Measurement of Higgs boson production in the decay channel with a pair of $\tau$ leptons

The CMS Collaboration

Abstract

Measurements of Higgs boson production in the channel where the Higgs boson decays to $\tau$ leptons are performed. The analysis uses events recorded in proton-proton collisions by the CMS experiment at the CERN LHC in 2016, 2017, and 2018 at a center-of-mass energy of 13 TeV. The data sets correspond to a total integrated luminosity of $137 \text{ fb}^{-1}$. The product of the $H \rightarrow \tau\tau$ signal production cross section and branching fraction is measured to be $0.85^{+0.12}_{-0.11}$ times the standard model expectation. This analysis targets primarily the gluon fusion and the vector boson fusion production modes. Measurements of the signal strengths and products of the cross section and branching fraction are also performed in the simplified template cross section scheme, providing precise measurements of the Higgs boson production at high transverse momentum and in event topologies with jets.
1 Introduction

In the standard model (SM) of particle physics [1–3], the masses of the Z and W bosons are obtained through their interaction with a fundamental field, in a process known as electroweak symmetry breaking and entering the theory via the Brout–Englert–Higgs mechanism [4–9]. The Higgs boson is the quantized manifestation of this field. A particle with properties compatible with those of an SM Higgs boson was observed by the ATLAS and CMS experiments in the ZZ, γγ, and W⁺W⁻ decay channels using data collected in 2011 and 2012 at center-of-mass energies of 7 and 8 TeV [10–12]. The properties of the new particle, including its spin and CP properties, have also been measured at both the CMS and ATLAS experiments and are consistent with those expected for the Higgs boson predicted by the SM [13–19]. The mass of the Higgs boson has been determined to be 125.09 ± 0.21 (stat) ± 0.11 (syst) GeV, from a combination of ATLAS and CMS measurements [20].

In the SM, the mass generation of fermions is achieved through Yukawa couplings with the Brout–Englert–Higgs field. There exists several theories beyond the SM, such as supersymmetry, that imply deviations of the couplings of the observed Higgs boson to down-type fermions, such as τ leptons. Therefore, it is necessary to demonstrate the direct coupling of the Higgs boson to the fundamental fermions and to demonstrate the proportionality of the Higgs boson coupling strength to their mass. A promising decay channel to do this is H → τ⁺τ⁻ because of the large branching fraction compared to the µ⁺µ⁻ channel and smaller contribution from background events with respect to the b̅b channel.

The first evidence for the coupling of the Higgs boson to down-type fermions was found at the LHC using CMS data collected at center-of-mass energies of 7 and 8 TeV [21]. A combination of the measurements performed by the ATLAS and CMS experiments at the same center-of-mass energies led to the observation of the H → τ⁺τ⁻ decay [22]. The first observation of H → τ⁺τ⁻ decays with a single experiment was obtained by the CMS experiment using data collected at a center-of-mass energy of 13 TeV in 2016 [23]. Higgs boson production rates have also been scrutinized using the Simplified Template Cross Section (STXS) framework, defined by the LHC Higgs Cross Section Working Group [24]. By using the STXS scheme to probe deviations from SM expectations, one can reduce the theory dependencies that must be directly folded into the measurements. A measurement in the τ⁺τ⁻ final state utilizing the STXS binning was previously performed by the CMS Collaboration using 77 fb⁻¹ of data collected in 2016 and 2017, where a differentiation between the individual signal and background sources is performed using a neural network (NN) classification algorithm providing several categories, with high purity in the respective signal or background process [25]. This approach is complementary to the cut-based approach presented here. The ATLAS experiment also performed measurements of the Higgs boson production cross section using the STXS binning at a center-of-mass of 13 TeV, which are in good agreement with the SM expectation [26].

This note reports the measurement of the product of the Higgs boson production cross section and branching fraction to τ leptons using data corresponding to an integrated luminosity of 137 fb⁻¹ and collected in proton-proton (pp) collisions at a center-of-mass energy of 13 TeV. The gluon fusion and vector boson fusion production cross sections are also measured in the context of the STXS framework. For simplicity, the signs of the particle charges will be omitted in the rest of this note.
2 The CMS detector

From the central interaction point, the CMS detector hosts 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. The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. The silicon pixel and tracking systems as well as the calorimeters are contained within the solenoid volume. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid.

The nominal pp bunch crossing rate at the LHC is 40 MHz. In order to reduce the rate of events that are recorded for offline analysis, events of interest are selected using a two-tiered trigger system [27]. The first level (L1) is composed of custom built electronics which makes use of high speed optical links and large Field Programmable Gate Arrays (FPGAs). L1 reduces the event rate from the nominal bunch crossing to a rate of around 100 kHz within a time interval of less than 3.5 µs. The second level, known as the High Level Trigger (HLT), consists of a farm of generic processors running a version of the full event reconstruction software that has been optimized for fast processing. The HLT reduces the event rate to about 1 kHz before data storage.

Since the 2012 data taking, significant upgrades of the L1 trigger have benefited this analysis, especially in the final state with two semi-hadronically decaying τ leptons, denoted as \( \tau_h \). These upgrades improved the \( \tau_h \) identification at L1 by giving more flexibility to object isolation, allowing new techniques to suppress the contribution from additional pp interactions per bunch crossing, and to reconstruct the L1 \( \tau_h \) object in a fiducial region that matches more closely that of a true \( \tau_h \) decay.

A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [28].

3 Simulated samples

The signal and some of the minor background processes are modeled with samples of simulated events. The signal samples with a Higgs boson produced through gluon-gluon fusion (ggF), vector boson fusion (VBF), or in association with a W or Z boson (WH or ZH), are generated at next-to-leading order (NLO) in perturbative quantum chromodynamics (QCD) with the POWHEG 2.0 [29–33] generator. The distributions of the Higgs boson \( p_T \) and of the jet multiplicity are tuned in the POWHEG simulation of the ggF production mode to match the NNLO accuracy obtained from full phase space calculations with the NNLOPS generator [34, 35]. The description of the decay of the Higgs boson to τ leptons is obtained using the PYTHIA generator [36, 37]. All samples are generated with the NNPDF30_nlo_as_0118 NLO parton distribution functions (PDFs).

The MadGraph5_aMC@NLO [38] generator is used to simulate the \( Z \rightarrow ee/\mu\mu + \text{jets} \) process at leading order (LO) with the MLM jet matching and merging [39]. The MadGraph5_aMC@NLO generator is also used to model the diboson production, whereas POWHEG 2.0 and 1.0 are used for tt and single top quark production, respectively. The generators are interfaced with PYTHIA 8.212 [37] to model the parton showering and fragmentation, as well as the decay of the τ leptons. The PYTHIA parameters affecting the description of the underlying event are set to the CUETP8M1 tune in 2016, except for the tt sample where the CUETP8M4 tune is used, and CP5 tune in 2017 and 2018 [40]. The NNPDF2.3 parton distribution function (PDF) set [41] is used
4. Event reconstruction

Simulated events are processed through a simulation of the CMS detector which is based on GEANT4 [43], and are reconstructed with the same algorithms used for data. Simulated samples are reconstructed with the same algorithms as those used for data. Additional pp interactions per bunch crossing, or “pileup” are included. The effect of pileup is taken into account by generating concurrent minimum bias collision events with PYTHIA.

