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Search for top quark decays $t \to qH$ with $H \to \gamma\gamma$ using the ATLAS detector

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Abstract: A search is performed for flavour-changing neutral currents in the decay of a top quark to an up-type (c, u) quark and a Higgs boson, where the Higgs boson decays to two photons. The proton-proton collision data set used corresponds to $4.7\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 7\,\mathrm{TeV}$ and $20.3\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 8\,\mathrm{TeV}$ collected by the ATLAS experiment at the LHC. Top quark pair events are searched for in which one top quark decays to qH and the other decays to bW. Both the hadronic and the leptonic decay modes of the W boson are used. No significant signal is observed and an upper limit is set on the $t \to qH$ branching ratio of 0.79% at the 95% confidence level. The corresponding limit on the tqH coupling combination $\sqrt{\lambda_{tcH}^2 + \lambda_{tuH}^2}$ is 0.17.

Keywords: Hadron-Hadron Scattering

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1 Introduction

The observation by the ATLAS [1] and the CMS [2] Collaborations of a new boson with a mass around 125 GeV, compatible with the long-sought Higgs boson [3–6], opens up the possibility of searching for the decay of a top quark to a Higgs boson plus an up-type (c, u) quark. Such a decay would proceed via a flavour-changing neutral current (FCNC). According to the Standard Model (SM), FCNC processes are forbidden at tree level and very much suppressed at higher orders due to the Glashow-Iliopoulos-Maiani (GIM) mechanism [7]. For instance, the expectation for the $t \to cH$ branching ratio is $\sim 3 \cdot 10^{-15}$ (see ref. [8] and references therein). Observations of FCNC decays of the top quark would therefore provide a clear signal of new physics.

Previous searches for FCNC were conducted in particular for the $t \to c(u)Z$ decay mode by the LEP and HERA experiments [9–14] (via the crossed processes), CDF [15], ATLAS [16] and CMS [17]. The current best limit for the branching ratio is 0.05% at the 95% confidence level [17].

In models beyond the SM, the GIM suppression can be relaxed, and loop diagrams mediated by new bosons may contribute, yielding effective couplings λ_{tqH} orders of magnitude larger than those of the SM. Examples of such extensions are the quark-singlet model (QS) [18–20], two-Higgs-doublet models (2HDM) of type I, with explicit flavour conservation, and of type II, such as the minimal supersymmetric standard model (MSSM) [21–27]. In 2HDM without explicit flavour conservation (type III) [28–36], the $tc(u)H$ couplings are present at tree level. For a review of the different models see ref. [8].

Among the published extensions of the SM, the largest branching ratio ($\sim 0.15\%$) is specific to the $t \to cH$ decay. It appears in 2HDM of type III and corresponds to a non-flavour-diagonal Yukawa coupling which scales with top-quark and light-quark masses, m_t and m_q, as $\lambda_{tqH} = \sqrt{2 m_q m_t}/v$, as proposed in ref. [28], where $v/\sqrt{2} = 174$ GeV is the Higgs field vacuum expectation value. In the other models discussed in ref. [8], the largest branching ratios for the $t \to qH$ decays are of the order of a few 10^{-5}.

In this paper a search for $t \to qH$ decays in $t\bar{t}$ production is undertaken using the $H \to \gamma\gamma$ decay channel. The analysis does not distinguish between the $t \to cH$ and $t \to uH$ final states which have similar acceptances. As theory favours $t \to cH$, this mode is used as reference throughout this work, unless otherwise stated. Despite its small branching ratio ($\sim 0.23\%$ for a Higgs boson mass around 125 GeV), the $H \to \gamma\gamma$ channel was chosen because of its demonstrated high importance for inclusive Higgs boson studies, with a rather large number of events and a clean signature [1, 37]. The remaining top quark in the event is searched for in two final states: a bottom quark and a hadronically decaying W boson, giving rise to events with four jets, or a leptonically decaying W boson, giving two jets, a lepton and missing transverse energy.

The branching ratio $\mathcal{B}$ of the $t \to qH$ process is estimated as the ratio of its partial width to the $t \to bW$ width, assumed to be dominant,

$$\mathcal{B} = (\lambda_{tcH}^2 + \lambda_{tuH}^2)/(g^2 \cdot |V_{tb}|^2 \cdot \chi^2), \tag{1.1}$$

where $|V_{tb}|$ is taken equal to 1, χ is a kinematic factor[1] and $g = 2m_W/v$ is the weak coupling constant. Using PDG averages [38] and applying NLO corrections to both the $t \to qH$ partial width [39] and the top quark total decay width [40] leads to $\chi g = 1.92 \pm 0.02$, which is used in the extraction of the coupling.

2 Detector and data set

The ATLAS detector [41] consists of an inner tracking detector (ID) surrounded by a superconducting solenoid providing a 2 T magnetic field, electromagnetic and hadronic calorimeters, and a muon spectrometer. The ID provides tracking in the pseudorapidity[2]

[1] $\chi^2 = (1 - 3x^4 + 2x^6)(1 - y^2)^{-2} x^{-2}/2$, where $x = m_W/m_t$, $y = m_H/m_t$, m_W and m_H are the W-boson and Higgs boson masses and the masses of the other quarks are neglected.

[2] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam line. Observables labelled as transverse are projected onto the xy plane. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upwards. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam line. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln \tan \frac{\theta}{2}$. The ΔR distance is defined as $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

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region $|\eta| < 2.5$ and consists of silicon pixel- and microstrip-detectors inside a transition radiation tracker. The electromagnetic calorimeter, a lead/liquid-argon sampling device, is divided into one barrel ($|\eta| < 1.475$) and two end-cap ($1.375 < |\eta| < 3.2$) sections. Longitudinally, it is divided into three layers. The first layer, referred to as the strip layer, has a fine segmentation in the regions $|\eta| < 1.4$ and $1.5 < |\eta| < 2.4$ to facilitate the separation of photons from neutral hadrons and to allow shower directions to be measured, while most of the energy is deposited in the second layer. In the range of $|\eta| < 1.8$ a presampler layer inside the cryostat allows for the correction of energy losses upstream of the calorimeter. The barrel ($|\eta| < 1.7$) hadronic calorimeter consists of steel and scintillating tiles, while the end-cap sections ($1.5 < |\eta| < 3.2$) are composed of copper and liquid argon. The forward calorimeter ($3.1 < |\eta| < 4.9$) uses copper and tungsten as absorber with liquid argon as active material. The muon spectrometer consists of precision ($|\eta| < 2.7$) and trigger ($|\eta| < 2.4$) chambers embedded in a toroidal magnet system which surrounds the hadronic calorimeter.

