Search for the associated production of a Higgs boson with a top quark pair in final states with a $\tau$ lepton at $\sqrt{s} = 13$ TeV

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Abstract

Results of a search for the standard model Higgs boson produced in association with a top quark pair in final states with $\tau$ leptons are presented. The analyzed dataset corresponds to an integrated luminosity of 35.9 fb$^{-1}$ which has been recorded in proton-proton collisions at $\sqrt{s} = 13$ TeV center-of-mass energy by the CMS experiment during LHC Run 2. The sensitivity of the search is improved by using matrix element and machine learning methods to separate the signal from backgrounds. The measured signal rate amounts to $0.72^{+0.62}_{-0.53}$ times the production rate expected in the standard model, with an observed (expected) significance of 1.4$\sigma$ (1.8$\sigma$). An upper limit on the signal rate of 2.0 the standard model production rate is set at the 95% confidence level.
1 Introduction

The observation of a Higgs (H) boson by the ATLAS and the CMS experiments [1, 2] represents a major step towards our understanding of the mechanism for electroweak symmetry breaking (EWSB). In a combined analysis of the data recorded by ATLAS and CMS, the mass of the H boson has been measured to be 125.09 ± 0.24 GeV [3]. The standard model (SM) makes precise predictions for all properties of the H boson, given its mass. Within uncertainties, all measured properties of the discovered resonance are consistent with expectations for the SM H boson, corroborating the mechanism for EWSB of the SM. In particular, the discovered particle is known to have a zero spin and a positive parity. Within the present experimental uncertainties, its coupling to fermions is found to be proportional to fermion mass, as predicted by the SM. In order to conclude that the mechanism for EWSB predicted by the SM is indeed realized in nature, it is important to measure the Higgs boson properties precisely.

The measurement of the Yukawa coupling of the H boson to the top quark, $y_t$, is of high phenomenological interest for several reasons. The extraordinarily large value of the top quark mass, compared to the masses of all other known fermions, may indicate that the top quark has a still-unknown special role in the EWSB mechanism. The measurement of the rate by which H bosons are produced in association with top quark pairs ($t\bar{t}H$ production) provides the most precise model independent determination of $y_t$. A typical Feynman diagram for $t\bar{t}H$ production in proton-proton (pp) collisions is shown in Fig. 1. A comparison of $y_t$ measured in $t\bar{t}H$ production with the H boson production rate measured in the gluon-fusion process, in which $y_t$ enters via top quark loops, will allow to set powerful constraints on new physics that, if present, would alter the gluon-fusion production rate via loop contributions.

![Figure 1: A typical Feynman diagram for $t\bar{t}H$ production with subsequent decay of the H boson to a pair of $\tau$ leptons.](image)

The associated production of a H boson with a top quark pair in pp collisions at $\sqrt{s} = 8$ and 13 TeV center-of-mass energies has been studied in the $H \rightarrow bb$ and $H \rightarrow \gamma\gamma$ decay modes as well as in final states with multiple leptons by the ATLAS and the CMS collaborations [4–13]. The final states with multiple leptons cover the decay modes $H \rightarrow WW$, $H \rightarrow ZZ$, and $H \rightarrow \tau\tau$. So far the $t\bar{t}H$ process has been studied in the following final states with $\tau$ leptons: in events containing two leptons (electrons or muons) of the same charge and one hadronically decaying $\tau$ lepton ($\tau_h$) and in events containing one lepton and two $\tau_h$. The first final state has been analyzed by the ATLAS collaboration at $\sqrt{s} = 8$ and 13 TeV and by the CMS collaboration at $\sqrt{s} = 13$ TeV and the second final state by the CMS collaboration at $\sqrt{s} = 8$ TeV. In this note
we present the results of a search for \( t\bar{t}H \) production in final states with \( \tau \) leptons in pp collision data corresponding to an integrated luminosity of 35.9 fb\(^{-1}\), recorded by the CMS experiment in 2016. This analysis targets \( t\bar{t}H \) final states with a reconstructed hadronic \( \tau \) and is sensitive not only to the \( H \to \tau\tau \) but also to the \( H \to WW \) and \( H \to ZZ \) decay modes. Three different final states are analyzed. The sensitivity of the analysis is enhanced by means of two different multivariate-analysis (MVA) techniques: by the matrix element method (MEM) \cite{14, 15} and by boosted decision trees (BDT) \cite{16, 17}.

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. A silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections, are positioned within the solenoid volume. The silicon tracker measures charged particles within the pseudorapidity range \(|\eta|<2.5\). Tracks of isolated muons of \( p_T = 100 \) GeV emitted at \(|\eta|<1.4\) are reconstructed with an efficiency close to 100\% and resolutions of 2.8\% in \( p_T \) and 10 (30) \( \mu m \) in the transverse (longitudinal) impact parameter \cite{18}. The ECAL is a fine-grained hermetic calorimeter with quasi-projective geometry, and is segmented in the barrel region of \(|\eta|<1.48\) and in two endcaps that extend up to \(|\eta|<3.0\). The HCAL barrel and endcaps similarly cover the region \(|\eta|<3.0\). Forward calorimeters extend the pseudorapidity coverage up to \(|\eta|<5.0\). Muons are measured and identified in the pseudorapidity range \(|\eta|<2.4\), by gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. A two level trigger system is used to reduce the rate of recorded events to a level suitable for data acquisition and storage. The first level of the CMS trigger system, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select the most interesting events in a fixed time interval of less than 4 \( \mu s \). The high-level trigger processor farm further decreases the event rate from around 100 kHz to less than 1 kHz. Details of the CMS detector and its performance, together with a definition of the coordinate system and the kinematic variables used in the analysis, can be found in Ref. \cite{19}.

3 Data samples and Monte Carlo simulation

The analyzed data has been collected in pp collisions at \( \sqrt{s} = 13 \) TeV center-of-mass energy during 2016. The events have been recorded using a combination of triggers based on the presence of one, two, or three electrons or muons or based on the presence of an electron or muon and a hadronic \( \tau \) decay. Only data-taking periods where all detector systems were fully operational are included in the analysis. The integrated luminosity of the analyzed dataset corresponds to 35.9 fb\(^{-1}\).