4 Event reconstruction

The reconstruction of both simulated and observed events is based on the particle-flow (PF) algorithm [44], which relies on the information from the different CMS subdetectors to reconstruct muons, electrons, and charged and neutral hadrons. These objects are combined to form more complex ones, like $\tau_h$ candidates or missing transverse momentum.

Muons are reconstructed and identified with requirements on the quality of the track reconstruction and on the number of hits in the tracker and muon systems [45]. They are selected with $p_T > 15\text{ GeV}$ and $|\eta| < 2.4$. Electrons are reconstructed using tracks from the tracking system, calorimeter deposits in the ECAL, and a veto on objects with a large HCAL to ECAL energy. They are identified using a multivariate discriminant combining several quantities that describe the shape of the energy deposits in the ECAL, the quality of tracks, and the compatibility of the measurements from the tracker and the ECAL [46]. In order to reject leptons that originate from nonprompt interactions or are misidentified, a relative lepton isolation is defined:

$$I_\ell \equiv \frac{\sum_{\text{charged}} p_T + \max(0, \sum_{\text{neutral}} p_T - \frac{1}{2} \sum_{\text{charged, PU}} p_T)}{p_T^\ell}. \quad (1)$$

In this equation, $\sum_{\text{charged}} p_T$ is the scalar sum of the transverse momenta of the charged particles originating from the primary vertex and located in a cone of size $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} = 0.4 \ (0.3)$ centered on the muon (electron) direction. The sum $\sum_{\text{neutral}} p_T$ is a similar quantity for neutral particles.

Jets are reconstructed using the anti-$k_T$ FASTJET algorithm with distance parameter $R = 0.4$ [47, 48]. Data collected in the ECAL endcaps were affected by large amounts of noise during the 2017 run, which led to disagreements between simulation and data. To mitigate this issue, jets used in the analysis of the 2017 data are discarded if they have $p_T < 50\text{ GeV}$ and $2.65 < |\eta| < 3.139$. Hadronic jets that contain b quarks are tagged using a deep neural network, called the DeepCSV algorithm [49].

All particles reconstructed in the event are used to determine the missing transverse momentum, $p_T^{\text{miss}}$. The missing transverse momentum is defined as the negative vectorial sum of the transverse momenta of all PF candidates [50]. It is adjusted for the effect of jet energy corrections. Corrections to the $p_T^{\text{miss}}$ are applied to reduce the mismodeling of the simulated $Z + \text{jets}$ and Higgs boson samples. These recoil corrections are applied to the simulated events on the basis of the vectorial difference of the measured $p_T^{\text{miss}}$ and total transverse momentum of neutrinos originating from the decay of the $Z, W$, or $H$ boson. Their average effect is the reduction of the $p_T^{\text{miss}}$ obtained from simulation by a few GeV.

The reconstruction of $\tau_h$ candidates is performed with the hadrons-plus-strip (HPS) algorithm. The algorithm works by combining the signature of charged hadrons, tracks left in the tracker and energy deposits in the hadronic calorimeter, with the electron/photon signature.
of neutral pions reconstructed by collecting energy inside of “strips” in \( \eta - \phi \) space inside of the ECAL \[51\]. The combination of these signatures provides the four-vector of the parent \( \tau_h \). Based on the overall neutral-versus-charged contents of the \( \tau_h \) reconstruction, a decay mode is assigned as either \( h^\pm, h^\pm \pi^0, h^\pm h^\mp h^\pm, \text{or } h^\pm h^\pm \pi^0 \). The identification of \( \tau_h \) candidates makes use of isolation discriminators to reject quark and gluon jets misidentified as \( \tau_h \). For this analysis, a deep neural network (DNN) discriminator is used. The input variables to the DNN include variables related to the \( \tau_h \) isolation, \( \tau_h \) lifetime, and other detector-related variables. The threshold on the output discriminant depends on the \( \tau_h \) ID and reconstruction efficiency of about 60%. Two other DNNs are used to reject electrons and muons misidentified as \( \tau_h \) candidates using dedicated criteria based on the consistency between the measurements in the tracker, the calorimeters, and the muon detectors.

In order to separate the \( H \rightarrow \tau \tau \) signal events from the significant contribution of irreducible \( Z \rightarrow \tau \tau \) events, the visible mass of the \( \tau \tau \) system, \( m_{\text{vis}} \), can be used. However, during the decay of the \( \tau \), a large fraction of energy is carried away by the neutrinos and this reduces the discriminating value of the \( m_{\text{vis}} \) variable. A simplified matrix-element algorithm \[52\] combines the \( p_T^{\text{miss}} \) and its covariance matrix with the four-vectors of both \( \tau \) candidates to calculate a more accurate estimate of the mass of the parent boson, denoted as \( m_{\tau\tau} \). The resolution of \( m_{\tau\tau} \) is between 15 and 20% depending on the \( \tau \tau \) final state.

### 5 Event selection

The selected events are classified into decay channels based upon the number of electrons, muons, and \( \tau_h \) candidates. To remove overlap events in the decay channels, events are rejected if they contain an additional loosely identified electron or muon. In the \( \tau_h \tau_h \) final state, events are selected with a trigger relying on the presence of two \( \tau_h \) candidates with \( p_T \) above 35 or 40 GeV depending on the year. In the \( e\tau_h (\mu\tau_h) \) final states, the triggers are based on the presence of an isolated electron (muon) with a \( p_T \) threshold in the range 25–32 GeV (22–27 GeV). The analysis acceptance is increased by additionally selecting events where the electron (muon) are below the single-lepton trigger thresholds, using a cross-trigger requiring an electron (muon) and a \( \tau_h \) candidate. For these cross-triggers the electron, muon, and \( \tau_h \) \( p_T \) thresholds are 24, 19–20, and 20–27 GeV, respectively. In the \( e\mu \) final state, the triggers require both an electron and a muon, where the leading object has \( p_T \) above 23 GeV, and the subleading object has \( p_T \) above 8 GeV if it is a muon, and above 12 GeV if it is an electron.

Leptons must meet the minimum requirement that the distance of closest approach to the primary vertex satisfies \( |d_z| < 0.2 \text{ cm} \) along the beam direction, and \( |d_{xy}| < 0.045 \text{ cm} \) in the transverse plane. The two leptons assigned to the Higgs boson decay are required to have opposite-sign (OS) electric charges. The selection criteria are summarized in Table 1.