This analysis uses the full proton-proton data set recorded by ATLAS in 2011 and 2012. After application of data-quality requirements, the integrated luminosity amounts to $4.7\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 7$ TeV, with a relative uncertainty of 1.8% [42], and $20.3\,\mathrm{fb}^{-1}$at $\sqrt{s} = 8$ TeV, with a relative uncertainty of 2.8%.[3] The data were recorded with instantaneous luminosities varying between $1 \times 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and $7.8 \times 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The mean number of interactions per bunch crossing was 9.1 in 2011 and 20.4 in 2012. The inelastic collisions that occur in addition to the hard interaction produce mainly low transverse momentum particles that form the so-called "pile-up" background.

The data considered here were selected using a diphoton trigger in which two clusters formed from energy depositions in the electromagnetic calorimeter are required. A transverse energy (E_T) threshold of 20 GeV was required at 7 TeV, while at 8 TeV the thresholds were increased to 35 GeV and 25 GeV on the leading (sorted in E_T) and sub-leading clusters. In addition, loose criteria were applied on the shape of the clusters requiring that they match the expectations for electromagnetic showers initiated by photons. For events satisfying the off-line selection, the efficiency of the diphoton trigger is measured to be $(98.9 \pm 0.2)\%$ for $\sqrt{s} = 7$ TeV data and $(99.6 \pm 0.5)\%$ at 8 TeV.

3 Experimental techniques

3.1 Photon reconstruction and identification

The photon reconstruction is seeded from clusters of energy deposits in the electromagnetic calorimeter. Clusters without any matching track in the ID are classified as unconverted photon candidates. Clusters with a matching conversion reconstructed from one or two tracks are classified as converted photon candidates [43]. The efficiency of the photon reconstruction is about 96.5% averaged over the E_T and η spectra expected for photons from a $m_H = 125$ GeV Higgs boson decay.

[3] The luminosity of the 2012 data set is derived, following the same methodology as that detailed in ref. [42], from a preliminary calibration of the luminosity scale derived from beam-separation scans performed in November 2012.

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The identification of photons (PID) is based on the shape of their showers in the electromagnetic calorimeter. An initial loose selection, also used at trigger level, is based on shower shapes in the second layer of the electromagnetic calorimeter and on the energy deposition in the hadronic calorimeter. The tight identification adds information from the finely segmented strip layer. The PID efficiency, averaged over η, ranges between 85% and 95% for the E_{T} range of interest.

The measurement of the uncertainty on the PID efficiency is based on the comparison of the efficiency obtained in the simulation and the combination of three data-driven measurements [44]. Taking into account possible correlations in η, E_{T} and conversion status, the resulting uncertainty on the diphoton inclusive signal yield is estimated to be 8.4% at 7 TeV and, owing to the larger sample and several analysis improvements, 2.4% at 8 TeV [37]. For the hadronic channel analysis, where four or more jets are required, the systematic uncertainty is 9.3% at 7 TeV and 4.6% at 8 TeV.

To further suppress jets faking photons, calorimetric and track isolation requirements are applied. The isolation-E_{T} is estimated by summing the E_{T} of positive-energy topological clusters[4] reconstructed in the electromagnetic and hadronic calorimeters in a cone of $\Delta R = 0.4$ around the photon candidate, where the region of size 0.125×0.175 in $\eta \times \phi$ around the photon barycentre is excluded. The isolation-E_{T} is corrected for leakage of the photon energy outside of the excluded region and for pile-up [46], and it is required to be below 4 GeV (6 GeV) for the 2011 (2012) data. For the 2012 data set, the scalar sum of the transverse momentum (p_{T}) of all tracks consistent with the primary vertex (see below), with p_{T} above 1 GeV and in a $\Delta R = 0.2$ cone around the photon direction is required to be below 2.6 GeV. Comparing data and simulation using electrons from $Z \to e^+e^-$ candidate events, and photons from $Z \to \ell^+\ell^-\gamma$ events, where $\ell = e$ or μ, a good agreement between efficiencies is found and the remaining small difference is accounted for as a systematic uncertainty of 1% on the diphoton signal yield for inclusive production. For events with four or more jets, the efficiency of the calorimetric isolation selection was found to be slightly smaller in data than in the simulation, resulting in a correction factor of 0.98 with a systematic uncertainty of $\pm 3\%$.

The energies of the clusters are calibrated separately for unconverted and converted photon candidates and for electrons.

The energy calibration for data is refined by applying η-dependent correction factors, which are about $\pm 1\%$, determined from $Z \to e^+e^-$ events. The simulation is corrected to reflect the energy resolution observed using $Z \to e^+e^-$ events in data, which requires an additional energy smearing of about 1% in the barrel region and between 1.5% and 2.5% in the end-cap region to account for the constant term in the calorimeter energy resolution and the imperfect description of the material in front of the calorimeter.

3.2 Other physics objects

The kinematic properties of all objects are determined with respect to a primary vertex selected [37] by combining:

[4] Topological clusters are three-dimensional clusters of variable size, built by associating calorimeter cells on the basis of the signal-to-noise ratio [45].

- an estimate of its z position obtained from the intersection of the beam line with the direction of the photons, as determined by the measurement using the longitudinal segmentation of the calorimeter, and the conversion point or hits in the ID when available;

- the scalar sum of the transverse momenta and the sum of the squared transverse momenta of the tracks associated with each reconstructed vertex;

- and, at 8 TeV, the difference in azimuth between the direction of the vector sum of the tracks momenta and the di-photon system.

In addition to photons, the analysis requires also jets, electrons or muons and missing transverse energy, $E_{\mathrm{T}}^{\mathrm{miss}}$. The main inputs to identify and measure these objects are summarised below.

- Jets are reconstructed from topological clusters in the calorimeters [45, 47], using the anti-k_t algorithm [48] with a radius parameter $R = 0.4$. They must have $|\eta| < 4.5$ and $p_{\mathrm{T}} > 25$ GeV. For the 8 TeV data set, this threshold is increased to 30 GeV for jets with $|\eta| > 2.4$. The dependence of the jet response on the number of reconstructed primary vertices and on the expected average number of interactions is removed, at $\sqrt{s} = 8$ TeV where the pile-up is largest, by applying an event-by-event subtraction procedure based on the jet area method [49]. In order to suppress jets produced in additional pile-up interactions, each jet is also required to have a sufficiently high jet vertex fraction (JVF) defined as the scalar sum of p_{T} of the tracks consistent with the primary vertex that fall into the jet area over the sum of track p_{T} from all primary vertices falling into the same jet area. A JVF larger than 0.75 (0.25) for the 7 TeV (8 TeV) data set is required. At 8 TeV, this cut is only applied for jets with $|\eta| < 2.4$ and $p_{\mathrm{T}} < 50$ GeV.

