 14 TeV. Throughout this work we focus on the range

\[ -1.5 < C_t < 1.5, \quad (9) \]

\footnote{The contribution to the $pp \rightarrow tqH$ cross section of the amplitude where the Higgs is radiated by the initial $b$-quark line is small (at the per-mil level in the $C_t$ range relevant here), and will be neglected in the present analysis.}
where the $C_t$ dependence is more critical, and the most favored regions of the LHC fits lie $[10, 11]$. Figure 2 shows that in the SM $C_t = 1$ case the destructive effect of the interference of the two diagrams in Figure 1 is maximal, and that a sign change in $Y_t$ produces a dramatic enhancement in the $pp \rightarrow tqH$ production cross sections.

Similarly, the destructive interference between the $W$ and top loops in the $H \rightarrow \gamma\gamma$ decay gives rise to an enhancement in the width $\Gamma_{\gamma\gamma}$ after switching the $C_t$ sign. On the other hand, the overall $BR_{\gamma\gamma}$ dependence on $C_t$ is mostly influenced, in the $C_f = C_t$ hypothesis, by the $C_f$ impact on the Higgs dominant decay widths into $b$ quarks, and $\tau$ leptons.

Since the cross section and $BR_{\gamma\gamma}$ dependencies on $C_t$ are both crucial for the results of the present analysis, we plot in Figure 3 (for $\sqrt{s} = 8$ TeV) and Figure 4 (for $\sqrt{s} = 14$ TeV) the ratios $R_i$ of the $C_t$ dependent $\sigma(pp \rightarrow tqH)$, $BR_{\gamma\gamma}$, and product $\sigma(pp \rightarrow tqH) \cdot BR_{\gamma\gamma}$ over the corresponding SM values, for $-1.5 < C_t < 1.5$. An enlargement of the positive $C_t$ range is given in the lower plots of both figures. Going to negative $C_f$ values has a dramatic effect on both cross sections and production rates for $H \rightarrow \gamma\gamma$. On the other hand, $BR_{\gamma\gamma}$ is mostly sensitive to a reduction of the $|C_f|$ magnitude, and less influenced by the $C_f$ sign.

For the sake of completeness, we also evaluated the total cross section and $C_t$ dependence for the top-Higgs associated production with a $W$ in the process $gb \rightarrow WtH$, and for the $s$-channel $q\bar{q}' \rightarrow tbH$. We obtain (summing up cross sections over the two charge-conjugated channels), at $\sqrt{s} = 14$ TeV,

\begin{align}
\sigma(gb \rightarrow WtH)^{SM} & \approx 16.0 \text{ fb}, \\
\sigma(gb \rightarrow WtH)_{C_t=0} & \approx 34.9 \text{ fb}, \\
\sigma(gb \rightarrow WtH)_{C_t=-1} & \approx 139. \text{ fb}, \\
\sigma(q\bar{q}' \rightarrow tbH)^{SM} & \approx 2.26 \text{ fb}, \\
\sigma(q\bar{q}' \rightarrow tbH)_{C_t=0} & \approx 1.49 \text{ fb}, \\
\sigma(q\bar{q}' \rightarrow tbH)_{C_t=-1} & \approx 0.39 \text{ fb},
\end{align}

(10) \hspace{1cm} (11) \hspace{1cm} (12) \hspace{1cm} (13) \hspace{1cm} (14) \hspace{1cm} (15)

to be compared with the $t$-channel cross sections, at $\sqrt{s} = 14$ TeV,

\begin{align}
\sigma(qb \rightarrow tq'H)^{SM} & \approx 71.8 \text{ fb}, \\
\sigma(qb \rightarrow tq'H)_{C_t=0} & \approx 276. \text{ fb}, \\
\sigma(qb \rightarrow tq'H)_{C_t=-1} & \approx 893. \text{ fb}.
\end{align}

(16) \hspace{1cm} (17) \hspace{1cm} (18)