In the \( \ell\tau_h \) channels, where \( \ell \) denotes an electron or a muon, the large \( W + \text{jets} \) background is reduced by requiring the transverse mass, \( m_T \), to satisfy

\[
m_T \equiv \sqrt{2p_T^{\ell}p_T^{\text{miss}}[1-\cos(\Delta \phi)]} < 50 \text{ GeV},
\]

where \( p_T^{\ell} \) is the transverse momentum of the lepton \( \ell \), and \( \Delta \phi \) is the azimuthal angle between its direction and the \( p_T^{\text{miss}} \).

In the \( e\mu \) channel, the \( t\bar{t} \) background is reduced by requiring \( D_\ell = p_\ell - 0.85p_\ell^{\text{vis}} > -30 \text{ GeV} \), where \( p_\ell \) is the component of the \( p_T^{\text{miss}} \) along the bisector of the \( p_T \) of the two leptons and \( p_\ell^{\text{vis}} \) is the sum of the components of the lepton \( p_T \) along the same direction \[53\]. This selection
6. Categorization

Event categories are designed to increase the sensitivity to the signal by isolating regions with large signal-to-background ratios, and to provide sensitivity to the stage-0 and stage-1 ggH and qqH parameters of the STXS framework. At stage-0, the Higgs boson signal is split between ggH, qqH, WH with leptonic W boson decays, ZH with leptonic Z boson decays, and tH production, where ggH includes both the ggF production and the gluon-initiated VH associated production with hadronic vector boson decays, and qqH includes both the VBF production and the quark-initiated VH associated production with hadronic vector boson decays. At stage-1, the ggH and qqH processes are divided on the basis of the number of jets, the Higgs boson dijet mass, and the invariant mass of the two leading jets when applicable. For all stage-1 cross section measurements, the absolute value of the Higgs rapidity, denoted as $|\eta_{h}|$, is required to be less than 2.5. The $H \to \tau \tau$ channel is expected to be particularly sensitive to the gluon fusion process with relatively high Higgs boson $p_T (> 100 \text{ GeV})$ and to the VBF topology, which are the primary targets in choosing the categories and observables of the analysis.
Events are distributed in different categories, which separate the different production modes of the Higgs boson, corresponding to stage-0 processes in the STXS scheme. The 0-jet category collects events with no reconstructed jet. The signal entering this category corresponds essentially to the $ggF$ production mode. The VBF category targets the VBF production of the Higgs boson. The selection is based on the presence of at least two jets with a large invariant mass or a large pseudorapidity separation. The background contributions are much smaller than in the 0-jet category. All other events enter the so-called “boosted category”, which contains mostly $ggF$ events with a Higgs boson recoiling against one or several jets, but also small contributions from VBF events that did not pass the VBF category selection, or from Higgs bosons produced in association with a vector boson decaying hadronically.

The three categories above are further subdivided to provide additional sensitivity to individual processes in the stage-1 of the STXS scheme. The definition of the stage-1.2 processes is illustrated in Figs 1 and 2 for the $ggH$ and $qqH$ groups, respectively. In the STXS 1.2 scheme for the $qqH$ process, events with 2 jets with an invariant mass above 350 GeV are primarily divided based on whether $p_T^H$ is less or greater than 200 GeV, with further subdivisions according to $m_{jj}$. Therefore the VBF category in the analysis is subdivided into two: events with reconstructed $p_T^H$ less or greater than 200 GeV. The division of the boosted category is based on the STXS 1.2 scheme for $ggF$ events with at least one jet. The primary subdivision is based on the number of jets, while the secondary subdivision relies on $p_T^H$. The boosted category is thus separated into a boosted category with 1 jet, and a boosted category with at least 2 jets. The 0-jet category is not split because the reconstructed $p_T^H$ resolution is too poor to efficiently separate events with $p_T^H$ less than or above 10 GeV. This leads to 5 categories for each final state.

![Figure 1: Binning of the ggH production in the STXS stage 1.2 scheme. The dashed black boxes indicate the process-based merging detailed in Section 9. The green boxes indicate the differences in merging for the topology-based merging explained in the same section.](image)

In each category two-dimensional (2D) distributions are built. The observables are chosen to separate the signal from the backgrounds, and to provide sensitivity to the individual STXS stage-1 processes, as the categories only separate the primary groups of STXS processes. One of the observables is always the reconstructed di-$\tau$ mass, $m_{\tau\tau}$. In the 0-jet category of the $e\tau_h$ and $\mu\tau_h$ final states, the $p_T$ of the $\tau_h$ candidate is taken as a second observable, as the contribution from backgrounds with misidentified $\tau_h$ candidates significantly decreases with $p_T$. In the $e\mu$ and $\tau_h\tau_h$ final states, where the sensitivity to 0-jet signal events is low, no second observable
7. Background estimation

To estimate the background contribution from SM processes, several techniques are used. For the dominant backgrounds, which contain either two true $\tau$ or at least one jet misidentified as one of the $\tau$ candidates, data-driven techniques are used and are described in the following sections. The contributions from diboson, $t\bar{t}$+jets, and single top quark productions are estimated from simulation. The $Z \to ee/\mu\mu$ process is also estimated from simulation, but dedicated corrections measured in data are applied to describe this background accurately. These corrections mostly consist in a reweighting of the $Z p_T$ distribution as determined from $Z \to \mu\mu$ data,
Figure 3: Composition of the subcategories in terms of the STXS stage 1.2 processes in the $\tau_h\tau_h$ final state. The numbers on the right indicate the total number of signal events expected in every subcategory.
Table 2: Analysis categories. The results are extracted by performing a maximum likelihood fit of 2D distributions in these categories using the observables listed in the last column.

<table>
<thead>
<tr>
<th>Final state</th>
<th>Category</th>
<th>Selection</th>
<th>Observables</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0-jet</td>
<td>0 jet</td>
<td>$m_{\tau\tau}$, $p_T^H (\ell\tau_h)$</td>
</tr>
<tr>
<td></td>
<td>VBF low $p_T^H$</td>
<td>$\geq 2$ jets, $m_{jj} &gt; 350$ GeV, $p_T^H &lt; 200$ GeV</td>
<td>$m_{\tau\tau}, m_{jj}$</td>
</tr>
<tr>
<td></td>
<td>VBF high $p_T^H$</td>
<td>$\geq 2$ jets, $m_{jj} &gt; 350$ GeV, $p_T^H &gt; 200$ GeV</td>
<td>$m_{\tau\tau}, m_{jj}$</td>
</tr>
<tr>
<td></td>
<td>Boosted 1 jet</td>
<td>1 jet</td>
<td>$m_{\tau\tau}, p_T^H$</td>
</tr>
<tr>
<td></td>
<td>Boosted $\geq 2$ jets</td>
<td>Not in VBF, $\geq 2$ jets</td>
<td>$m_{\tau\tau}, p_T^H$</td>
</tr>
<tr>
<td></td>
<td>$\tau_h\tau_h$</td>
<td>0-jet</td>
<td>$m_{\tau\tau}$</td>
</tr>
<tr>
<td></td>
<td>VBF low $p_T^H$</td>
<td>$\geq 2$ jets, $\Delta\eta_{jj} &gt; 2.5$ (2.0 for 2016), $100 &lt; p_T^H &lt; 200$ GeV</td>
<td>$m_{\tau\tau}, m_{jj}$</td>
</tr>
<tr>
<td></td>
<td>VBF high $p_T^H$</td>
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<td>$m_{\tau\tau}, p_T^H$</td>
</tr>
</tbody>
</table>

and a correction of the momentum scale of electrons misidentified as $\tau_h$ candidates.