- The tagging of bottom quark jets is performed using a neural network identifier [50], which includes information from the impact parameter of tracks and from displaced vertices from hadron decays. The threshold values are set so as to give, on average, a 70% efficiency for jets containing a bottom hadron in $t\bar{t}$ events. The efficiency for charm jets is about 20%, and it is less than 1% for light-quark jets. Small differences between data and simulation are taken into account by a global factor determined by propagating to the simulated signal samples the differences between data and simulation measured on dedicated samples ($t\bar{t}$ in particular).

- Electron candidates consist of clusters of energy deposited in the electromagnetic calorimeter that are associated with ID tracks [51]. Their transverse energy is computed from the cluster energy and the track direction at the interaction point, and they are required to satisfy $|\eta| < 2.47$ and $E_{\mathrm{T}} > 15$ GeV.

  Electron candidates have to pass a set of requirements on the hadronic leakage, shower shapes, track quality and track-cluster matching variables. Furthermore, they must be isolated: the calorimetric isolation E_{T} in a $\Delta R = 0.4$ cone divided by the electron

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candidate's E_{T} is required to be less than 0.2, and the scalar sum of the p_{T} of tracks consistent with the primary vertex, in a cone of $\Delta R = 0.2$ around the electron candidate's track, divided by its E_{T}, has to be less than 0.15.

- Muon candidates are required to pass the conditions $|\eta| < 2.7$ and $p_{\mathrm{T}} > 10$ GeV, and they must be isolated with the same criteria as for electrons. The muon tracks must have a transverse impact parameter $|d_0| < 1$ mm and a longitudinal impact parameter $|z_0| < 10$ mm.
- The missing transverse energy is calculated as the magnitude of the sum of the $\vec{p}_{\mathrm{T}}$ of all identified objects in an event. Clusters of calorimeter cells with $|\eta| < 4.9$ not associated with any of the objects described above are also added.

A given particle may be reconstructed as more than one object (for example both as a photon and a jet). This possible duplication, as well as any real overlap in a narrow ΔR interval, is suppressed by an overlap removal procedure (within $\Delta R = 0.2$ between photons and electrons, 0.4 between photons and jets, 0.4 between muons and either jets or photons) in which the highest priority is given to photons, followed by electrons, jets and finally muons.

3.3 Signal and background simulation

The simulations of the signal and of the SM Higgs boson production (resonant background) are used to estimate the corresponding acceptances. The relevant non-resonant backgrounds are due to diphoton production and $t\bar{t}$ and W production. These backgrounds are simulated in order to constrain the shape of the fitted non-resonant background in control regions of the data.

Signal events corresponding to $t\bar{t}$ production, with one top quark decaying into a charm quark and a Higgs boson (which is constrained to decay into two photons) were generated using PROTOS 2.2 [52], with PYTHIA6 [53] for parton shower (PS), multiple interactions (MI) and hadronisation, with a set of parameters as defined by the Perugia2011C tune [54]. A top quark mass of 172.5 GeV and a Higgs boson mass of 125 GeV were chosen.

Four samples of 30,000 events were generated: two samples correspond to $\sqrt{s} = 8$ TeV and the other two to $\sqrt{s} = 7$ TeV. At each energy there is one sample for which the second top quark decays only hadronically and one sample where the W boson from the second top quark decays leptonically, including tau leptons which are decayed using TAUOLA [55]. The hadronic and the leptonic samples are added with weights corresponding to the respective decay fractions of the W boson. At 8 TeV, two additional samples were generated where one top quark decays to an up quark (instead of a charm quark) and a Higgs boson, which allow for the determination of the ratio of the acceptances of the $t \to uH$ and $t \to cH$ decay modes.

The contributions of known SM sources of Higgs boson production are estimated simulating Higgs boson production by gluon fusion (ggF), by vector boson fusion (VBF), Higgs-strahlung associated production (WH and ZH), and associated production of Higgs boson and a $t\bar{t}$ pair ($t\bar{t}H$). The first two were produced using POWHEG [56, 57] interfaced to PYTHIA8 [58] for the Higgs boson decay, PS, MI and hadronisation, and the last three by PYTHIA8.

Non-resonant production of two-photon final states with several additional jets dominates the background in the hadronic selection. This was simulated using SHERPA [59] with up to three additional partons in the primary hard interaction (this sample, of about 10^7 events, is called $\mathrm{S}_{\gamma\gamma j}$ in the following). The same final state where one of the photons is a fake photon candidate resulting from jet misidentification also contributes to the hadronic background (see refs. [37, 60]). The level of this additional contribution, for final states with several jets, is estimated by data-driven methods to be about 18% of the background with two real photons. Comparative studies using dedicated simulations for the hadronic background with fake photon candidates show that, within the limited statistical precision of these simulations due to the high rejection power of the photon identification, the distributions relevant for the hadronic analysis (see section 4.1) are compatible with those from the $\mathrm{S}_{\gamma\gamma j}$ sample. The latter is thus used in the following to represent both backgrounds.

Finally samples of $t\bar{t}$ ($\sim 1.5 \cdot 10^7$ events) and $W(\gamma)$ ($\sim 2.3 \cdot 10^7$ events) production simulated with MC@NLO [61] and ALPGEN [62], respectively, interfaced to HERWIG [63] and JIMMY [64], were used to estimate the contribution of these processes.

The $W(\gamma)$ sample is a W sample in which the production of one photon at the matrix element level is imposed, and a lepton filter is applied.

In all samples but the $\mathrm{S}_{\gamma\gamma j}$ one, PHOTOS [65] is employed to describe additional photon radiation from charged leptons.

All samples were processed through a full simulation of the ATLAS detector [66] based on the GEANT4 package [67]. A modelling of the event pile-up from the same and nearby bunch crossings, tuned to the data, is also included. The simulations are corrected using weights to reflect the number of interactions per bunch crossing and the spread of the z position of the primary vertex observed in data. Differences in efficiencies between data and simulation for object reconstruction and identification are corrected in the same way.

4 Analysis strategy and candidate event selection

Events are first required to fulfill the criteria used for the Higgs boson analysis in the $\gamma\gamma$ channel [37], namely to contain at least two reconstructed photon candidates in the fiducial region of the calorimeter $|\eta| < 2.37$, but excluding the transition region between the barrel and endcap calorimeters, $1.37 < |\eta| < 1.56$. The leading (subleading) photon candidate is required to have $E_{\mathrm{T}} > 40$ GeV (30 GeV). Tight identification and isolation criteria, as described above, are applied to both photon candidates.

Additional requirements are applied in order to select events compatible with a $t\bar{t}$ intermediate state.

Finally the diphoton mass distribution of the selected events is analysed using a sideband technique in order to estimate the background in the signal region.