The data is compared to signal and background estimations, based on Monte-Carlo (MC) simulated samples and data-driven techniques. The following processes are taken into account as backgrounds: \( Z+jets, W+jets, t\bar{t}, \) single top, diboson (WW, WZ, and ZZ) and triboson (WWW, WWZ, WZZ and ZZZ) production, and a few selected “rare” processes. These exotic processes, such as \( t\bar{t}t\bar{t} \), the production of same-sign W boson pairs, and the production of W and Z bosons in association with photons (\( W\gamma+jets \) and \( Z\gamma+jets \)), typically have very small cross sections, but may nevertheless yield non-negligible background contributions. Separate samples are produced to simulate the production of top quark pairs and of single top quarks in association with jets, photons, W, and Z bosons. The \( t\bar{t}+jets \) samples are produced using the leading-order (LO)
matrix elements implemented in the MADGRAPH5_AMC@NLO 2.2.2 program [20]. Samples for other background processes and for the $t\bar{t}H$ signal are generated using next-to-leading-order (NLO) matrix elements implemented in the programs MADGRAPH5_AMC@NLO and POWHEG v2 [21–23]. The signal events are generated for a $H$ boson mass of $m_H = 125$ GeV. The samples are generated with the NNPDF3.0 set of parton distribution functions (PDF) [24–26]. Parton shower and hadronization processes are modelled using the generator PYTHIA 8.2 with the tune CUETP8M1 [27] for the background samples and the tune CUETP8M2T4 for the signal sample. The CUETP8M1 tune is based on the Monash tune [28], while the CUETP8M2T4 tune has been derived by CMS to improve the jet-multiplicity modeling. The decays of $\tau$ leptons, including polarization effects, are modelled by PYTHIA. The $Z/\gamma^* \rightarrow \ell\ell$, W+jets, and $t\bar{t}$ events are normalized to cross sections computed at next-to-next-to-leading-order (NNLO) accuracy [29, 30]. A reweighting is applied to MC-generated $t\bar{t}$ events to improve the modelling of the $p_T$ spectrum of the top quark relative to data [31, 32]. The cross sections for single top quark [33–35] and diboson [36] production are computed at NLO accuracy.

Minimum bias events generated with PYTHIA are overlaid on all simulated events, according to the luminosity profile of the analyzed data and for a pp inelastic cross section of 69.2 mb. In the analyzed dataset, approximately 30 inelastic pp interactions (pileup) occur per bunch crossing on average.

All generated events are passed through a detailed simulation of the CMS apparatus, based on GEANT4 [37], and are reconstructed using the same version of the CMS event reconstruction software as used for data.

Small corrections are applied to simulated events in order to improve the modeling of the data. The efficiency of the triggers based on the presence of one, two, or three electrons or muons, as well as the efficiency for electrons or muons to pass the lepton reconstruction, identification and isolation criteria is measured using $Z/\gamma^* \rightarrow ee$ and $Z/\gamma^* \rightarrow \mu\mu$ events [12]. The efficiency of the triggers based on the presence of an electron or muon and a hadronic $\tau$ decay, the efficiency for hadronic $\tau$ decays to pass the $\tau_h$ identification criteria, and the energy scale with which hadronic $\tau$ decays are reconstructed is measured using $Z/\gamma^* \rightarrow \tau\tau$ events [38]. The b-tag efficiency and mistag rate is measured in $t\bar{t}$ and $Z/\gamma^* \rightarrow \ell\ell$ events [39], respectively. Differences in $E_T^{miss}$ response and resolution between data and simulation are measured in $Z/\gamma^* \rightarrow \ell\ell$ and $\gamma$+jets events [40] and corrected as described in Ref. [41].

4 Event reconstruction

The information provided by all CMS subdetectors is employed by a particle-flow (PF) algorithm [42–45] to identify and reconstruct individual particles in the event, namely muons, electrons, photons, charged and neutral hadrons. These particles are then used to reconstruct jets, $\tau_h$ candidates and the missing transverse energy vector $\vec{p}_T^{miss}$, as well as to quantify the isolation of leptons.

Collision vertices are reconstructed using a deterministic annealing algorithm [46, 47]. The reconstructed vertex position is required to be compatible with the location of the LHC beam in the $x$-$y$ plane. The tracks associated to each vertex are clustered using the anti-$k_T$ algorithm [48]. For each vertex, a weighted $p_T^2$ is then computed using those jets, remaining single tracks including identified leptons and the missing transverse momentum associated to the vertex, to account for neutral particles. The primary vertex (PV) is then selected as the one with the largest $p_T^2$. All the subsequent reconstructed electrons, muons and hadronic $\tau$ candidates are required to be compatible with originating from the selected PV.
Electrons are reconstructed by an algorithm [42, 49] that matches tracks reconstructed in the silicon tracker to energy deposits in the ECAL. Tracks of electron candidates are reconstructed by a dedicated algorithm [50] which accounts for the emission of Bremsstrahlungs-photons. The energy loss due to Bremsstrahlung is determined by searching for energy deposits in the ECAL located in direction tangent to the track. A multivariate (MVA) approach based on boosted decision trees (BDTs) [16] is employed to distinguish electrons from hadrons mimicking an electron signature [51]. Observables that quantify the quality of the electron track, the compactness of the electron cluster in direction transverse and longitudinal to the electron direction, and the matching between track momentum and direction with the sum and position of energy deposits in the ECAL are used as inputs to the BDT. The BDT has been trained on samples of genuine electrons and fakes, produced using the MC simulation for pp collisions at $\sqrt{s} = 13$ TeV center-of-mass energy. The electron energy scale is calibrated using J/$\psi \rightarrow ee$, $\Upsilon \rightarrow ee$ and $Z \rightarrow ee$ decays. Additional requirements are applied in order to remove electrons originating from photon conversions.

The identification of muons is based on linking track segments reconstructed in the silicon tracking detector and in the muon system [52]. The matching between track segments is done outside-in, starting from a track in the muon system, and inside-out, starting from a track reconstructed in the inner detector. In case a link can be established, the track parameters are refitted using the combination of hits in the inner and outer detectors and the track is referred to as global muon track. Quality requirements are applied on the multiplicity of hits, on the number of matched segments and on the quality of the global muon track fit, quantified by $\chi^2$.

Additional selection criteria are applied for electrons and muons, using the same BDT as in [12]. This BDT is trained to discriminate prompt leptons produced in the decays of W bosons, Z bosons, and $\tau$ leptons, from the non-prompt leptons produced in c and b quark decays. Separate BDTs are trained to identify electrons and muons. Leptons selected in the signal region are required to pass a tight selection on the BDT output. Relaxed lepton selection criteria are defined for the purpose of estimating the contribution of background processes, described in detail in Section 6. The relaxed criteria are referred to as “fakeable” lepton selection.