### 7.1 Estimation of $\tau\tau$ events with embedded data

The dominant background resonance that produces two $\tau$ leptons from a neutral boson is the $Z \rightarrow \tau\tau$ decay process. To estimate this background process more precisely than with simulation alone, a dedicated algorithm is used on a data sample to construct a background distribution that minimizes or eliminates several sources of uncertainties in the calibration of the simulated detector response. The process begins by taking well identified $Z \rightarrow \mu\mu$ events from data. Muons are then removed from the selected events and simulated $\tau$ leptons are embedded with the same kinematics as that of the replaced muons. The net effect of employing the embedded samples at the analysis level is a more accurate description of the $\slashed{p}_T$ and jet related variables, and an overall reduction in the systematic uncertainties that arise when simulations must be corrected to better describe data. Scale factors related to the simulated $\tau$ decays are computed for the embedded samples. Embedded samples cover all backgrounds with two real $\tau$ leptons decaying semi-hadronically or leptonically. Therefore, all background events with 2 $\tau$ leptons are discarded to avoid double counting. This includes a small fraction of the $t\bar{t}$ and diboson backgrounds.

### 7.2 Estimation of the backgrounds with jets misidentified as $\tau_h$ candidates

One of the dominant backgrounds consists in events where a quark- or gluon-initiated jet is misidentified as a $\tau_h$ candidate. Such processes include mostly QCD multijet and $W +$ jets events, as well as semi-leptonic and fully-hadronic $t\bar{t} +$ jets decays. This background is estimated from data, using the so-called fake rate method. The details of the method slightly differ between the $\tau_h\tau_h$ and the $\ell\tau_h$ channels because of different background compositions.

In the $\tau_h\tau_h$ channel, the misidentified-$\tau_h$ background is almost entirely comprised of QCD multijet events. The rate with which loosely isolated jets are misidentified as isolated $\tau_h$ is measured in data in a QCD-enriched region. This region is defined in the same way as the
signal region, with the exception that the $\tau_h$ candidates are required to have the same charge. The misidentification rate of the leading $\tau_h$ candidate is measured as a function of the $\tau_h$ $p_T$ in three different jet-multiplicity bins (0, 1, >1 jets) and parameterized with the sum of a Landau function and a first-order polynomial.

Events in the QCD-enriched region with an anti-isolated $\tau_h$ candidate are weighted with the measured fake rates. By construction, the leading $\tau_h$ $p_T$ distribution matches that of events with an isolated $\tau_h$ candidate in that region, but their subleading $\tau_h$ $p_T$ distributions do not agree. Closure corrections as a function of the subleading $\tau_h$ $p_T$ are derived for each jet-multiplicity bin to remove the bias. After applying this correction, the distributions of all important variables in the analysis are well described.

Finally, a correction is derived to account for the inversion of the sign requirement in the QCD control region. It is measured by comparing the $m_{\tau\tau}$ mass distribution of unweighted events with an isolated leading $\tau_h$ and an anti-isolated subleading $\tau_h$ with OS, to the $m_{\tau\tau}$ distribution of weighted events with an isolated leading $\tau_h$ and an anti-isolated subleading $\tau_h$ with OS. The latter events are weighted with the fake rates measured in the corresponding SS region and evaluated as a function of the leading $\tau_h$ $p_T$ and decay mode. The correction ranges between about 5 and 15% for visible masses between 0 and 200 GeV.

In the $\ell\tau_h$ channels, backgrounds with misidentified $\tau_h$ candidates mostly come from QCD multijet and W+jets events, and to a lesser extent from $t\bar{t}$+jets events. The misidentification rates are measured separately for these three processes, as a function of the $\tau_h$ $p_T$. A QCD-enriched region is obtained by inverting the sign requirement of the $\ell\tau_h$ pair, whereas a W+jets region is selected by requiring $m_T$ to be greater than 70 GeV. Obtaining a pure $t\bar{t}$ control region with semi-leptonic decays is not possible, and the misidentification rate of jets as $\tau_h$ candidates are measured in simulation for this subdominant process. The misidentification rates are measured in three different jet-multiplicity bins (0, 1, >1 jets) for the QCD multijet and W+jets processes, and inclusively for the $t\bar{t}$ process, and they are parameterized with linear functions.

In the $\ell\tau_h$ channel, non-closure corrections are derived as a function of the $p_T$ of the $\ell$ using the fake-enriched control region. All other distributions are well modelled after these corrections. An additional correction for the inversion of the $m_T$ requirement for the W+jets misidentification rates is derived from simulation, while an OS/SS correction for the inversion of the sign requirement is derived for the QCD misidentification rates based on data as explained for the $\tau_h\tau_h$ channel.

The background with misidentified $\tau_h$ in the signal region of the $\tau_h\tau_h$ channel is obtained by reweighting events where the leading $\tau_h$ candidate is anti-isolated, with the product of the fake rates and corrections, computed on an event-by-event basis. In the $\ell\tau_h$ channel, the fake rates and corrections are weighted according to the expected contributions of the QCD multijet, W + jets, and $t\bar{t}$+ jets events in a given category and for a given $m_{\tau\tau}$ value. The expected relative contributions of the different processes are determined from simulation, except for the QCD multijet background, which is estimated as the difference between SS events selected in data and SS events from all other background processes as estimated from simulation, scaled by an extrapolation factor in the range 1.0–1.1. The weighted fake rates are applied to events with an anti-isolated $\tau_h$ candidate to estimate the reducible background in the signal region. Events with a real $\tau_h$ or with light leptons misidentified as a $\tau_h$ candidate are estimated based on simulation and subtracted from the anti-isolated region. Simulated events with a jet misidentified as a $\tau_h$ candidate are discarded from the signal region to avoid double counting.
7.3 Estimation of the backgrounds with misidentified jets in the \( e\mu \) final state

In the \( e\mu \) final state, backgrounds where at least one jet is misidentified as an electron or a muon candidate are estimated from data using events with an electron and a muon with SS charge. Contributions from other processes are estimated from simulation and subtracted from data in this SS control region. Scale factors to extrapolate from the SS control region to the OS signal region are measured as a function of the jet multiplicity and the \( \Delta R \) separation between the electron and the muon.