In the $\sqrt{s} = 8$ TeV data set, candidates which contain one and only one lepton are treated in the leptonic analysis while events having no leptons are treated in the hadronic analysis, and events with two or more leptons are rejected. At 7 TeV no analysis in the

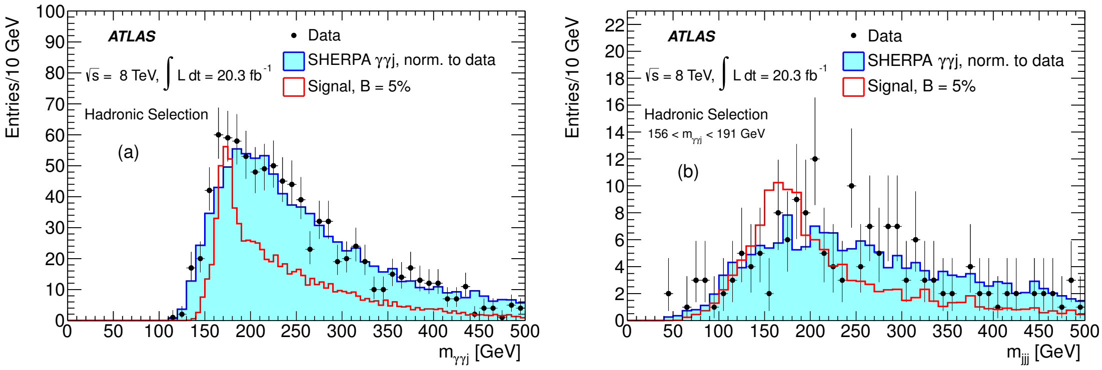

Figure 1. (a) Distribution of the invariant mass $m_{\gamma\gamma j}$ (*Top1*), for events selected by the hadronic analysis (see text for details) in the $\sqrt{s} = 8$ TeV data set, with at least one b-tagged jet. For each event there are four $m_{\gamma\gamma j}$ combinations, and all four are displayed. (b) Distribution of the invariant mass m_{jjj} for the complementary top candidates (*Top2*) decaying into 3 jets; only combinations for which $m_{\gamma\gamma j}$ is between 156 and 191 GeV enter in the distribution.

leptonic channel was performed. Due to the smaller data sample and the lower sensitivity of the leptonic channel compared to the hadronic one, this has no significant impact on the precision of the final results.

4.1 Selection of hadronically decaying top quarks

Events are required to have at least four jets among which at least one is b-tagged. In case of more than four jets, the four leading ones (ordered in decreasing p_{T}) are considered. However, the jet ranked 4^{th} in p_{T} is replaced by the 5^{th} one if the former is not b-tagged and the latter is. This procedure is extended to the 6^{th} jet if the 5^{th} is not b-tagged either. The signal sample shows that such a jet replacement happens for about 6% of the events, and that the acceptance is increased by about the same amount.

After the selection of four jets, one top-quark candidate, *Top1*, is constructed from the two photons and one jet, and another top-quark candidate, *Top2*, is formed from the three remaining jets. At least one of the four possible pairs must have masses $m_1 \equiv m_{\gamma\gamma j}$ and $m_2 \equiv m_{jjj}$ that lie within certain mass windows of size Δm_1 and Δm_2 around the top-quark mass (see below). Additional requirements, such as associating the b-tagged jet with *Top2* and imposing the invariant mass of the remaining two jets of *Top2* to be compatible with the W-boson mass were considered but not retained as they did not significantly improve the expected significance.

Figure 1(a) shows the distribution of m_1 (four entries per event) for all selected events before mass cuts in the $\sqrt{s} = 8$ TeV data set.

In the simulated signal sample, normalised to the expectation for an arbitrary 5% $t \to cH$ branching ratio, the narrow peak associated with the top quark is clearly visible. The combinatorial background has a shape similar to the distribution obtained with the $\mathrm{S}_{\gamma\gamma j}$ sample (normalised to data in the mass region [0,500] GeV). The background from $t\bar{t}$ and $W(\gamma)$ production is negligible. The chosen Δm_1 interval is [156,191] GeV.

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	$t \to cH$ (%)		Data (events)	
	7 TeV	8 TeV	7 TeV	8 TeV
$\gamma\gamma$ selection	34.5	34.2	23683	118500
$\mathrm{N_{jets}} \geq 4$	15.2	15.1	227	1349
Mass requirements	5.9	6.1	36	210
At least 1 b-tag	4.2±0.1	4.0±0.1	7	43

Table 1. Efficiency (in percent) for $t \to cH$ signal simulation and number of events for data, at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV for the hadronic selection, at different stages of the event selection. The uncertainties on the efficiencies for the full selection, shown in the last row, are statistical only.

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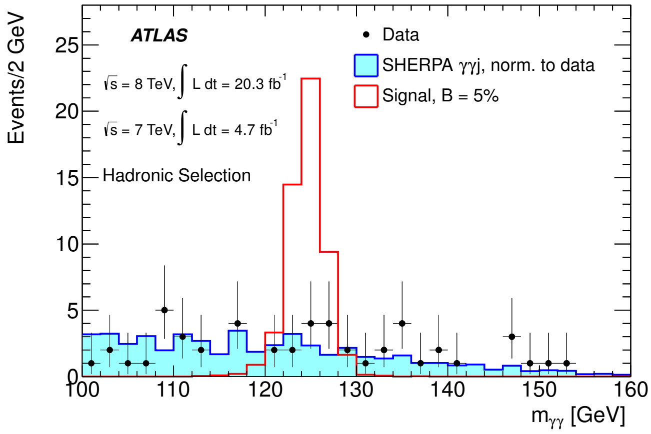

Figure 2. Distribution of the invariant mass of the two photons, $m_{\gamma\gamma}$, for events passing the full hadronic selection (see text for details). The $S_{\gamma\gamma j}$ background sample is normalised to data.

The distribution of m_2 is shown in figure 1(b). Only combinations for which m_1 fulfills the Δm_1 condition enter in this figure. The simulated signal distribution shows that the peak associated with *Top2* is broader than for *Top1*. The combinatorial background has a shape similar to the distribution obtained with the $\mathrm{S}_{\gamma\gamma j}$ sample (normalised as for the *Top1* case). The chosen Δm_2 interval is [130,210] GeV. The Δm_1 and Δm_2 intervals are determined on the basis of the mass resolutions observed in the simulation. The expected significance is stable with respect to moderate variations of the mass criteria around the chosen values. The reconstructed mass distributions of top candidates at $\sqrt{s} = 7$ TeV are similar to the ones shown at 8 TeV, and the same mass intervals are used.

An overview of the hadronic selection at various stages of the analysis is shown in table 1 for both the $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV samples.

The $\gamma\gamma$ mass ($m_{\gamma\gamma}$) spectrum for data after the complete selection is shown in figure 2 together with the corresponding distribution for the $\mathrm{S}_{\gamma\gamma j}$ sample. The latter shows a satisfactory modeling of the background outside the expected signal mass range, as is also the case at earlier stages of the analysis with much larger statistics.