Although there is a nice sensitivity to $C_t$ also in the $W$-associated production, we do not concentrate on this process here, because of its lower rates with respect to the $t$-channel $qb \rightarrow tq'H$. Nevertheless, we checked that its contribution to our event selection analysis, optimized for the $pp \rightarrow tqH$ process, is negligible.
Figure 3: Enhancement factors $R_i$ for the $pp \rightarrow tqH$ production cross section $\sigma$, $BR_{\gamma\gamma}$, and their product with respect to their SM values, versus $C_t$, for $\sqrt{s} = 8$ TeV. The lower plot is just an enlarged view of the positive $C_t$ range.
Figure 4: Enhancement factors $R_i$ for the $pp \rightarrow tqH$ production cross section $\sigma$, $BR_{\gamma\gamma}$, and their product with respect to their SM values, versus $C_t$, for $\sqrt{s} = 14$ TeV. The lower plot is just an enlarged view of the positive $C_t$ range.
4 Signal versus irreducible backgrounds

The irreducible SM backgrounds for the $pp \rightarrow tqH \rightarrow tq\gamma\gamma$ process, for the top hadronic decay $t \rightarrow bq'q'$, correspond to final states containing two photons, one $b$-jet, and at least three light jets, i.e., $2\gamma + b + (\geq 3j)$. The main partonic channels contributing are top production (either single or in pair) and multi-jet final states, when accompanied by two high-$p_T$ photons,

$$pp \rightarrow 2\gamma + t + j ,$$
$$pp \rightarrow 2\gamma + t + t ,$$
$$pp \rightarrow 2\gamma + b + 3j ,$$

with subsequent decay $t \rightarrow bq'q'$. We always require the $b$-jet identification in the final state.

To study the above channels we have used the same simulation package and parton distribution functions described in Section 3 with the renormalization and factorization scale set at the default dynamical scale value in MADGRAPH5 [26].

As discussed in Section 1, we postpone the study of the channels contributing to the reducible background through misidentified particles to a more in-depth analysis, being confident that the bulk of the final background will originate from the irreducible one. In our analysis, jets are defined at the parton level.

In order to tag an event, we require the final particles to pass the following selection criteria, modeled according to present searches [23][24]:

$$p_T^{\gamma_1} > 40 \text{ GeV}, \quad p_T^{\gamma_2} > 30 \text{ GeV}, \quad p_T^{j,b} > 25 \text{ GeV}, \quad |\eta_{\gamma,b}| < 2.5, \quad |\eta_j| < 4.5.$$ (22)

From now on, $b$ stands for a $b$-jet. We assume a $b$-tagging efficiency of 60%, which should guarantee a very good light-jet rejection factor [32]. The isolation requirement between the final state photons, light jets $j$, and $b$-jets is

$$\Delta R_{i,j} = \sqrt{\Delta \eta_{i,j}^2 + \Delta \phi_{i,j}^2} > 0.4 ,$$ (23)

with $i$ and $j$ running over all the final photons and jets (including $b$-jets), $\Delta \eta$ is the rapidity gap, and $\Delta \phi$ is the azimuthal angle gap between the particle pair. Because the $pp \rightarrow tqH$ signal comes from a $t$-channel $W$ exchange process, the light jet in the final state has normally large rapidity and high transverse momentum. In the chain of subsequent cuts applied, we therefore first require a forward jet (defined as the highest rapidity light-jet in the final state) with $|\eta| > 2.5$ and $p_T > 30$ (50) GeV at $\sqrt{s} = 8$ TeV (14 TeV) [33][22]. Then, we require a top quark fully reconstructed in the hadronic mode, i.e., the invariant mass of 3-jets (out of which one is a $b$-jet) must peak at the top mass within a mass window of 20 GeV. Then, the invariant mass of the two light jets, contributing to the top quark invariant mass, must peak at the $W$ mass within a mass window of 15 GeV. Finally, we impose that the invariant mass of the di-photon system reconstructs the Higgs mass centered at 125 GeV within a mass window of $\pm 3$ GeV. This set of selection cuts is quite conservative, and consistent with the present experimental analyses at the LHC.
The results of the above selection procedure are shown in Table 1 (for $\sqrt{s} = 8$ TeV, and integrated luminosity of $60$ fb$^{-1}$) and Table 2 (for $\sqrt{s} = 14$ TeV, and integrated luminosity of $600$ fb$^{-1}$). At $\sqrt{s} = 8$ TeV, 60 fb$^{-1}$ could correspond to the maximal integrated luminosity expected by collecting both the ATLAS and CMS data by the end of 2012.