The OS/SS scale factor for QCD multijet events is estimated from data using events with an anti-isolated muon and an isolated electron. To increase the number of selected events, the \( D_\tau \) and \( m_T \) criteria applied in the signal region are not applied here. The scale factor is taken as the ratio between the estimated OS and SS contributions for events with an anti-isolated muon. The \( \Delta R \) dependency comes from the variation of the contribution from \( b\bar{b} \) events to the QCD multijet background, and is parameterized with a linear function. The OS/SS scale factor typically ranges between 2.5 and 3.0 for \( \Delta R = 0.3 \), and between 1.0 and 1.5 for \( \Delta R = 5.0 \), with differences between data taking years and between jet multiplicity bins.

The OS/SS scale factor does not only depend on the number of jets and the separation between the electron and the muon, but also on the electron and muon \( p_T \). The lepton arising from the semi-leptonic c quark decay tends to be softer in \( p_T \) and less isolated resulting in a reduction in the number of such events passing the \( p_T \) and isolation requirements. The softer \( p_T \) spectra for leptons produced in the SS configuration also explains the observed dependence of the OS/SS factors on the electron/muon \( p_T \). To correct for that effect, 2D weights are derived as function of the electron and muon \( p_T \), by applying the scale factors measured in the previous step to SS events with an anti-isolated muon, and adjusting the 2D distribution to match the gap between the observed data and the predicted backgrounds.

Finally, to cover for a potential mismodeling of the OS/SS scale factors in the signal region introduced by anti-isolating the muon, an additional correction is derived by measuring the OS/SS scale factors in two other event configurations: in events where the muon is isolated but the electron is anti-isolated, and in events where both the electron and the muon are anti-isolated. The ratio of these factors is taken as the correction for anti-isolating the muon.

The OS/SS correction is taken as a weighted average of the scale factors measured in data for the QCD multijet process, and measured in simulation for the semileptonic \( t\bar{t} \) process, according to their expected relative contributions in each category.

8 Systematic uncertainties

8.1 Uncertainties in the object reconstruction and identification

The uncertainties in the electron and muon tracking, reconstruction, identification, and isolation both amount to 2%, as measured from a tag-and-probe method. The triggering of electrons and muons contributes an additional 2% uncertainty in the yield of simulated processes selected with these triggers. The muon momentum scale uncertainty ranges between 0.4 and 2.7% depending on the muon pseudorapidity, whereas the electron momentum scale uncertainty is typically less than 1% and depends on \( p_T \) and \( \eta \).

The \( \tau_1 \) reconstruction and identification efficiency is measured with a tag-and-probe method separately for different \( \tau_1 \) decay modes and \( p_T \) ranges. The uncertainty in the individual measurements ranges between 2 and 3%. As the measurements are statistically dominated and
therefore mostly independent, the uncertainties for different decay modes or $p_T$ ranges are considered as uncorrelated. They affect the $m_{\tau\tau}$ distributions of simulated processes. Similar uncertainties are also taken into account for the embedded $\tau\tau$ background, and are treated as half correlated with the simulation uncertainties since the measurement is made using the same data. An additional 3% uncertainty is added to the $e\tau_h$ channel to account for the use of different working points of the discriminators against electrons and muons. For electrons and muons misidentified as $\tau_h$ candidates, an uncertainty derived in bins of $p_T, \eta$, and decay mode of the misidentified $\tau_h$ candidate is applied and amounts to 40% and between 10 and 70%, respectively.

The uncertainty in the $\tau_h$ momentum scale ranges between 0.7 and 1.2% depending on the decay mode, without correlation between decay modes as the measurements are statistically dominated. This uncertainty is half correlated between embedded backgrounds and simulated processes. For electrons and muons misidentified as $\tau_h$ candidates, the uncertainty in the momentum scale amounts to 1% for muons and up to 7% for electrons.

Uncertainties in the jet energy scale come from different sources with limited correlations. The sources typically affect different regions of the detector. The magnitude of the uncertainty depends on the jet kinematics, and is in general larger at high pseudorapidity. Uncertainties in the jet energy scale have an impact in the $m_{\tau\tau}$ distribution since the uncertainties are propagated to $p_T^{\text{miss}}$, and create migrations between categories defined on the basis of the jet multiplicity or $m_{jj}$. Uncertainties in the jet energy resolution are also taken into account; they typically have a lower impact than the sum of the jet energy scale uncertainties, and create mostly migrations between $m_{jj}$-defined categories.

Uncertainties in $p_T^{\text{miss}}$ affect the $m_{\tau\tau}$ and $p_T^H$ distributions, as well as the $m_T$ and $D_\tau$ selection criteria. For simulated events with recoil corrections applied, the uncertainties in the correction are taken into account, without correlation between jet multiplicity bins, for which individual measurements are performed. Other processes suffer from uncertainties in the unclustered energy scale. The magnitudes of these corrections are event-dependent.

The rate uncertainty related to discarding events with a $b$-tagged jet is up to 10% for background with heavy-flavor jets. The uncertainty in the mistagging rate of gluon and light-flavor jets is less than 1%.

### 8.2 Background estimation uncertainties

In the $e\tau_h$ and $\mu\tau_h$ final states, the raw fake factors are parameterized with a linear function in the $\tau_h p_T$. Two uncertainties per fit function are taken into account to describe the fit uncertainties. For each jet multiplicity bin and process type, the uncertainty in the light lepton $p_T$ closure correction is considered as equal to 10% for events passing the $\ell + \tau_h$ cross-trigger and equal to the correction magnitude otherwise. The uncertainty in the OS/SS corrections in the $e\tau_h$ and $\mu\tau_h$ final states for the QCD multijet fake rates is equal to the correction magnitude. Finally, the linear parameterization of the $m_T$ correction for the $W + \text{jets}$ fake rates leads to two additional uncertainties in the reducible background estimation.

In the $\tau_h\tau_h$ final state, the fake rates in QCD multijet events are parameterized with the sum of a Landau function and a linear polynomial. The uncertainty is taken as using a linear function up to 80 GeV and then a flat fake rate above as an alternative description of the fake rate dependency with the $\tau_h p_T$. The uncertainty in the non-closure correction function of the subleading $\tau_h p_T$ is taken as equal to the correction magnitude. The uncertainty in the SS-to-OS extrapolation scale factor is negligible. A normalization uncertainty of 5% is considered for each
individual jet multiplicity bin to cover the results of the closure test performed in anti-isolated events.