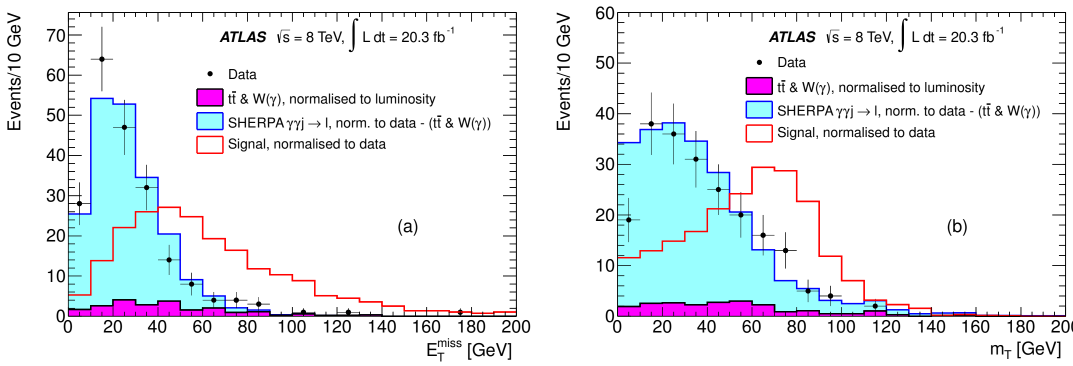

Figure 3. Distributions of (a) the missing transverse energy $E_{\mathrm{T}}^{\mathrm{miss}}$ and (b) the transverse mass m_{T} of the W candidates for events with two high p_{T} photons and one lepton. The $t\bar{t}\&W(\gamma)$ and $\mathrm{S}_{\gamma\gamma j\to\ell}$ background samples are defined in the text.

4.2 Selection of leptonically decaying top quarks

The aim of the leptonic analysis is to identify candidate events in which the W boson from the second top quark decays leptonically. Only electrons and muons are considered as identified leptons, and only events with exactly one lepton are considered. Events with two or more jets are retained for the subsequent steps. The lepton p_{T} is used together with $E_{\mathrm{T}}^{\mathrm{miss}}$ to calculate the transverse mass m_{T} of the W candidate, and $m_{\mathrm{T}} > 30$ GeV is required. At this stage, no event is selected in the $\mathrm{S}_{\gamma\gamma j}$ sample, due to the high rejection power of the electron and muon identification requirements. In order to have a larger event sample to represent this background, one randomly chosen jet per event, among jets with $|\eta| < 2.5$ and $p_{\mathrm{T}} > 15$ GeV, was replaced by a lepton with the same momentum vector. This sample, named $\mathrm{S}_{\gamma\gamma j\to\ell}$, gives a good description of the data, as shown in figure 3(a) for $E_{\mathrm{T}}^{\mathrm{miss}}$ and figure 3(b) for m_{T}. In figure 3 the sample referred to as $t\bar{t}\&W(\gamma)$ originates from the $t\bar{t}$ and $W(\gamma)$ simulations, normalised to the luminosity of the data set, while the $\mathrm{S}_{\gamma\gamma j\to\ell}$ sample is normalised to data, after subtraction of the $t\bar{t}\&W(\gamma)$ background.

The two leading jets are considered. However, as for the hadronic selection, some priority is given to b-tagged jets: if the jet ranked second is not b-tagged and if there is a b-tagged third jet that passes all other requirements, the second jet is replaced by the third. The replacement procedure is repeated in case there is a 4^{th} b-tagged jet and the second and third were not b-tagged. The signal simulation shows that such a jet replacement happens for about 9% of the events and that the acceptance is increased by about the same amount.

After the above selection of two jets, one top-quark candidate, *Top1*, is constructed from the two photons and one jet; its invariant mass is $m_1 \equiv m_{\gamma\gamma j}$. Another top-quark candidate, *Top2*, is built from the remaining selected jet, the lepton and the neutrino, with invariant mass $m_2 \equiv m_{\ell\nu j}$. The longitudinal momentum of the neutrino is estimated using a W-mass constraint. In the case of two real solutions,[5] the one giving m_2 closer

[5]In case no real solution exists, the constraint is applied by replacing m_W by m_{T} + 100 MeV, which ensures two, almost degenerate, real solutions.

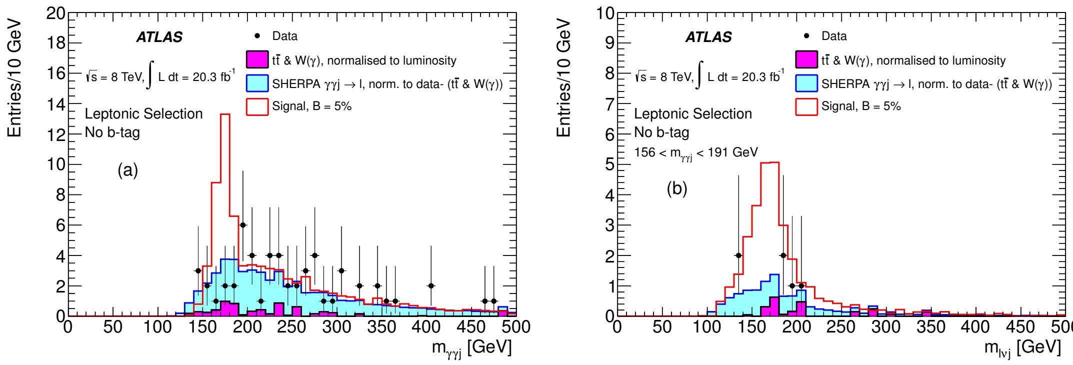

Figure 4. (a) Distribution of the invariant mass $m_{\gamma\gamma j}$ (*Top1*) candidates , for events selected by the leptonic analysis (see text for details) in the $\sqrt{s} = 8$ TeV data set, before b-tagging requirement. For each event there are two combinations, and both are displayed. (b) Distribution of the invariant mass $m_{l\nu j}$ for the complementary top candidates (*Top2*) decaying into one jet, a lepton and a neutrino; only combinations for which $m_{\gamma\gamma j}$ is between 156 and 191 GeV enter in the distribution.

to the top-quark mass is chosen. At least one of the two possible (*Top1, Top2*) pairs must have masses that lie within certain windows around the top-quark mass (see below). Furthermore it is required that at least one of the two jets is b-tagged.