The numbers of events passing the sequential cuts defined above are reported for the $pp \to tqH \to tq\gamma\gamma$ signal, for different ($C_t = \pm 1, 0$) values (assuming $C_f = C_t$ in $BR_{\gamma\gamma}$), and main irreducible backgrounds. The first row refers to the total number of events passing the photon- and jet-tagging definition in Eqs. (22) and (23), while the last column shows the total number of background events $B_{\text{tot}}$. One can see the efficiency of the different cuts applied to enhance the signal-to-background ratio. The signal rate is only affected by the forward-jet tag, with a corresponding reduction of a factor about 2, and passes almost unaltered the remaining cuts (the small reduction in the event numbers arising from the light-jets originating from the $t$ decay being tagged as forward jets). The largest contribution to the background comes from the $2\gamma + b + 3j$ non-resonant final state, that is considerably affected by both the forward-jet cut and the top- and Higgs-resonance requirements. The next background for importance is the single-top production $2\gamma + t + j$, while the top-pair channel $2\gamma + \bar{t}t$ contributes to $B_{\text{tot}}$ negligibly.

### Table 1: Number of events passing sequential cuts for the signal $pp \to tqH \to tq\gamma\gamma$ and irreducible SM backgrounds at $\sqrt{s} = 8$ TeV, and integrated luminosity of 60 fb$^{-1}$, assuming $C_f = C_t$.

| $\sqrt{s} = 8$ TeV (60 fb$^{-1}$) | Signal (S) | Background (B) |
|----------------------------------|------------|----------------|
| **Cut**                          | $C_t = -1$ | $C_t = 0$ | $C_t = 1$ | $2\gamma + t + j$ | $2\gamma + tt$ | $2\gamma + b + 3j$ | $B_{\text{tot}}$ |
| $2\gamma + b + (\geq 3j)$        | 7.7        | 6.1         | 0.21       | 9.8           | 11          | 299          | 320     |
| $|\eta_{Fj}| > 2.5$ & $p_T > 30$ GeV | 3.7        | 3.0         | 0.09       | 4.0           | 0.46        | 26           | 31      |
| $|M_{bjj} - m_t| < 20$ GeV       | 3.6        | 2.9         | 0.09       | 4.0           | 0.29        | 6.5          | 11      |
| $|M_{jj(top)} - M_W| < 15$ GeV | 3.4        | 2.8         | 0.08       | 3.8           | 0.23        | 2.1          | 6.1      |
| $|M_{\gamma\gamma} - m_H| < 3$ GeV | 3.4        | 2.8         | 0.08       | 0.14          | 0.02        | 0.68         | 0.84     |

### Table 2: Number of events passing sequential cuts for the signal $pp \to tqH \to tq\gamma\gamma$ and irreducible SM backgrounds at $\sqrt{s} = 14$ TeV, and integrated luminosity of 600 fb$^{-1}$, assuming $C_f = C_t$.