Hadronic $\tau$ decays are reconstructed by the “hadrons plus strips” (HPS) algorithm [53]. The algorithm allows to reconstruct individual hadronic decay modes of the $\tau$: $\tau^\pm \rightarrow h^\pm \nu_\tau$, $\tau^\pm \rightarrow h^\pm \pi^0 \nu_\tau$, and $\tau^\pm \rightarrow h^\pm h^\mp \pi^0 \nu_\tau$, where $h^\pm$ denotes either a charged pion or kaon. Hadronic $\tau$ candidates are built by combining the charged hadrons reconstructed by the PF algorithm with neutral pions. The neutral pions are constructed by clustering the photons reconstructed by the PF algorithm within rectangular strips, that are narrow in $\eta$-, but wide in $\phi$-direction, to account for the broadening of energy deposits in the ECAL in case one of the photons produced in $\pi^0 \rightarrow \gamma \gamma$ decays converts within the tracking detector. While strips of a fixed size of $0.20 \times 0.05$ in $\eta$–$\phi$ direction have been used in CMS analyses of LHC run 1 data, an improved version of the strip reconstruction has been developed for data analyses during run 2. In the improved version the size of the strip is adjusted as function of $p_T$, taking into consideration that the bending of charged particles in the magnetic field increases inversely proportional to $p_T$. Further details of the improved strip reconstruction and its validation with LHC run 2 data are given in Ref. [38]. Due to the all silicon tracking detector of CMS, the probability for photon conversions is sizable. For this reason, the electrons reconstructed by the PF algorithm are considered in the construction of the neutral pions too. The main handle to distinguish hadronic $\tau$ decays from a large background of quark and gluon jets is to apply tight isolation requirements. The sums of scalar $p_T$ values of charged particles and of photons is used as input to a MVA-based $\tau_h$ identification discriminant. The isolation is computed within a cone of size $\Delta R = 0.5$, centred on the $\tau_h$ direction, in the standard CMS $\tau_h$ identifi-
cation algorithm. Dedicated $\tau_h$ identification discriminants that use a cone of size $\Delta R = 0.3$ have been developed for this analysis, in order to improve the efficiency in signal events with high hadronic activity. Separate input variables are used for those charged particles that are compatible with originating from the $\tau_h$ production vertex and for those that are not. The list of input variables is complemented by the reconstructed $\tau_h$ decay mode and by observables that provide sensitivity to the lifetime of the $\tau$. The transverse impact parameter of the “leading” (highest $p_T$) track of the $\tau_h$ candidate with respect to the PV is used for $\tau_h$ candidates reconstructed in any decay mode. In case of $\tau_h$ candidates reconstructed in the decay mode $\tau^- \rightarrow h^- h^+ h^- \nu_\tau$, a fit of the three tracks to a common secondary vertex is attempted and the distance to the PV is used as additional input variable to the MVA. The MVA has been trained on samples of genuine hadronic $\tau$ decays and jets, produced using the MC simulation for pp collisions at $\sqrt{s} = 13$ TeV center-of-mass energy. Loose, medium, and tight working points (WP), corresponding to different $\tau_h$ identification efficiencies and jet $\rightarrow \tau_h$ misidentification rates, are defined by varying the selections on the MVA output. The selections are adjusted as function of the $p_T$ of the $\tau_h$ candidate such that the $\tau_h$ identification efficiency for each WP is constant as function of $p_T$. Hadronic $\tau$ decays selected in the signal region of the $2\ell ss + 1\tau_h$ and $3\ell + 1\tau_h$ categories ($\ell^+ + 2\tau_h$ category) are required to pass the medium (tight) WP and must have a reconstructed $p_T > 20$ GeV and $|\eta| < 2.3$. For the purpose of estimating background contributions arising from the misidentification of jets in the $1\ell + 2\tau_h$ category, relaxed selection criteria are defined by requiring hadronic $\tau$ candidates to pass the loose WP. The latter is referred to as “fakeable” $\tau_h$ selection, in analogy to the relaxed criteria for electrons and muons.

Jets within the range $|\eta| < 4.7$ are reconstructed by the anti-$k_T$ algorithm [48] with a distance parameter $R = 0.4$. Reconstructed jets are required not to overlap with identified electrons, muons or hadronic $\tau$ decays within $\Delta R < 0.4$ and to pass identification criteria that aim to reject fake jets arising from calorimeter noise [54]. The energy of reconstructed jets is calibrated as function jet $p_T$ and $\eta$ [55]. Fastjet-$\rho$-based [56, 57] jet energy corrections are applied in order to compensate for pileup effects. Jets selected for this analysis must have a transverse momentum larger than 25 GeV and $|\eta| < 2.4$. Jets originating from the hadronization of b quarks are identified by the “combined secondary vertex” (CSV) algorithm [39], which exploits observables related to the long lifetime of b hadrons and to the higher particle multiplicity and mass of b-jets compared to light quark and gluon jets.

The missing transverse energy, $E_T^{\text{miss}}$, is calculated as the negative of the vector sum of the transverse momenta of all particles reconstructed by the PF algorithm. No attempt is made to include particles originating from pileup interactions. The magnitude of the vector is referred to as $E_T^{\text{miss}}$. The $E_T^{\text{miss}}$ resolution and response are improved by propagating the difference between calibrated and uncalibrated jets to the $E_T^{\text{miss}}$ and by applying corrections that account for pileup effects, as described in Ref. [41].

The missing transverse energy is complemented by the observable $H_T^{\text{miss}}$, defined as the magnitude of the vectorial transverse momentum sum of leptons, $\tau_h$, and jets:

$$H_T^{\text{miss}} = \sum_{\text{leptons}} |p_T^{\ell} + \sum_{\tau_h} |p_T^{\tau_h} + \sum_{\text{jets}} |p_T^{\text{jets}}|.$$  \hspace{1cm} (1)

Leptons and $\tau_h$ decays entering the sum are required to pass the “fakeable” selection criteria, while the jets correspond to those selected in this analysis ($p_T > 25$ GeV, $|\eta| < 2.4$). The resolution on $H_T^{\text{miss}}$ is worse compared to the resolution on $E_T^{\text{miss}}$. The advantage of the observable $H_T^{\text{miss}}$ is that leptons, hadronic $\tau$ decays, and high $p_T$ jets predominantly originate from the hard-scatter interaction and seldomly from pileup interactions, which makes $H_T^{\text{miss}}$ less sensitive to variations in pileup conditions.
The two observables $E_T^{\text{miss}}$ and $H_T^{\text{miss}}$ are combined into a linear discriminant [12]:

$$E_T^{\text{miss}} - \text{LD} = 0.6 \times E_T^{\text{miss}} + 0.4 \times H_T^{\text{miss}},$$

exploiting the fact that $E_T^{\text{miss}}$ and $H_T^{\text{miss}}$ are less correlated in events in which the reconstructed missing transverse energy is due to instrumental effects compared to events with genuine missing transverse energy.

## 5 Event selection

The study of $t\bar{t}H$ production in final states with a $\tau$ lepton presented here complements the analysis of $t\bar{t}H$ production in multilepton final states [12]. The event selection used here is designed not to overlap with the event selection in the multilepton final states, allowing for the results of both analyses to be combined at a later point in time. This analysis is performed in three event categories, based on the number of reconstructed leptons and $\tau_h$: the one lepton plus two $\tau_h$ ($1\ell + 2\tau_h$), the two lepton same-sign plus one $\tau_h$ ($2\ell_{ss} + 1\tau_h$), and the three lepton plus $1\tau_h$ ($3\ell + 1\tau_h$) category.

Events in the $2\ell_{ss} + 1\tau_h$ ($3\ell + 1\tau_h$) category are selected by a combination of triggers based on the presence of one or two (one, two, or three) leptons, either electrons or muons, in the event. The $p_T$ threshold of the single electron (muon) trigger amounts to 27 GeV (22 GeV). The $p_T$ thresholds of the double electron (muon) triggers amount to 23 GeV (17 GeV) for the leading (highest $p_T$) and 12 GeV (8 GeV) for the subleading (second highest $p_T$) lepton. Events containing electron plus muon pairs pass the trigger selection if either the electron satisfies the condition $p_T > 23$ GeV and the muon $p_T > 8$ GeV or the muon satisfies the condition $p_T > 23$ GeV and the electron $p_T > 8$ GeV. The triple lepton triggers used in the $3\ell + 1\tau_h$ category allow to reduce the $p_T$ thresholds to 8 GeV (5 GeV) in case the lepton of third highest $p_T$ is an electron (muon).