Figure 4(a) shows the invariant mass distribution of the *Top1* combinations (two entries per event) for all selected events before the mass selections, and without the b-tagging requirement. In the signal sample, normalised to the expectation for a 5% $t \to cH$ branching ratio, the narrow peak associated with the top quark is clearly visible, as well as a tail at higher masses corresponding to the wrong combination of final state objects. The $\mathrm{S}_{\gamma\gamma j\to\ell}$ sample, together with the $t\bar{t}$ and $W(\gamma)$ contributions give a reasonable description of the data. The interval Δm_1 chosen for the m_1 selection is [156,191] GeV, as in the hadronic case. Only combinations for which m_1 fulfills the Δm_1 selection enter in the *Top2* distribution (figure 4(b)). Based on the width of the peak in the signal simulation, the interval Δm_2 is chosen to be [135,205] GeV, a little narrower than for the hadronic mode.

Table 2 shows an overview of the leptonic selection at various stages of the analysis. Inclusive $t\bar{t}$ and $W(\gamma)$ production, normalised to the luminosity of the data, are expected to contribute about 0.7 and 0.3 events, respectively, and the $\mathrm{S}_{\gamma\gamma j\to\ell}$ background about half an event. In the data a single event remains with a $\gamma\gamma$ mass of 147 GeV and a muon with p_{T} of 47 GeV.

The satisfactory agreement observed between data and background expectations indicates a good understanding of the background composition. However, as a sideband technique is used, only the shape of the background is relevant. Out of the three main contributions to the background ($t\bar{t}$, $W(\gamma)$ and hadronic) the first two suffer from low statistics in the simulation. At earlier stages of the analysis, where more events are available, the distributions are smooth and exhibit a decreasing slope, compatible with the function used in section 5.2 to describe the background shape.

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	$t \to cH$	$t\bar{t}$ &$W(\gamma)$	$\mathrm{S}_{\gamma\gamma j\to\ell}$	Data
	(%)	Events		
$\gamma\gamma$ selection	34.9	313.7		118500
1 lepton	6.0	21.8	188.2	210
$\mathrm{N_{jets}} \geq 2$, $m_{\mathrm{T}} > 30$ GeV	3.8	3.4	18.8	30
Mass requirements	1.9	1.2	3.5	4
At least 1 b-tag	1.3±0.1	0.9±0.5	0.5±0.2	1

Table 2. Efficiency (in percent) for $t \to cH$ signal simulation and numbers of events selected for data or expected ($t\bar{t}$&$W(\gamma)$, $\mathrm{S}_{\gamma\gamma j\to\ell}$) at different stages of the analysis, in the leptonic selection. The column denoted by "$t\bar{t}$&$W(\gamma)$" is normalised to the luminosity of the data. The column denoted by $\mathrm{S}_{\gamma\gamma j\to\ell}$ is normalised to data after subtraction of the expected background from $t\bar{t}$ and $W(\gamma)$ at the "2 photons + 1 lepton" selection step. The uncertainties are statistical only for $t \to cH$ and $t\bar{t}$&$W(\gamma)$, but include the normalisation uncertainty for $S_{\gamma\gamma j\to\ell}$.

5 Statistical analysis and results

The parameter of interest is the branching ratio $\mathcal{B}$ of the decay $t \to c(u)H$. A fit to the data is performed using a likelihood function defined as the product of the likelihoods for the individual search channels, whose sensitivities as a function of $\mathcal{B}$ are given in section 5.1. Hypothesised values of $\mathcal{B}$ are evaluated with a test statistic based on the profile likelihood ratio [68]. In the hadronic selection, which combines the 7 and 8 TeV data, $m_{\gamma\gamma}$ is used as discriminating variable in the fit. The analysis in the leptonic selection is based on event counting in two $m_{\gamma\gamma}$ regions: the signal region (SR) from 122 to 129 GeV, and the control region (CR) from 100 to 122 GeV and from 129 to 160 GeV.

The theoretical uncertainties enter mainly through the $t\bar{t}$ production cross-section, the Higgs boson branching ratio to $\gamma\gamma$, the background due to SM Higgs production (section 5.3) and the signal generator uncertainties (section 5.4). The experimental systematic uncertainties are detailed in section 5.4. All these uncertainties are introduced as nuisance parameters in the likelihood.

5.1 Expected signal event yields

The expected signal event yields in the three channels (hadronic 7 TeV, hadronic 8 TeV and leptonic 8 TeV) are estimated using the signal efficiencies given in tables 1 and 2, the $t\bar{t}$ production cross-sections at 7 and 8 TeV [69, 70], and the integrated luminosities of the corresponding data sets. They are listed in table 3, where they are expressed in terms of the number of events expected for a $t \to cH$ branching ratio of 1%. The same study with $t \to uH$ shows that the efficiency of the hadronic analysis is 1% higher than for $t \to cH$, while it is 6% lower for the leptonic analysis. These variations are small enough to justify taking the same sensitivity for both modes.

The sensitivities are evaluated for a Higgs boson mass of 125.5 GeV [37]. A correction of -1% (+1.5%) is applied on the hadronic (leptonic) efficiency, obtained from a linear

Selection	Hadronic		Leptonic
Centre of mass energy	7 TeV	8 TeV	
$t\bar{t}$ cross-section (pb)	$177\ ^{+10}_{-11}$	253^{+13}_{-15}	
$H \to \gamma\gamma$ Br (%)	0.23±0.01		
Signal efficiency (%)	4.2±0.1	4.0±0.1	1.3±0.1
Exp. events for $\mathcal{B}$ = 1%	1.6±0.1	9.3±0.7	3.0±0.3

Table 3. Expected signal efficiencies and event yields for a $t \to cH$ branching ratio of 1% and m_t=172.5 GeV in the three analysis channels. The values used for the $t\bar{t}$ cross-section and the $H \to \gamma\gamma$ branching fraction are quoted for completeness.

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interpolation of the acceptances estimated at particle level for simulations with masses of 125 and 126.8 GeV. Changing the top quark mass from 172.5 to 173.1 GeV increases the acceptances by about 1.6% while the $t\bar{t}$ production cross-section is decreased by about 1.8%. The net effect is thus neglected. The effect of small differences between data and simulation in b-tagging and photon isolation efficiencies is also included in table 3. The generator and the experimental systematic uncertainties, not included in table 3, are described in section 5.4. As pointed out above, the 7 TeV and the 8 TeV hadronic channels are treated as a single channel, whose combined expected event yield is 10.9 ± 0.8 events for $\mathcal{B} = 1\%$.

5.2 Signal and background modelling

The shape of the signal diphoton mass distribution is similar to the shape used in the $H \to \gamma\gamma$ inclusive analysis [37], for a signal mass hypothesis $m_H = 125.5$ GeV. It is described by the sum of a wide Gaussian and a Crystal Ball function with width $\sigma \simeq 1.7$ GeV, and differs slightly between the 7 and 8 TeV analyses. The fraction of the signal that falls into the SR is estimated to be $\sim$ 90%. The same shape is used for the resonant background from SM Higgs boson production.