| $\sqrt{s} = 14$ TeV (600 fb$^{-1}$) | Signal (S) | Background (B) |
|----------------------------------|------------|----------------|
| **Cut**                          | $C_t = -1$ | $C_t = 0$ | $C_t = 1$ | $2\gamma + t + j$ | $2\gamma + tt$ | $2\gamma + b + 3j$ | $B_{\text{tot}}$ |
| $2\gamma + b + (\geq 3j)$        | 311        | 249         | 8.9        | 407           | 396          | 12079         | 12881   |
| $|\eta_{Fj}| > 2.5$ & $p_T > 50$ GeV | 121        | 99          | 3.5        | 161           | 19          | 551           | 731     |
| $|M_{bjj} - m_t| < 20$ GeV       | 118        | 97          | 3.5        | 161           | 11          | 136           | 308     |
| $|M_{jj(top)} - M_W| < 15$ GeV | 112        | 92          | 3.3        | 154           | 8.3         | 43            | 205     |
| $|M_{\gamma\gamma} - m_H| < 3$ GeV | 112        | 92          | 3.3        | 7.2           | 0.28        | 14            | 22      |
5 Signal significance versus $C_t$

By comparing the signal- and background- event numbers passing all the selection cuts in the last row of Table 1 and 2, the sensitivity of the $pp \to tqH \to tq\gamma\gamma$ process to a change of sign of $Y_f$ gets clearly manifest. While a SM coupling configuration $Y_f/Y_f^{SM} \simeq 1$ provides a signal-to-background ratio $S/B \sim 10\% (15\%)$ at $\sqrt{s} = 8\, (14)$ TeV, when $Y_f/Y_f^{SM} \simeq -1$ one reaches $S/B$ as large as $\sim 4\,(5)$ at $\sqrt{s} = 8\,(14)$ TeV. At $\sqrt{s} = 8$ TeV, the signal event number is quite small. For $C_f \simeq -1$, one expects about $S \approx 3$ with $B \lesssim 1$, for $60$ fb$^{-1}$.

On the other hand, at $\sqrt{s} = 14$ TeV with $600$ fb$^{-1}$, one gets about $S \approx 100$ with $B \simeq 20$ in all the negative $Y_f$ range considered ($-1.5 \lesssim C_f \lesssim 0$), with corresponding statistical significances

| $\sqrt{s} = 14$ TeV (600 fb$^{-1}$) | $C_t = -1.5$ | $C_t = -1$. | $C_t = -0.5$ | $C_t = 0$ | $C_t = 0.5$ | $C_t = 1$. | $C_t = 1.5$ |
|----------------------------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|
| $S[2\gamma + b + (\geq 3\,j)]_\text{tag}$ | 287 | 311 | 338 | 249 | 47 | 8.9 | 6.6 |
| $S[\text{passing cuts}]$ | 104 | 112 | 122 | 92 | 17 | 3.3 | 2.2 |
| $S/\sqrt{S + B}$ | 9.3 | 9.7 | 10. | 8.6 | 2.7 | 0.67 | 0.45 |

Table 3: Number of tagged events, and number of events passing all selection cuts for the $pp \to tqH \to tq\gamma\gamma$ signal at $\sqrt{s} = 14$ TeV, and integrated luminosity of $600$ fb$^{-1}$, versus $C_t$ (assuming $C_f = C_t$). Statistical significances of the signal are shown, based on the background event numbers presented in Table 2.

| $\sqrt{s} = 14$ TeV (60 fb$^{-1}$) | $C_t = -1.5$ | $C_t = -1$. | $C_t = -0.5$ | $C_t = 0$ | $C_t = 0.5$ | $C_t = 1$. | $C_t = 1.5$ |
|----------------------------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|
| $S[2\gamma + b + (\geq 3\,j)]_\text{tag}$ | 29 | 31 | 34 | 25 | 4.7 | 0.89 | 0.66 |
| $S[\text{passing cuts}]$ | 10 | 11 | 12 | 9.2 | 1.7 | 0.33 | 0.22 |
| $S/\sqrt{S + B}$ | 2.9 | 3.1 | 3.2 | 2.7 | 0.86 | 0.21 | 0.14 |