Several shape uncertainties affect the estimation of the background where a jet is misidentified as an electron or a muon in the $e\mu$ final state. The first group covers statistical uncertainties in the fit of the OS/SS correction as a function of $\Delta R(e, \mu)$. The second set covers statistical uncertainties in the 2D lepton $p_T$ corrections, individually for each bin of the 2D correction. The last uncertainty applied covers the systematic uncertainty related to inverting the muon isolation to determine the OS/SS extrapolation factor. The combined effect of these uncertainties is of the order of 10% for the normalization of the reducible background.

Uncertainties related to the embedded technique are taken into account in addition to the object uncertainties already described for embedded samples. Embedded samples include all events with 2 $\tau$ candidates, essentially Drell-Yan events but also some diboson and $t\bar{t}$ events. An uncertainty in the contamination from these non Drell-Yan events is taken into account and treated as a shape uncertainty. It amounts to 10% of the $t\bar{t}$ and diboson contribution to embedded samples, as estimated from simulation. Data events with muons are selected with a muon trigger before embedding the simulated $\tau$ leptons. The uncertainty in this trigger requirement amounts to 4%, uncorrelated between data-taking periods because of different triggers. A tracking uncertainty for the embedded samples is also applied and is correlated between the $h^\pm$ and $h^\pm h^\mp h^\pm$ decay modes, and uncorrelated with the tracking uncertainty in the $h^\pm \pi^0$ decay mode where reconstruction effects of the neutral pion are taken into account.

### 8.3 Signal prediction uncertainties

The theoretical uncertainty in the branching fraction of the Higgs boson to $\tau$ leptons is equal to 2.1%. The inclusive uncertainty related to the PDFs amounts to 3.2, 2.1, 1.9, and 1.6%, respectively, for the ggF, VBF, WH, and ZH production modes [24]. The corresponding uncertainty for the variation of the renormalization and factorization scales is 3.9, 0.4, 0.7, and 3.8%, respectively [24].

The inclusive renormalization and factorization scale uncertainty mentioned above for the ggF signal is replaced by the uncertainty scheme proposed in Ref. [24]. It includes 9 nuisance parameters taking into account uncertainties in the cross section prediction for exclusive jet bins including the migration between jet-multiplicity bins, the 2-jet and 3 jet-VBF phase spaces, different $p_T^H$ regions, and the uncertainty in the $p_T^H$ distribution related to missing higher order finite top quark mass corrections.

Theoretical QCD uncertainties related to the STXS scheme are also taken into account for the VBF component of the signal. There are 9 uncertainties: 1 yield uncertainty on the inclusive cross section, as well as 8 migration uncertainties. Six of the migration uncertainties describe the $m_{jj}$ spectrum, one describes the migration between the 1- and 2-jet categories, one describes the migration between the categories separated by the cut $p_T^H > 200$ GeV. These uncertainties have been computed by varying the QCD scales using POWHEG or FO NNLO, and the bins acceptance is computed with POWHEG.

Acceptance effects, within a given stage-1 category, of varying the renormalization and factorization scales in the analysis are also taken into account. They are treated as shape uncertainties. Uncertainties related to the PDF choice and to $\alpha_s$ are also considered in the analysis, their combined effect is typically below the percent level and can be up to 1.5% in VBF-like topologies. The uncertainty in the parton showering in the PYTHIA simulations is obtained by varying the scales in the initial state radiation and final state radiation modeling; the effect is
typically between 1–3% but can be up to about 10% for ggF events in VBF-like topologies.

### 8.4 Other uncertainties

Uncertainties in the $t\bar{t} + \text{jets}$, Drell-Yan, diboson, and single top quark production cross sections amount to 4.2, 2.0, 5.0, and 5.0%, respectively. Uncertainties related to the finite number of simulated events, or to the limited number of events in data control regions, are taken into account. They are considered for all bins of the distributions used to extract the results. The uncertainty in the integrated luminosity varies between 2 and 3% depending on the data taking year. In 2016 and 2017, the uncertainty in the prefiring of electrons at trigger level ranges between 0.2 and 1.3% depending on the process.

The systematic uncertainties considered in the analysis are summarized in Table 3.

### 9 Results

The results are extracted with a binned maximum likelihood fit to the 2D distributions obtained in all categories for the different channels and data taking years. For each parameter of interest the fit is performed using minimization of a test likelihood statistic with the form:

$$
q(r) = -2\Delta \ln \mathcal{L} = -2\Delta \ln \frac{\mathcal{L}(\text{data}|s(r) + b, \theta_r)}{\mathcal{L}(\text{data}|\hat{s}(\hat{r}) + b, \theta_{\hat{r}})}
$$

(3)

where $s$ represents the signal distribution, $b$ the backgrounds, and $r$ represents the signal parameters being profiled. The term $\theta$ denotes the best-fit estimate for the nuisance parameters given a freely floating value of the signal parameters $\hat{r}$. The likelihood function can be expressed as a product over the reconstruction bins of the analysis as:

$$
\mathcal{L} = \prod_i \text{Poisson}(|\text{data}_i|s(r)_i + b_i) \cdot C(\theta_i(r)).
$$

(4)

In this function, “Poisson” refers to Poisson errors derived from statistics for the data given the signal parameters. $C$ are the constraints from nuisance parameters for each bin $i$ of the analysis. Results are extracted in minimizations using 1, 2, or 11 simultaneous freely floating signal parameters as input of the likelihood function for the inclusive, stage 0 and stage 1 signal extractions, respectively. Nuisance parameters may be further categorized as normalization effects, in which case their probability distribution function is modeled as a log-normal distribution around the central value of the affected process and affects the normalization of the process without changing its shape, or shape effects which are modeled in such a way to allow the shape of the given process to morph. The values of signal parameters that cause a crossing of the negative log likelihood at 1, and 4 represent $1\sigma$ and $2\sigma$ confidence intervals.

The postfit distributions in the various 0-jet, VBF, and boosted categories are shown in Figs 4–8 for the different final states, combining years together as well as the $e\tau_h$ and $\mu\tau_h$ decay channels. The signal is scaled to its best-fit signal strength of 0.85.

The measurements of the stage-0 and inclusive signal strengths are given in Table 4 for the different years, channels, and their combination. Observed and expected $m_{\tau\tau}$ distributions
Table 3: Sources of systematic uncertainties.