Background estimate for the hadronic channel. Due to low statistics the data distribution in the CR alone cannot be used to constrain the background shape. Instead, the diphoton mass spectrum from the $\mathrm{S}_{\gamma\gamma j}$ sample (see figure 2) smoothed using the algorithm of ref. [71] is employed. Pseudo-data have been generated following this distribution, with on average 45.2 events (given by the sum of the 38 data events in the CR and the associated SR contribution of 7.2 events assuming that the true probability density function is the smoothed one). The corresponding $m_{\gamma\gamma}$ spectra have been fitted with different parametrisations for the background shape. For fits with only the background, a bias has been defined as the difference, in the SR, between the true number of events and the number of events predicted by the fit. For fits including the signal, the bias is defined as the number of fitted signal events. The criterion used to select a background parametrisation as valid is that these biases should be smaller than 10% of the number of signal events at the expected limit ($\sim$ 6 events). The background-only and the signal+background fits give consistent results. Both 2^{nd} and 3^{rd} order polynomial distributions satisfy the criterion, and the 2^{nd} order polynomial was chosen. The associated bias with respect to the smoothed $\mathrm{S}_{\gamma\gamma j}$ distribution is ~ 0.6 event. It is added as a systematic uncertainty in the final fit.

Background estimate for the leptonic analysis. The background in the leptonic channel is estimated via a transfer factor α, defined as the ratio of the background shape integral over the SR and its integral over the CR. The central value of α in the fit is given by the smoothed function used for the hadronic analysis, $\alpha = 0.15$. For a flat $m_{\gamma\gamma}$ distribution $\alpha \simeq 0.13$ would be obtained. A Gaussian constraint on α with a conservative width of 30% is included in the likelihood function.

5.3 Background from SM Higgs production

The estimate of the expected number of background events from SM Higgs production is obtained by combining the cross-sections for Higgs boson production via the ggF, VBF, WH, ZH and $t\bar{t}H$ processes [72, 73], assuming they all follow the SM predictions, the integrated luminosities of the 7 TeV and 8 TeV data sets, and the event selection efficiencies determined using full simulation for each production mode (see section 3.3). The uncertainties on the cross-sections are obtained by a linear sum of the renormalisation and factorisation scale uncertainties on one hand, and of the parton distribution functions and α_s uncertainties on the other hand, as they appear in refs. [72, 73]. The VBF process gives a negligible contribution. In the absence of fully simulated samples for the tH production, for which the cross-section was only recently calculated [74, 75], the acceptance is obtained from particle level simulation, scaled by the ratio of acceptances for full and particle level simulations obtained for topologically similar final states (tcH and $t\bar{t}H$ final states were used).

Since the ggF and WH processes produce a Higgs boson with a small number of jets, among which there is in general no b-jet, an additional systematic uncertainty is added. For the ggF mode, several variations of POWHEG+PYTHIA8 [76] with up to three partons at the matrix element level were compared, from which a 40% uncertainty was deduced. For the WH process, which is simulated at LO, the uncertainty is enlarged to 100%. The uncertainty on ZH is not increased as this process produces b-jets from the Z-boson decay.

In total, for the hadronic selection, the background from SM Higgs production is 0.24±0.05 event at 8 TeV and 0.04±0.01 at 7 TeV, with uncertainties taken as fully correlated. The largest contribution is from the $t\bar{t}H$ mode, which represents about 60% of the total. In the leptonic selection, the total background due to SM Higgs production amounts to 0.05±0.01 event, and 90% of this background arises from $t\bar{t}H$ production.

5.4 Experimental systematic uncertainties

The experimental systematic uncertainties are listed in table 4.

- The uncertainties related to photons are described in section 2 for the trigger efficiency, and in section 3.1 for the photon identification and isolation.

Selection	Hadronic		Leptonic
Centre of mass energy	7 TeV	8 TeV	8 TeV
Trigger efficiency	± 0.2	± 0.5	± 0.5
Photon identification	± 9.3	± 4.6	± 2.4
Photon isolation	± 3.0		± 1.0
Jet Energy Scale	± 5.4	$^{+7.4}_{-4.5}$	$^{+3.2}_{-2.8}$
Jet Energy Resolution	± 0.2		± 0.2
Jet Vertex Fraction	± 1.0		± 1.0
b-tagging	± 3.5	± 4.8	± 5.2
Lepton reco./ID/scale	—	—	± 0.6
$E_{\mathrm{T}}^{\mathrm{miss}}$ scale	—	—	$^{+1.4}_{-0.4}$
ISR/FSR	$^{+7.0}_{-3.0}$		$^{+8.0}_{-2.0}$
Underlying event	± 3.5		± 1.8
Combined uncertainty	$^{+14.1}_{-12.6}$	$^{+13.1}_{-9.8}$	$^{+10.6}_{-7.1}$

Table 4. Summary of experimental and generator (see text) uncertainties on the signal and SM Higgs boson background yields (in percent, per event). The last row gives the sum in quadrature of all these uncertainties.

- The systematic uncertainty associated with the Jet Energy Scale (JES) is determined by changing by one standard deviation, in each direction and one at a time, each of the parameters to which the energy scale is sensitive. The most sensitive parameters are associated with pile-up and jet flavour. At 8 TeV the quadratic sum of the uncertainties obtained from all variations gives a total effect on the expected signal yield of (+7.4%,−4.5%). At 7 TeV the global effect is more symmetric (±5.4%). The smaller JES uncertainty in the leptonic channel was obtained in the same way and includes its impact on $E_{\mathrm{T}}^{\mathrm{miss}}$. The same methodology was used for the Jet Energy Resolution (JER), whose uncertainty has a smaller impact on the signal yield.

- The systematic uncertainty associated with the JVF selection is estimated by varying the corresponding requirement within the boundaries resulting from dedicated studies [77]. It amounts to 1% for both the hadronic and the leptonic selections. The same uncertainty is also used at 7 TeV.

- In order to take into account the small differences in b-tagging efficiency between data and simulation for each jet flavour (light, charm and bottom-quark jets) [50], the nominal values of the associated scale factors are included in the event weights of the simulated samples. Replacing the nominal scale factors by the values obtained when adding (subtracting) their uncertainty induces variations of the expected signal yield of the order of 5%.

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- The uncertainty associated with the lepton energy scale, identification and reconstruction efficiency, averaged for electrons and muons, is 0.6%.

- The uncertainty, of about 1%, associated with $E_{\mathrm{T}}^{\mathrm{miss}}$ was obtained with the same methodology as that used for the jet energy scale, applied to low-E_{T} topological clusters included in the estimate of $E_{\mathrm{T}}^{\mathrm{miss}}$ and which are not associated with any of the objects used to reconstruct the final state.

The generator uncertainties are evaluated as follows:

- The uncertainty labelled "ISR/FSR" in table 4 corresponds to the variation of the signal acceptance observed at particle level when the parameters governing QCD initial and final state radiation in PYTHIA6 are varied within the allowed range [78].