Table 4: Number of tagged events, and number of events passing all selection cuts for the $pp \to tqH \to tq\gamma\gamma$ signal at $\sqrt{s} = 14$ TeV, and integrated luminosity of $60$ fb$^{-1}$, versus $C_t$ (assuming $C_f = C_t$). Statistical significances of the signal are shown, based on the background (rescaled) event numbers presented in Table 2.

| $\sqrt{s} = 8$ TeV (60 fb$^{-1}$) | $C_t = -1.5$ | $C_t = -1$. | $C_t = -0.5$ | $C_t = 0$ | $C_t = 0.5$ | $C_t = 1$. | $C_t = 1.5$ |
|----------------------------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|
| $S[2\gamma + b + (\geq 3\,j)]_\text{tag}$ | 7.4 | 7.7 | 8.7 | 6.1 | 1.1 | 0.21 | 0.16 |
| $S[\text{passing cuts}]$ | 3.2 | 3.4 | 3.8 | 2.75 | 0.52 | 0.08 | 0.06 |
| $S/\sqrt{S + B}$ | 1.6 | 1.7 | 1.8 | 1.5 | 0.45 | 0.08 | 0.06 |

Table 5: Number of tagged events, and number of events passing all selection cuts for the $pp \to tqH \to tq\gamma\gamma$ signal at $\sqrt{s} = 8$ TeV, and integrated luminosity of $60$ fb$^{-1}$, versus $C_t$ (assuming $C_f = C_t$). Statistical significances of the signal are shown, based on the background event numbers presented in Table 7.
Figure 5: Signal significance versus $C_t$. Different assumptions are made for the value of $R_{BR}^{\gamma\gamma} = BR_{\gamma\gamma} / BR_{\gamma\gamma}^{SM}$. The black solid line represents the Yukawa universal-rescaling hypothesis, where $R_{BR}^{\gamma\gamma}$ is just a function of $C_t$, with $C_b = C_\tau = C_t$. The remaining (colored) lines refer to the constant $R_{BR}^{\gamma\gamma} = 1, 2, 3, 4$ hypothesis.

$S/\sqrt{(S+B)} \sim 10$. This is shown in Table 3, where, for a set of different $C_t$ values, we report the corresponding significances $S/\sqrt{(S+B)}$ at $\sqrt{s} = 14$ TeV, and integrated luminosity of 600 fb$^{-1}$. For reference, we also show the number of tagged signal events according to the object definitions in Eqs. (22) and (23), and the number of tagged events passing all the sequence of selection cuts. The relevant number of background events ($B = B_{tot}$) can be found in Table 2. For convenience, we present in Table 4, the number of signal events and significances at $\sqrt{s} = 14$ TeV, for a reduced integrated luminosity of 60 fb$^{-1}$, that could be collected by ATLAS and CMS over about the first year of LHC running at $\sqrt{s} = 14$ TeV. In Table 5, the corresponding results are shown at $\sqrt{s} = 8$ TeV, and integrated luminosity of 60 fb$^{-1}$, where a few signal events could be detected for negative $C_t$ values, with statistical significances less than 2.

In Table 3 one can notice that, in the SM ($C_f = C_t = 1$), the large integrated luminosities foreseen at the high luminosity (HL) LHC project (a few $10^3$fb$^{-1}$) are required in order to measure a $pp \to tqH \to tq\gamma\gamma$ signal.