Events in the $1\ell + 2\tau_h$ category are recorded by a combination of single electron and muon triggers with triggers that select events containing either an electron of $p_T > 24$ GeV in combination with a $\tau_h$ of $p_T > 30$ GeV or a muon of $p_T > 19$ GeV in combination with a $\tau_h$ of $p_T > 20$ GeV.

Selected events are further required to contain either at least one jet that passes tight b-tagging criteria or at least two jets that pass loose b-tagging criteria.

Events containing lepton pairs of mass less than 12 GeV are rejected, as these events are not well modeled by the MC simulation.

Further category specific selection criteria are detailed in the following.

### 5.1 $1\ell + 2\tau_h$ category

The $1\ell + 2\tau_h$ category consists of events containing a single tight lepton together with at least two $\tau_h$, making it mostly sensitive to $t\bar{t}H$ events where the H boson decays into a pair of $\tau$ leptons, which both decay hadronically, while the lepton is produced in the decay of one of the top quarks. The transverse momentum of the lepton is required to satisfy $p_T > 25$ GeV ($p_T > 20$ GeV) if it is an electron (muon), while $|\eta| < 2.1$. The two $\tau_h$ are required to pass the tight WP of the MVA-based $\tau_h$ identification algorithm and the transverse momentum of the leading $\tau_h$ must be larger than 30 GeV. The two $\tau_h$ are required to be of opposite charge, the combination of charges expected for a $\tau_h$ pair produced in a H boson decay. In addition, selected events are also required to contain at least three hadronic jets.
5.2 $2\ell ss + 1\tau_h$ category

The $2\ell ss + 1\tau_h$ category includes events with exactly two leptons that pass the tight lepton selection criteria together with at least one $\tau_h$. Background contributions are reduced significantly by requiring the two leptons to be of the same charge. The leading lepton is required to satisfy $p_T > 25$ GeV, while the subleading lepton must satisfy $p_T > 15$ GeV ($p_T > 10$ GeV) in case it is an electron (muon). The $\tau_h$ is required to pass the medium WP of the MVA-based $\tau_h$ identification algorithm and to be of opposite charge with respect to the leptons. In addition, selected events are also required to contain at least three jets.

Background contributions arising from events containing two leptons of opposite charge, in which the charge of one lepton is mismeasured, are reduced by applying additional quality criteria on the charge measurement. In case of electrons, the consistency of the charge measurements based on different tracking algorithms and on hits reconstructed in: either the silicon pixel detector or the combination of silicon pixel and strip detectors, is required. In case of muons, the curvature of the track reconstructed based on hits in the silicon detectors and in the muon system is required to be measured with a precision of better than 20%.

The probability to mismeasure the charge is significantly higher for electrons compared to muons. To further suppress the background contributions arising from $Z$+jets events in which the charge of one lepton is mismeasured, di-electron events where the mass of the electron pair is within a window of size 10 GeV around the $Z$ boson mass or $E_T^{miss}$-LD < 30 GeV are vetoed.

5.3 $3\ell + 1\tau_h$ category

Events selected in the $3\ell + 1\tau_h$ category are required to contain at least three leptons passing the tight lepton selection criteria and at least one $\tau_h$. The leading (subleading and third) lepton is required to satisfy $p_T > 20$ GeV ($p_T > 10$ GeV). The $\tau_h$ is required to pass the medium WP of the MVA-based $\tau_h$ identification algorithm. The sum of the charges of the three leptons and of the $\tau_h$ is required to be equal to zero. Events selected in the $3\ell + 1\tau_h$ category are required to contain at least two jets.

Contributions of background processes with $Z$ bosons ($Z$+jets, $WZ$, $t\bar{t}Z$) are suppressed by vetoing events that contain a pair of leptons of the same flavor, opposite charge, and mass that is within a window of size 10 GeV around the $Z$ boson mass. The events are further required to satisfy the condition $E_T^{miss}$-LD > 30 GeV. The requirement on $E_T^{miss}$-LD is tightened to the condition $E_T^{miss}$-LD > 45 GeV in case the event contains a pair of leptons of the same flavor and opposite charge. For events with four or more jets, the contamination from background processes with $Z$ bosons is smaller and no requirement on $E_T^{miss}$-LD is applied.

6 Background estimation

Owing to the small signal rate, even small background contributions are relevant for the statistical analysis, with the consequence that a variety of different background processes needs to be taken into account in the analysis. Background contributions arise from “reducible” as well as from “irreducible” sources.

A background is considered as “reducible” in case at least one of the electrons or muons passing the tight lepton selection is due to a non-prompt lepton (i.e. originating from the decay of a charm or bottom quark) or to the misidentification of a hadron, or in case one or more of the $\tau_h$ is due to the misidentification of a jet.

In the $2\ell ss + 1\tau_h$ category, further sources of reducible backgrounds arise from events that
contain lepton pairs of opposite charge in which the charge of either lepton is mismeasured and from the production of top quark pairs in association with either real or virtual photons.

The dominant reducible backgrounds, arising from the misidentification of leptons or τ_h (“fake” background) or from the mismeasurement of the lepton charge (charge “flip” background), are determined from data. The procedures are described in Sections 6.1 and 6.2.

The background contribution arising from t\bar{t} production in association with photons is studied in the context of the analysis of t\bar{t}H production in multilepton final states [12]. The contribution of t\bar{t} events containing real photons is typically due to asymmetric conversions of the type γ → e^+e^−, in which one electron or positron carries most of the energy of the photon, while the other electron or positron is of low energy and fails to get reconstructed. These events are suppressed by the photon conversion rejection criteria and by requiring that the tracks of electron candidates have hits in each layer of the pixel detector that is crossed by the track. In case t\bar{t} events are produced in association with virtual photons, the virtual photons typically produce electron or muon pairs of low mass, which are suppressed very effectively by the event selection criterion m_ℓℓ > 12 GeV that is applied in all events categories. As a consequence, the background contribution of t\bar{t} events with photons is small in the 2ℓss + 1τ_h category and negligible in the 3ℓ + 1τ_h and 1ℓ + 2τ_h categories.

Irreducible background contributions are modeled using the MC simulation. The dominant contributions are due to the production of top quark pairs in association with W or Z bosons and to the production of W or Z boson pairs in association with jets. Minor contributions arise from the production of single W or Z bosons, from triboson production, and from the production of single top quarks. The modeling of the data by the simulation is validated in specific control regions, enriched in the contribution of one of the dominant irreducible background processes t\bar{t}W, t\bar{t}Z, and WZ+jets each.

Reconstructed τ_h that are matched to electrons or muons on generator level are considered to constitute an irreducible background. The background contribution arising from events containing electrons or muons which fail the loose lepton identification criteria described in Section 4 and get misidentified as hadronic τ decays is very small. This type of background is not included in the “fake” background estimate obtained from data and is taken from the MC simulation.

6.1 Non-prompt lepton and jet to τ_h fake background

We denote as “fake” background the sum of all background events in which at least one reconstructed electron or muon arises from either the misidentification of a non-prompt lepton or of a hadron and/or at least one reconstructed τ_h arises from the misidentification of a quark or gluon jet.