- The systematic uncertainty associated with the underlying event modelling is estimated by scaling, in the simulation, the transverse momenta of particles produced at $|\eta| > 2$ within the range allowed by the differences between tunes[6] and re-estimating the selection efficiency.

5.5 Results

A fit using the likelihood described at the beginning of this section is performed on the selected data sample, consisting of 50 events in the hadronic channel and one event in the leptonic channel.

The diphoton mass spectrum in the hadronic channel is shown in figure 5, together with the fitted background shape and the signal shape for a Higgs boson mass fixed at 125.5 GeV. The fitted branching ratio is $\mathcal{B} = 0.22^{+0.31}_{-0.26}\%$, which corresponds to a total number of signal events (hadronic and leptonic) of $3.1^{+4.3}_{-3.7}$. The probability that the background can produce a fluctuation greater than or equal to the excess observed in data is 18%. As no significant signal is found, limits on the $t \to cH$ and $t \to uH$ branching ratios are set based on the $\mathrm{CL_s}$ prescription [79].

The evolution of the signal confidence level $\mathrm{CL_s}$ as a function of the branching fraction $\mathcal{B}$ for $t \to qH$ is shown in figure 6. Pseudo-experiments have been used to determine the distributions of the test statistic under the signal+background and the background-only hypotheses. The green and yellow areas represent the one and two standard deviation bands around the expectation. The observed (expected) limit on $\mathcal{B}$ is 0.79 (0.51)% at the 95% confidence level. The observed limit is not as stringent as the expectation due to a slight excess over the total background expectation in the vicinity of $m_{\gamma\gamma}\sim$ 126 GeV, as seen in figure 5. From this limit, an upper limit on the λ_{tcH} coupling of 0.17 was obtained, with an expected value of 0.14. As the analysis is equally sensitive to the $t \to uH$ and $t \to cH$ modes, the limit obtained on the couplings can be written as $\sqrt{\lambda_{tcH}^2 + \lambda_{tuH}^2} < 0.17$, with an expectation of 0.14.

[6] The particle flow observed in various data samples for $|\eta| < 2$ is well described by standard QCD PS and MI tunes.

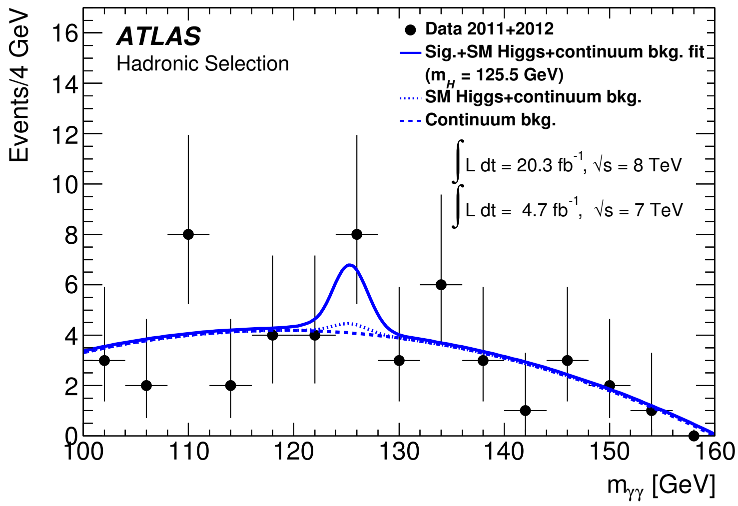

Figure 5. Distribution of $m_{\gamma\gamma}$ for the selected events in the hadronic channel. The result of a fit to the data of the sum of a signal component with the mass of the Higgs boson fixed to $m_H = 125.5$ GeV and a background component (dashed) described by a second-order polynomial is superimposed. The small contribution from SM Higgs boson production, included in the fit, is also shown (difference between the dotted and dashed lines).

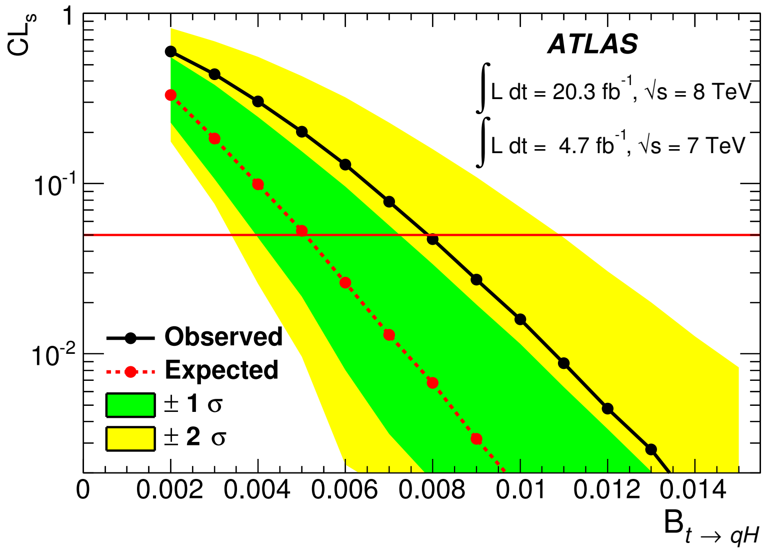

Figure 6. Evolution of $\mathrm{CL_s}$ as a function of the branching fraction $\mathcal{B}$ of the $t \to qH$ decay for the observation of a signal at 125.5 GeV (solid line) and the expectation in the absence of signal (dashed line). The 1 and 2 σ uncertainty bands around the expected curve are also shown.

6 Conclusions

The FCNC $t \to qH$ decay, followed by $H \to \gamma\gamma$, has been searched for in a data set of proton-proton collisions recorded by the ATLAS experiment, consisting of $4.7\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 7$ TeV and $20.3\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 8$ TeV.

Candidate events were selected by requiring the presence of two high-E_T isolated photons. Further selection criteria included the presence of four jets (at least one b-tagged) for

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the hadronic selection, or two jets (at least one b-tagged), $E_{\mathrm{T}}^{\mathrm{miss}}$ and an isolated lepton for the leptonic selection, plus kinematic conditions designed to enhance the fraction of events with a $t\bar{t}$ topology.

A sideband technique was used to constrain the background, and an expected upper limit on the $t \to cH$ decay branching ratio in the absence of signal of 0.51% was calculated. No statistically significant excess was observed in the data, and a limit of 0.79% was set at the 95% confidence level for $m_H = 125.5$ GeV. From this limit, an upper limit on the λ_{tcH} coupling of 0.17 was obtained, with an expected value of 0.14. As the analysis is equally sensitive to the $t \to uH$ and $t \to cH$ modes, the limit obtained can more generally be expressed as $\sqrt{\lambda_{tcH}^2 + \lambda_{tuH}^2} < 0.17$.

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