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_h$ ID</td>
<td>$p_T$/decay-mode dependent (2–3%)</td>
</tr>
<tr>
<td>$\tau_h$ against e/µ</td>
<td>3%</td>
</tr>
<tr>
<td>e → $\tau_h$ ID</td>
<td>40%</td>
</tr>
<tr>
<td>$\mu$ → $\tau_h$ ID</td>
<td>10–70%</td>
</tr>
<tr>
<td>e ID</td>
<td>2%</td>
</tr>
<tr>
<td>$\mu$ ID</td>
<td>2%</td>
</tr>
<tr>
<td>b jet veto</td>
<td>0–10%</td>
</tr>
<tr>
<td>Luminosity</td>
<td>2–3%</td>
</tr>
<tr>
<td>Trigger</td>
<td>2% for e/µ, $p_T$-dep. for $\tau_h$</td>
</tr>
<tr>
<td>$t\bar{t}$ cross section</td>
<td>4.2%</td>
</tr>
<tr>
<td>Diboson cross section</td>
<td>5%</td>
</tr>
<tr>
<td>Single top cross section</td>
<td>5%</td>
</tr>
<tr>
<td>Drell-Yan cross section</td>
<td>2%</td>
</tr>
<tr>
<td>Prefiring</td>
<td>Event-dependent (0.2–1.3%)</td>
</tr>
<tr>
<td>$B(H \rightarrow \tau\tau)$</td>
<td>2.1%</td>
</tr>
<tr>
<td>$\tau_h$ energy scale</td>
<td>0.7–1.2%</td>
</tr>
<tr>
<td>e → $\tau_h$ energy scale</td>
<td>1–7%</td>
</tr>
<tr>
<td>$\mu$ → $\tau_h$ energy scale</td>
<td>1%</td>
</tr>
<tr>
<td>Electron energy scale</td>
<td>Event-dependent</td>
</tr>
<tr>
<td>Muon energy scale</td>
<td>0.4–2.7%</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>Event-dependent</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>Event-dependent</td>
</tr>
<tr>
<td>$p_T^{miss}$ unclustered energy scale</td>
<td>Event-dependent</td>
</tr>
<tr>
<td>$p_T^{miss}$ recoil corrections</td>
<td>Event-dependent</td>
</tr>
<tr>
<td>STXS ggF theory</td>
<td>Event-dependent</td>
</tr>
<tr>
<td>STXS VBF theory</td>
<td>Event-dependent</td>
</tr>
<tr>
<td>Parton showering</td>
<td>0.5–10%</td>
</tr>
<tr>
<td>PDF and $\alpha_S$ accept.</td>
<td>0.3–1.5%</td>
</tr>
<tr>
<td>$\mu_R$ and $\mu_F$ accept.</td>
<td>1.0–10%</td>
</tr>
<tr>
<td>QCD multijet in eµ</td>
<td>Event-dependent</td>
</tr>
<tr>
<td>jet→ $\tau_h$, mis-ID</td>
<td>Event-dependent</td>
</tr>
<tr>
<td>Embedded yield</td>
<td>4%</td>
</tr>
<tr>
<td>$t\bar{t}$ in embedded</td>
<td>10%</td>
</tr>
</tbody>
</table>
Figure 4: Observed and predicted 2D distributions in the 0-jet category of the $e\mu$ (top), $\ell\tau_h$ (middle), and $\tau_h\tau_h$ (bottom) final states. The normalization of the predicted background distributions corresponds to the result of the global fit. The signal distribution is normalized to its best fit signal strength. The background histograms are stacked. The "Others" background contribution includes events from diboson and single top quark production, as well as Higgs boson decays to a pair of W bosons. The uncertainty bands account for all sources of uncertainty, systematic as well as statistical, after the global fit.
Figure 5: Observed and predicted 2D distributions in the VBF low $p_T^H$ category of the $e\mu$ (top), $\ell\tau_h$ (middle), and $\tau_h\tau_h$ (bottom) final states.
Figure 6: Observed and predicted 2D distributions in the VBF high $p_T^H$ category of the $e\mu$ (top), $\ell\tau_h$ (middle), and $\tau_h\tau_h$ (bottom) final states.
Figure 7: Observed and predicted 2D distributions in the boosted monojet category of the $e\mu$ (top), $\ell\tau_b$ (middle), and $\tau_h\tau_h$ (bottom) final states.
Figure 8: Observed and predicted 2D distributions in the boosted multijet category of the $e\mu$ (top), $\ell\tau_h$ (middle), and $\tau_h\tau_h$ (bottom) final states.
obtained by reweighting every \( m_{\tau\tau} \) distribution of each category, year, and final state by the ratio between the signal and background yields in bins with \( 90 < m_{\tau\tau} < 150 \) GeV is shown in Fig. 9.

The inclusive signal strength is measured to be \( \mu = 0.85_{-0.11}^{+0.12} \), which is a significant improvement with respect to previous measurements in the final state of two \( \tau \) leptons [23, 25] and corresponds to an observed significance well above the observation threshold. The increased sensitivity primarily comes from the larger integrated luminosity analyzed, from the better separation between real \( \tau_h \) objects and quark- and gluon-initiated jets obtained by the DNN discriminant, and from improvements in the background estimation methods, which rely on observed data to a larger extent. The finer categorization, aligned with STXS stage-1 separations, also improved the analysis sensitivity by about 10%. The inclusive measurement is now dominated
by systematic uncertainties, where those related to the signal prediction, especially at high Higgs boson $p_T$, play the largest role. Splitting the total uncertainty between sources, we obtain a best-fit inclusive signal strength of $\mu = 0.85^{+0.07}_{-0.06}$ (theory) $^{+0.06}_{-0.06}$ (syst) $^{+0.08}_{-0.07}$ (stat) $^{+0.04}_{-0.03}$ (bbb), where “theory” contains all theoretical uncertainties in the signal prediction, “bbb” all uncertainties related to the limited size of the simulated and embedded samples and of the data control regions, and “syst” the remaining systematic uncertainties.

The measurements of the signal strengths of stage-0 processes, $\mu_{ggH} = 0.98^{+0.20}_{-0.19}$ and $\mu_{qqH} = 0.67^{+0.23}_{-0.19}$, are also largely improved with respect to previous results and are in agreement with the predictions of the SM. The statistical uncertainty dominates the $\mu_{qqH}$ measurement, whereas systematic uncertainties, in particular those related to the signal prediction at high Higgs boson $p_T$, play a leading role in the $\mu_{ggH}$ measurement. A summary of the inclusive and stage-0 signal strength measurements, with the uncertainties split between sources, is shown in Fig. 10.