In the 2ℓss + 1τ_h and 3ℓ + 1τ_h categories, the residual contamination from events with at least one non-prompt leptons is estimated from data by means of the fake factor (FF) method, as used in [12]. In the 1ℓ + 2τ_h category, this method is extended to also cover events with at least one reconstructed τ_h originating from a jet.

The FF method makes use of the so-called fake factor f, which represents the probability for an e, μ, or τ_h that passes the fakeable selection criteria to pass the tight selection criteria. The fake factors f are measured separately for e, μ, and τ_h and are parametrized as function of p_T and η. Various control regions, enriched in the contributions of different background processes and referred to as “measurement regions”, are utilised to measure the fake factors. The measurement regions for e and μ are chosen carefully, with the aim of having similar fractions
of non-prompt leptons and hadrons in the measurement and in the application region. The background estimation is then derived from a sideband control region where at least one of the objects fails the tight selection using the corresponding fake factors, after subtraction of events with genuine prompt objects based on Monte Carlo.

In the $2\ell ss + 1\tau_h$ and $3\ell + 1\tau_h$ categories, the fake factor method does not cover the contamination from events with two prompt leptons and a jet to $\tau_h$ fake, which is estimated from simulation instead. The motivation for this is that in about one third of $t\bar{t}H$ signal events selected in the signal region of the $2\ell ss + 1\tau_h$ and $3\ell + 1\tau_h$ categories the reconstructed $\tau_h$ is due to the misidentification of a quark or gluon jet. These events would be included in the estimate of the “fake” background in case the FF method were extended to also cover jet to $\tau_h$ fakes and could not be used for the purpose of inferring the production rate of the $t\bar{t}H$ signal, reducing the sensitivity to measure the signal rate parameter $\mu$ (see Section 8) by about 30%.

### 6.2 Charge “flip” background

The charge “flip” background in the $2\ell ss + 1\tau_h$ category arises mainly from $t\bar{t}$+jets dileptonic events for which the charge of one the lepton is misreconstructed. The charge misidentification rates for electrons and muons are measured using $Z/\gamma^* \rightarrow ee$ and $Z/\gamma^* \rightarrow \mu\mu$ events and are parametrized as function of $p_T$ and $\eta$. This rate is found to be negligible for muons, while it varies from around 0.02% in the barrel up to around 0.4% in the endcaps for electrons.

This background is estimated from data, using events that pass all selection criteria of the signal region, except that the two leptons are required to be of opposite charge. The events in this application region are then reweighed by the charge misidentification rate associated to the lepton with opposite-sign with respect to the selected $\tau_h$.

### 7 Systematic uncertainties

Various imprecisely known or simulated effects can alter the event yield and/or the shape of the distribution in the observable used for signal extraction, for the $t\bar{t}H$ signal as well as for background processes. Systematic uncertainties are categorized depending on whether they affect only the normalization (referred to as yield uncertainties), or normalization and shape (referred to as shape uncertainties). Both types of uncertainties are taken into account via nuisance parameters in the maximum likelihood fit that is used for the signal extraction (cf. Section 8). Shape uncertainties are propagated to the analysis varying the corresponding quantities and rerunning the event reconstruction and event selection steps of the analysis. Effects arising from the same source cause correlations across different event categories, which are taken into account in the statistical analysis.

#### 7.1 Yield systematics

- **Luminosity**
  
  The uncertainty in the integrated luminosity amounts to 2.6%. This value is obtained from dedicated Van-der-Meer scans and stability of detector response during the data taking [58].

- **Trigger efficiencies**
  
  The efficiency to pass trigger requirements in the $1\ell + 2\tau_h$ category is known with an uncertainty of 3% (2%) for events containing an electron (muon). In the $2\ell ss + 1\tau_h$ category the uncertainty in the trigger efficiency amounts to 1% (2%) for events.
containing either two muons or one electron and one muon (two electrons). In case of the $3\ell + 1\tau_h$ category, the uncertainty amounts to 3%.

- **Identification and isolation efficiency for $e$, $\mu$ and $\tau_h$**
  The uncertainty for electrons and muons to pass the loose (tight) lepton selection criteria amount to 2% (3%) while the uncertainty to reconstruct and identify hadronic $\tau$ decays amounts to 5%.

- **Charge mismeasurement**
  The yield of the charge “flip” background in the $2\ellss + 1\tau_h$ category has an associated uncertainty of 30%, based on the statistical uncertainty in the charge misidentification measurement and on the closure test performed on simulated events.

- **Signal and background yields**
  The uncertainties in the SM $t\bar{t}H$ cross section, computed at NLO accuracy, amount to $^{+5.8}_{-9.1}$% due to missing higher orders and to $\pm 3.6$% due to the uncertainties in the PDF and $\alpha_s$ [59]. The corresponding uncertainties with $t\bar{t}W$ ($t\bar{t}Z$) backgrounds are 12% (11%) for the higher order corrections and 4% (3%) for the PDF and $\alpha_s$. The rate of the WZ+jets background is assigned an uncertainty of up to 100% depending on the categories, while the rate of other (small) irreducible backgrounds is assigned an uncertainty of 50%.

### 7.2 Shape systematics

- **Jet and $\tau_h$ energy scales**
  Uncertainties in the energy scale of jets are parametrized as function of jet $p_T$ and $\eta$ and typically vary between 1% and 4%. The energy scale of $\tau_h$ is attributed an uncertainty of 3%.

- **$b$-tagging efficiency**
  Uncertainties in $b$-tagging efficiencies and mistag rates are applied as function of jet $p_T$ and $\eta$ and typically amount to 3% and 10%, respectively.

- **Modelling of $t\bar{t}H$ signal and $t\bar{t}W$, $t\bar{t}Z$ backgrounds**
  Uncertainties of theoretical origin on the modelling of the $t\bar{t}H$ signal and of the $t\bar{t}W$ and $t\bar{t}Z$ backgrounds are estimated by varying the renormalization and factorization scales within a factor two relative to their nominal values.

- **“Fake” backgrounds**
  The uncertainties in the measurement of the jet to $\tau_h$ misidentification rate are treated as $p_T$- and $\eta$-dependent effects. Uncertainties in the normalization and shape of the fake background arising from the misidentification of electrons and muons are taken from Ref. [12].

### 8 Signal extraction

The sample of events selected in the signal region of the $1\ell + 2\tau_h$, $2\ellss + 1\tau_h$, and $3\ell + 1\tau_h$ categories is still dominated by background processes. The sensitivity of the statistical analysis is enhanced by extracting the signal rate by means of a maximum likelihood fit to the distribution in a “discriminating” observable. In each event category, a different discriminating observable is chosen, in order to achieve the maximal shape separation between the $t\bar{t}H$ signal and background processes. The distributions observed in data are fitted with shape templates for the $t\bar{t}H$ signal and background processes.