In Figures 5–7, we compare, at different $\sqrt{s}$ and integrated luminosities, the $pp \to tqH \to tq\gamma\gamma$ signal significances obtained in the Yukawa universal-rescaling hypothesis $C_f = C_t$, with the more model-independent framework of fixed values of the ratio $R_{BR}^{\gamma\gamma} = BR_{\gamma\gamma} / BR_{\gamma\gamma}^{SM}$. In the latter case, the $BR_{\gamma\gamma}$ enhancement could arise from a new mechanism beyond the SM, that affects only $BR_{\gamma\gamma}$ without influencing the $pp \to tqH$ production cross section apart from its $C_t$ dependence. For example, the presence of new heavy physical states could contribute to the $H \to \gamma\gamma$ width, without affecting the $pp \to tqH$ cross section. One can see that an
Figure 6: Signal significance versus $C_t$. Different assumptions are made for the value of $R_{BR}^{\gamma\gamma} = BR_{\gamma\gamma}/BR_{\gamma\gamma}^{SM}$. The black solid line represents the Yukawa universal-rescaling hypothesis, where $R_{BR}^{\gamma\gamma}$ is just a function of $C_t$, with $C_b = C_{\tau} = C_t$. The remaining (colored) lines refer to the constant $R_{BR}^{\gamma\gamma} = 1, 2, 3, 4$ hypothesis.

Figure 7: Signal significance versus $C_t$. Different assumptions are made for the value of $R_{BR}^{\gamma\gamma} = BR_{\gamma\gamma}/BR_{\gamma\gamma}^{SM}$. The black solid line represents the Yukawa universal-rescaling hypothesis, where $R_{BR}^{\gamma\gamma}$ is just a function of $C_t$, with $C_b = C_{\tau} = C_t$. The remaining (colored) lines refer to the constant $R_{BR}^{\gamma\gamma} = 1, 2, 3, 4$ hypothesis.
enhancement factor $R_{BR}^{γγ} \gtrsim 2$ is required in order to get at least $3\sigma$ significances for $C_t \sim -1$, at $\sqrt{s} = 14$ TeV, and integrated luminosity of $60\text{ fb}^{-1}$.

6 Conclusions

We have analyzed the $t$-channel $pp \to tqH \to tq\gamma\gamma$ potential for determining the relative sign of the $ttH$ and $WWH$ couplings at the LHC. As previously noted, the $pp \to tqH$ production cross section is extremely sensitive to a sign switch with respect to the SM. On the other hand, the actual potential of the single-top plus Higgs associated production depends on the additional theoretical assumptions on $BR_{γγ}$. We have made a parton-level simulation of the $H \to γγ$ decay signal for the $pp \to tqH$ channel, and studied the corresponding main irreducible backgrounds with a quite conservative set of selection cuts on the kinematics of the final particles. We have found that the first year of the LHC running at 14 TeV could be sufficient, if $C_f = C_t \lesssim 0$, to have a considerable signal event number with moderate background. In particular, an integrated luminosity of $60\text{ fb}^{-1}$ would give about 10 signal events versus less than 0.3 background events over all the negative range $-1.5 \lesssim C_t \lesssim 0$. This is to be confronted with the result corresponding to the SM parameter setup, that would require the integrated luminosities of the HL-LHC in order to reach an observable event statistics.

We then urge the LHC experimental groups to consider the single-top plus Higgs associated production $pp \to tq\gamma\gamma$ through a full-simulation analysis. We also leave to further work the assessment of the potential of the $pp \to tqH$ process as a probe of an anomalous top Yukawa behavior by means of the Higgs decays other than $H \to γγ$.

Acknowledgments

We thank Fabio Maltoni for pointing out to us the single-top plus Higgs production sensitivity to anomalous top Yukawa couplings. Discussions with Aleksandr Azatov, Roberto Contino, Kirtiman Ghosh, Pradipta Ghosh, Satyanarayan Mukhopadhyay, and Saurabh Niyogi are thankfully acknowledged. We also thank Gennaro Corcella, Leandro Nisati, and Fulvio Piccinini for advice on event simulation, and the RECAPP, Harish-Chandra Research Institute, for providing some extra cluster computing resources. E.G. would like to thank the PH-TH division of CERN for its kind hospitality during the preparation of this work. This work was supported by the ESF grant MTT60, by the recurrent financing SF0690030s09 project and by the European Union through the European Regional Development Fund.
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