A BDT discriminant is used to discriminate the $t\bar{t}H$ signal from the dominant $t\bar{t}$ background in
the $1\ell + 2\tau_h$ category. In the $2\ell ss + 1\tau_h$ and $3\ell + 1\tau_h$ categories, the $t\bar{t}W$ and $t\bar{t}Z$ backgrounds become more important and additional discriminants are used to improve the separation of the $t\bar{t}W$ and $t\bar{t}Z$ backgrounds from the $t\bar{t}H$ signal. A discriminant based on the MEM approach has been developed to separate the $t\bar{t}H, H \rightarrow \tau\tau$ signal from $t\bar{t}Z$ and $t\bar{t}W$ backgrounds in the $2\ell ss + 1\tau_h$ category. The details of the MEM discriminant are given in Section A of the appendix. In the $3\ell + 1\tau_h$ category, two BDTs are used that have been trained to discriminate the $t\bar{t}H$ signal from the $t\bar{t}W$ and $t\bar{t}Z$ backgrounds as well as from the $t\bar{t}$ background. Based on the expected signal-to-background ratio the output of the BDTs is mapped into a single discriminant, referred to as $D_{MVA}$, which is used for the signal extraction.

The BDTs used for the signal extraction in the $1\ell + 2\tau_h$ and $3\ell + 1\tau_h$ categories are trained on simulated signal and background events. The BDT for the $1\ell + 2\tau_h$ category uses the following observables as inputs:

- The invariant mass and $\Delta R$ separation of the two reconstructed $\tau_h$.
- The transverse momenta of the two reconstructed $\tau_h$.
- The observable $H_T^{\text{miss}}$, computed according to Eq. (1).
- The average $\Delta R$ separation between any pair of jets.
- The multiplicity of jets, with and without b-tagging criteria applied.

The observables used for the $3\ell + 1\tau_h$ category are the following:

- The transverse momenta of the leading lepton and of the trailing lepton.
- The maximum $|\eta|$ of the two leading leptons.
- The multiplicity of jets.
- The $\Delta R$ separation of the leading and of the subleading lepton with respect to the nearest jet.
- The transverse mass of the leading lepton and the missing transverse energy vector.
- The observable $H_T^{\text{miss}}$.
- The average $\Delta R$ separation between any pair of jets.

The observable $H_T^{\text{miss}}$ and the average $\Delta R$ separation between jets (the $p_T$ of the leading and third lepton) are used in case of the BDT that separates the $t\bar{t}H$ signal from the $t\bar{t}$ ($t\bar{t}W$ and $t\bar{t}Z$) background only.

The events selected in the $2\ell ss + 1\tau_h$ category are analyzed in two subcategories. The “no-missing-jet” subcategory contains events in which a pair of jets compatible with originating from the hadronic decay of a W boson is reconstructed, which allows for a full reconstruction of the decay chain $t\bar{t}H \rightarrow bWbW\tau\tau \rightarrow b\bar{b}\ell\nu\ell\nu\tau\nu\tau$, in signal events, while the “missing-jet” category contains events with no such pair of jets. Signal events contribute to the “missing-jet” category in case one of the jets produced in the W boson decay is e.g. outside of the $p_T$ and $\eta$ acceptance or if it overlaps with another jet.

The likelihood function $L$ that is used in the maximum likelihood fit to the data is given by the product of Poisson probabilities to observe $n_i$ events in each bin $i$ of the distributions in the discriminating observables, given that a total of $\nu_i$ events is expected from the $t\bar{t}H$ signal and from background processes in that bin:

$$L(\mu, \theta) = \mathcal{P}(\text{data}|\mu, \theta) \ p(\tilde{\theta}|\theta) = \prod_i \frac{n_i^{\nu_i}}{n_i!} \exp(-\nu_i) \ p(\tilde{\theta}|\theta).$$ (3)
The number of expected events depends on the signal rate $\mu$ and on the values of nuisance parameters $\theta$. The signal rate $\mu$ represents the parameter of interest (POI) of the fit. It is measured in units of the SM \(t\bar{t}H\) production rate.

Additional uncertainties to those presented in Section 7 arise from the limited amount of events available to model the shape of the distribution in the discriminating observable for the \(t\bar{t}H\) signal and for the background processes. Limitations in number of events on the shape templates are accounted for by the approach described in Refs. [60, 61]. Nuisance parameters are added to the likelihood function $L$ which allow the number of $\nu_i$ events expected in a given bin to vary within statistical uncertainties during the fit. In order to make the maximum likelihood fits less demanding in terms of computing time, we neglect statistical uncertainties which are smaller than 10% times the background contribution expected in a given bin.

Results are presented both in terms of the measured value $\mu_{\text{obs}}$, i.e. the value of $\mu$ which maximizes the likelihood function $L$, and in terms of an upper limit on $\mu$ at 95% confidence level (CL).

The uncertainty in $\mu_{\text{obs}}$ is obtained by determining lower and upper bounds, $\mu_{\text{min}}$ and $\mu_{\text{max}}$, for which the value of $-2 \ln L$ exceeds the maximum by one unit, corresponding to a coverage probability of 68%. The differences $\delta_+ = \mu_{\text{max}} - \mu_{\text{obs}}$ and $\delta_- = \mu_{\text{obs}} - \mu_{\text{min}}$ represent the uncertainty on the POI that arises from the combination of statistical and systematic uncertainties. The nuisance parameters are profiled, that is, their values are chosen such that the likelihood function $L$ reaches its local maximum, subject to the constraint that the POI value equals $\mu_{\text{min}}$ and $\mu_{\text{max}}$, respectively.

The 95% CL upper limits on the \(t\bar{t}H\) signal rate are computed following a modified frequentist approach, known as the $C_{\text{L}}$ method [62].

9 Results

The number of events observed in the $2\ell ss + 1\tau_h$, $3\ell + 1\tau_h$, and $1\ell + 2\tau_h$ categories is compared to the SM expectation in Table 1. The event yield in the $1\ell + 2\tau_h$ category is given in the signal-like region $\text{MVA} > 0.2$ of the output of the BDT that is used for the signal extraction. The expected yield of signal events is computed for the case that the \(t\bar{t}H\) signal is produced at the rate predicted by the SM. The signal and background rates are computed for the values of nuisance parameters obtained from the maximum likelihood fit. The event yields observed in data are in agreement with the SM expectation.

Distributions in the discriminating observables used for the signal extraction in the $2\ell ss + 1\tau_h$, $3\ell + 1\tau_h$, and $1\ell + 2\tau_h$ categories are shown in Fig. 2. The distributions observed in the $2\ell ss + 1\tau_h$ category are shown separately for the “no-missing-jet” and “missing-jet” subcategories.

Signal rates $\mu$ are computed for each of the categories $2\ell ss + 1\tau_h$, $3\ell + 1\tau_h$, and $1\ell + 2\tau_h$ individually and for their combination. The results are shown in Fig. 3. Numerical values are given in Table 2. The signal rates measured in each of the three categories are compatible with each other and with the SM expectation. For the combination of all three event categories, the observed (expected) signal rate is $\mu = 0.72^{+0.62}_{-0.53} (1.00^{+0.67}_{-0.57})$ times the SM \(t\bar{t}H\) production rate, with an observed (expected) significance of $1.4\sigma (1.8\sigma)$.

Upper limits on the signal rate, computed at 95% CL, are shown in Fig. 4. Numerical values are given in Table 3. The limits are computed for each of the categories $2\ell ss + 1\tau_h$, $3\ell + 1\tau_h$, and $1\ell + 2\tau_h$ individually and for their combination. The observed limit computed for the
Figure 2: Distributions in the discriminating observables used for the signal extraction in the $1\ell + 2\tau_h$ (a) and $3\ell + 1\tau_h$ (b) categories and in the “no-missing-jet” (c) and “missing-jet” (d) sub-categories of the $2\ell ss + 1\tau_h$ category, compared to the SM expectation for the $t\bar{t}H$ signal and for background processes. The distributions expected for the $t\bar{t}H$ signal and for the backgrounds are shown for the values of nuisance parameters obtained from the maximum likelihood fit. The lowest bin of the MEM discriminant in the “missing-jet” subcategory collects events for which the kinematics of the reconstructed objects is not compatible with the $t\bar{t}H$, $H \rightarrow \tau\tau$ signal hypothesis.
Table 1: Number of events events selected in the $2\ell ss + 1\tau_h$, $3\ell + 1\tau_h$, and $1\ell + 2\tau_h$ categories compared to the SM expectation for the $ttH$ signal and background processes. The event yield in the $1\ell + 2\tau_h$ category is given in the signal-like region MVA $> 0.2$ of the output of the BDT that is used for the signal extraction. The event yields expected for the $ttH$ signal and for the backgrounds are shown for the values of nuisance parameters obtained from the maximum likelihood fit. Quoted uncertainties represent the combination of statistical and systematic uncertainties.

<table>
<thead>
<tr>
<th>Process</th>
<th>$1\ell + 2\tau_h$</th>
<th>$3\ell + 1\tau_h$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ttH, H \rightarrow \tau\tau$</td>
<td>2.84 ± 1.35</td>
<td>1.01 ± 0.65</td>
</tr>
<tr>
<td>$ttH, H \rightarrow WW$</td>
<td>0.07 ± 0.04</td>
<td>0.63 ± 0.29</td>
</tr>
<tr>
<td>$ttH, H \rightarrow ZZ$</td>
<td>0.02 ± 0.01</td>
<td>0.09 ± 0.04</td>
</tr>
<tr>
<td>$ttZ$</td>
<td>4.07 ± 0.56</td>
<td>3.78 ± 0.62</td>
</tr>
<tr>
<td>$ttW$</td>
<td>0.21 ± 0.05</td>
<td>0.24 ± 0.05</td>
</tr>
<tr>
<td>Electroweak</td>
<td>1.10 ± 1.05</td>
<td>0.32 ± 0.05</td>
</tr>
<tr>
<td>Fake</td>
<td>20.98 ± 3.87</td>
<td>1.07 ± 0.34</td>
</tr>
<tr>
<td>Other</td>
<td>0.54 ± 0.23</td>
<td>0.24 ± 0.08</td>
</tr>
<tr>
<td>Total expected background</td>
<td>26.91 ± 3.84</td>
<td>5.65 ± 0.85</td>
</tr>
<tr>
<td>SM expectation</td>
<td>29.85 ± 4.07</td>
<td>7.38 ± 1.10</td>
</tr>
<tr>
<td>Observed data</td>
<td>24</td>
<td>7</td>
</tr>
</tbody>
</table>

| Process                        | $2\ell ss + 1\tau_h$ | “no-missing-jet” | “missing-jet” |
|--------------------------------|----------------------|------------------|
| $ttH, H \rightarrow \tau\tau$  | 1.38 ± 0.89          | 2.86 ± 1.68      |
| $ttH, H \rightarrow WW$       | 1.03 ± 0.47          | 2.09 ± 1.01      |
| $ttH, H \rightarrow ZZ$       | 0.06 ± 0.03          | 0.06 ± 0.04      |
| $ttZ$                          | 3.07 ± 0.46          | 8.33 ± 1.08      |
| $ttW$                          | 1.10 ± 0.15          | 7.18 ± 0.80      |
| Electroweak                    | 0.21 ± 0.19          | 3.73 ± 3.39      |
| Fake                           | 1.66 ± 0.52          | 7.80 ± 2.51      |
| Charge flip                    | 0.05 ± 0.01          | 0.39 ± 0.10      |
| Other                          | 0.50 ± 0.20          | 2.44 ± 1.01      |
| Total expected background      | 6.59 ± 0.88          | 29.87 ± 4.75     |
| SM expectation                 | 9.06 ± 1.33          | 34.88 ± 5.05     |
| Observed data                  | 8                   | 41                |

The combination of all three event categories amounts to 2.0 times the SM $ttH$ production rate. The observed limit is compatible with the limit that is expected in case a $ttH$ signal of SM rate is present in the data, amounting to 2.2 times the SM $ttH$ production rate. In the absence of a $ttH$ signal in the data, an upper limit on the signal rate of 1.1 times the SM $ttH$ production rate is expected.

We conclude that the background-only ($\mu = 0$) hypothesis is disfavored, but not excluded, by these results.
Table 2: Signal rates $\mu$, in units of the SM $t\bar{t}H$ production rate, measured and expected in each of the categories $2\ell ss + 1\tau_{h}$, $3\ell + 1\tau_{h}$, and $1\ell + 2\tau_{h}$ individually and for the combination of all three categories.

<table>
<thead>
<tr>
<th>Category</th>
<th>Measured signal rate ±1$\sigma$</th>
<th>Expected signal rate ±1$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1\ell + 2\tau_{h}$</td>
<td>$-1.20^{+1.30}_{-1.00}$</td>
<td>$1.00^{+1.75}_{-1.57}$</td>
</tr>
<tr>
<td>$2\ell ss + 1\tau_{h}$</td>
<td>$0.86^{+0.86}_{-1.00}$</td>
<td>$1.00^{+0.77}_{-0.64}$</td>
</tr>
<tr>
<td>$3\ell + 1\tau_{h}$</td>
<td>$1.22^{+1.34}_{-1.00}$</td>
<td>$1.00^{+1.41}_{-1.06}$</td>
</tr>
<tr>
<td>Combined</td>
<td>$0.72^{+0.82}_{-0.53}$</td>
<td>$1.00^{+0.87}_{-0.57}$</td>
</tr>
</tbody>
</table>

Table 3: 95% CL upper limits on the $t\bar{t}H$ signal rate, in units of the SM $t\bar{t}H$ production rate, obtained in each of the categories $2\ell ss + 1\tau_{h}$, $3\ell + 1\tau_{h}$, and $1\ell + 2\tau_{h}$ individually and for the combination of all three event categories. The observed limit is compared to the limits expected for the background-only hypothesis ($\mu = 0$) and for the case that a $t\bar{t}H$ signal of SM production rate is present in the data ($\mu = 1$). The limits expected in the case $\mu = 1$ are computed using an Asimov dataset, while the limits expected in the case $\mu = 0$ are computed for the values of nuisance parameters obtained from a maximum likelihood fit of the background-only hypothesis to the data. The ±1$\sigma$ uncertainty intervals of the limits expected in case of the background-only hypothesis are also given in the table.

<table>
<thead>
<tr>
<th>Category</th>
<th>Observed limit</th>
<th>Expected limit ($\mu = 0$)</th>
<th>Expected limit ($\mu = 1$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1\ell + 2\tau_{h}$</td>
<td>2.6</td>
<td>$3.4^{+1.0}_{-1.0}$</td>
<td>4.4</td>
</tr>
<tr>
<td>$2\ell ss + 1\tau_{h}$</td>
<td>2.4</td>
<td>$1.4^{+0.6}_{-0.4}$</td>
<td>2.4</td>
</tr>
<tr>
<td>$3\ell + 1\tau_{h}$</td>
<td>4.0</td>
<td>$2.7^{+1.3}_{-0.8}$</td>
<td>3.8</td>
</tr>
<tr>
<td>Combined</td>
<td>2.0</td>
<td>$1.1^{+0.6}_{-0.3}$</td>
<td>2.2</td>
</tr>
</tbody>
</table>
Figure 3: Signal rates $\mu$, in units of the SM $t\bar{t}H$ production rate, measured in each of the categories $2\ell ss + 1\tau_h$, $3\ell + 1\tau_h$, and $1\ell + 2\tau_h$ individually and for the combination of all three categories.

Figure 4: 95% CL upper limits on the $t\bar{t}H$ signal rate, obtained in each of the categories $2\ell ss + 1\tau_h$, $3\ell + 1\tau_h$, and $1\ell + 2\tau_h$ individually and for the combination of all three event categories. The expected limits are computed for the background-only ($\mu = 0$) hypothesis.
10 Summary

A search for the associated production of a H boson with top quark pair in final states with a τ lepton has been presented. The analyzed dataset corresponds to 35.9 fb$^{-1}$ of pp collision data recorded in 2016 by the CMS experiment at $\sqrt{s} = 13$ TeV. The analysis is performed in three event categories: $1\ell + 2\tau$, $2\ell ss + 1\tau$, and $3\ell + 1\tau$. The sensitivity of the analysis is enhanced by using multivariate analysis techniques, based on the matrix element method and boosted decision trees. The results of the analysis are in agreement with the SM expectation. The measured signal rate amounts to $0.72^{+0.62}_{-0.53}$ times the SM $t\bar{t}H$ production rate, with an observed (expected) significance of 1.4$\sigma$ (1.8$\sigma$). An upper limit on the signal rate of 2.0 times the SM $t\bar{t}H$ production rate at 95% CL is set.
A Computation of MEM discriminants

A discriminant based on the MEM approach has been developed for the $2\ell ss + 1\tau_h$ category, in order to improve the separation of the $t\bar{t}H$ signal with respect to the main backgrounds. The computation of the discriminant is based on combining the knowledge of differential theoretical cross sections for the $t\bar{t}H$ signal and for background processes with the knowledge of the experimental resolution of the detector.

The matrix element (ME) $M_{\Omega}(x)$ associated to a given process $\Omega$ depends on a set of kinematic variables $x$ that corresponds to the four-momenta, at parton level, of the particles in the initial and final state. We use bold letter to indicate vector quantities. The square of the ME is convoluted with a function $W(y|x)$, referred to as “transfer function”, which represent the experimental resolution. The function $W(y|x)$ represents the probability that a set of observables $y$ is measured in the detector, given that the corresponding parton-level momenta are equal to $x$. In case of the $2\ell ss + 1\tau_h$ category, the vector $y$ consists of the four-momenta of the two leptons, of the $\tau_h$ and of the jets reconstructed in the event as well as of the components $E_{y}^{\text{miss}}$ and $E_{x}^{\text{miss}}$ of the missing transverse momentum vector $\vec{p}_T^{\text{miss}}$.

The MEM computes the differential cross section of the process $\Omega$ with respect to the observables $y$, while integrating over the unmeasured or poorly measured parton-level quantities $x$, as well as the Bjorken scaling variables $[63]$ $x_a$ and $x_b$ of the colliding protons. A weight $w_\Omega(y)$ is computed to quantify the compatibility for an observed event, characterised by the measured observables $y$, with the hypotheses that the event is produced by the process $\Omega$:

$$w_\Omega(y) \propto \sum_{p} \int dx_a dx_b f_i(x_a, Q) f_j(x_b, Q) \frac{\delta^4(x_a p_a + x_b p_b - \sum p_k)|M_{\Omega}(x)|^2 W(y|x)}{x_a x_b s}.$$  \hspace{1cm} (4)

The sum $\sum_p$ extends over all possible associations between parton-level and reconstructed objects. The square of the ME, $|M_{\Omega}(x)|^2$, is computed at LO using MADGRAPH [20]. The symbols $f_i(x_a, Q)$ and $f_j(x_b, Q)$ denote the parton distribution functions, which we evaluate numerically using the CTEQ6.6 set [64]. The four-dimensional $\delta$-function $\delta^4(x_a p_a + x_b p_b - \sum p_k)$ ensures the conservation of energy and momentum. The integral on the right-hand side is first transformed analytically, in order to eliminate the $\delta$-function and to make the computation of the integral numerically tractable, and then evaluated numerically using the VEGAS algorithm [65].

The weights $w_\Omega(y)$ are computed for the $t\bar{t}H$ signal and for the following background processes:

- $t\bar{t}Z, Z \rightarrow \tau\tau$.
- $t\bar{t}Z, Z \rightarrow \ell\ell$ with one lepton misidentified as a $\tau_h$.
- $t\bar{t} \rightarrow b\ell\nu + \bar{b}\tau\nu$ with one additional non-prompt lepton produced in either a $b$ or a $\bar{b}$ quark decay.

The transfer functions $W(y|x)$ are obtained from the MC simulation and are used to model:

- The jet $p_T$ resolution.
- The resolution on $E_{x}^{\text{miss}}$ and $E_{y}^{\text{miss}}$.
- The angular and $p_T$ resolution of the charged lepton and of the hadrons produced in $\tau \rightarrow \ell\nu\nu\tau$ and $\tau \rightarrow \tau_h\nu\tau$ decays.
- The resolution on $p_T$ for leptons misidentified as $\tau_h$.
- The $p_T$ resolution for non-prompt leptons produced in $b$ or $\bar{b}$ quark decays.
The MEM is computed separately for events selected in the “no-missing-jet” category and events selected in the “missing-jet” category (cf. Section 8). In case events are selected in the “missing-jet” category, the integral on the right-hand-side of Eq. (4) is extended by an integration over the \( \eta \) and \( \phi \) of the missing jet. The energy of the missing jet is determined by the constraint that the mass of the missing jet and of the other, reconstructed, jet produced in the \( W \) boson decay matches the literature value for the \( PW \) boson mass.

According to the Neyman lemma [66], the ratio of weights \( w_{\Omega}(y) \) computed for the signal and for the background hypothesis constitutes an optimal observable to separate the \( ttH \) signal from backgrounds:

\[
\mathcal{L}(y) = \frac{w_{ttH}(y)}{w_{ttH}(y) + \sum_B \kappa_B w_B(y)}
\]

and is used as discriminant for the signal extraction in the \( 2\ell ss + 1\tau_h \) category. The coefficients \( \kappa_B \) that quantify the relative importance of different background processes \( B \) are determined by a numerical optimization, in order to achieve the maximal separation of the \( ttH \) signal from all background processes.
References


[8] ATLAS Collaboration, “Combination of the searches for Higgs boson production in association with top quarks in the γγ, multilepton, and b\bar{b} decay channels at \(\sqrt{s} = 13\) TeV with the ATLAS detector”, ATLAS Conference Note ATLAS-CONF-2016-068, 2016.