![Figure 10](image-url)

---

**Signal strengths**

Signal strengths are measured for individual or combinations of stage-1 processes. Parameters are combined when the per-process sensitivity is poor and when there are large correlations between several processes because of reconstruction resolution effects. We measure stage-1 signal strengths for 2 merging schemes, corresponding to different combinations of stage-1 processes. In each case, the signal strengths or the merged processes are fitted simultaneously. In the first scheme, the $ggH$ and $qqH$ productions are always treated separately, and the following processes are fitted simultaneously:

- $qqH$ non-VBF topology: $qqH$ events with less than 2 jets or $m_{jj} < 350$ GeV;
- $qqH$ medium $m_{jj}$: $qqH$ events with $p_T^H < 200$ GeV, at least 2 jets and $350 < m_{jj} < 700$ GeV;
- $qqH$ high $m_{jj}$: $qqH$ events with $p_T^H < 200$ GeV, at least 2 jets and $m_{jj} > 700$ GeV;
9. Results

- qqH BSM: qqH events with $p_T^H > 200$ GeV;
- $\text{ggH} > 1$ jet: ggH events with at least 2 jets and $p_T^H < 200$ GeV;
- $\text{ggH} 200 < p_T^H < 300$ GeV: ggH events with $200 < p_T^H < 300$ GeV;
- $\text{ggH} p_T^H > 300$ GeV: ggH events with $p_T^H > 300$ GeV;
- ggH 0 jet: ggH events with $p_T^H < 200$ GeV and 0 jet;
- ggH 1 jet low $p_T$: ggH events with 1 jet and $p_T^H < 60$ GeV;
- ggH 1 jet medium $p_T$: ggH events with 1 jet and 60 < $p_T^H <$ 120 GeV;
- ggH 1 jet high $p_T$: ggH events with 1 jet and 120 < $p_T^H <$ 200 GeV.

In the second scheme, the ggH and qqH productions are tied together for events with a VBF-like topology, consisting of two jets with a large invariant mass, resulting in the following set of processes:

- qqH non-VBF topology: qqH events with less than 2 jets or $m_{jj} < 350$ GeV;
- Medium $m_{jj}$: qqH and ggH events with $p_T^H < 200$ GeV, at least 2 jets and $350 < m_{jj} < 700$ GeV;
- High $m_{jj}$: qqH and ggH events with $p_T^H < 200$ GeV, at least 2 jets and $m_{jj} > 700$ GeV;
- qqH BSM: qqH events with $p_T^H > 200$ GeV;
- ggH low $m_{jj}$: ggH events with at least 2 jets with $m_{jj} < 350$ GeV and $p_T^H < 200$ GeV;
- $\text{ggH} 200 < p_T^H < 300$ GeV: ggH events with $200 < p_T^H < 300$ GeV;
- $\text{ggH} p_T^H > 300$ GeV: ggH events with $p_T^H > 300$ GeV;
- ggH 0 jet: ggH events with $p_T^H < 200$ GeV and 0 jet;
- ggH 1 jet low $p_T$: ggH events with 1 jet and $p_T^H < 60$ GeV;
- ggH 1 jet medium $p_T$: ggH events with 1 jet and 60 < $p_T^H <$ 120 GeV;
- ggH 1 jet high $p_T$: ggH events with 1 jet and 120 < $p_T^H <$ 200 GeV.

Both merging schemes can be visualized in Figs. 1 and 2. The correlations between the signal strengths of the various STXS parameters in the process-based stage-1 merged scheme are shown in Fig. 11.

The resulting best-fit signal strengths for these processes, as determined from a simultaneous binned maximum likelihood fit, are shown in Fig. 12 for the two merging schemes. Because of the larger integrated luminosity analyzed with respect to previous analyses in the $\tau\tau$ final state, and therefore lower impact of the statistical uncertainty, the signal strengths of stage-1 processes have been measured with a finer granularity, and show a particularly good sensitivity to Higgs bosons produced with high $p_T$ or produced in association with jets, for example in VBF topologies. Stage-1 signal strength measurements are dominated by statistical uncertainty.

The product of the production cross section and branching fraction to $\tau$ leptons is extracted in a similar way as the signal strengths for the stage-0, and stage-1 Higgs boson production, except that theoretical uncertainties in the cross section and branching fraction predictions are not included. The measured cross sections are given in Table 5 for the inclusive and stage-0 processes, and in Tables 6–7 for the stage-1 processes in the different merging schemes. A summary of the products of production cross section $\sigma$ and branching fraction $B(H \rightarrow \tau\tau)$ for
the inclusive, stage-0, and stage-1 STXS processes is given in Fig. 13.

Table 5: Product of the production cross section $\sigma$ and branching fraction $\mathcal{B}(H \rightarrow \tau\tau)$ measured for the inclusive and stage-0 processes.

<table>
<thead>
<tr>
<th>Process</th>
<th>Measured (fb)</th>
<th>SM Prediction (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclusive</td>
<td>2960$^{+394}_{-370}$</td>
<td>3422$^{+172}_{-172}$</td>
</tr>
<tr>
<td>ggH</td>
<td>3060$^{+392}_{-352}$</td>
<td>3051$^{+160}_{-160}$</td>
</tr>
<tr>
<td>qqH</td>
<td>221$^{+9.67}_{-73.3}$</td>
<td>329$^{+9.67}_{-5.67}$</td>
</tr>
</tbody>
</table>

A likelihood scan is performed for $m_H = 125.09$ GeV in the $(\kappa_V, \kappa_f)$ parameter space, where $\kappa_V$ and $\kappa_f$ quantify, respectively, the ratio between the measured and the SM value for the couplings of the Higgs boson to vector bosons and fermions, with the methods described in Ref. [56]. All nuisance parameters are profiled for each point of the scan. As shown in Fig. 14 (left), the observed likelihood contour is consistent within one standard deviation with the SM expectation of $\kappa_V$ and $\kappa_f$ equal to unity. Fig. 14 (right) shows a scan of the negative log-likelihood difference as a function of the signal strengths for the ggF and VBF productions. In this scan the VH production is constrained to the SM prediction, for both leptonic and hadronic decays of the vector boson. In both scans, decays of the Higgs boson to other particles than $\tau$ leptons are treated as a background, and the best-fit value observed is about one standard deviation away from the predictions of the SM.
10. Summary

A measurement of the $H \to \tau\tau$ signal strength, using events recorded in proton-proton collisions by the CMS experiment at a center-of-mass energy of 13 TeV and corresponding to an integrated luminosity of 137 fb$^{-1}$, has been presented. The event categories are designed to increase the signal sensitivity, to separate the gluon fusion and vector boson fusion productions, and to provide sensitivity to the simplified template cross section framework, especially at high Higgs boson $p_T$ and in event topologies with jets. The results are extracted via maximum likelihood fits in two-dimensional distributions. All results are compatible with the standard model expectation. The best fit of the product of the observed $H \to \tau\tau$ signal production cross...
Table 6: Product of the production cross section $\sigma$ and branching fraction $B(H \to \tau\tau)$ measured in the process-based merging scheme.

<table>
<thead>
<tr>
<th>Process</th>
<th>Measured (fb)</th>
<th>SM Prediction (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>qqH non-VBF topology</td>
<td>$374^{+252}_{-515}$</td>
<td>$209^{+6.11}_{-6.11}$</td>
</tr>
<tr>
<td>qqH medium $m_{jj}$</td>
<td>$-18.9^{+45.8}_{-46.0}$</td>
<td>$34.4^{+0.909}_{-0.909}$</td>
</tr>
<tr>
<td>qqH high $m_{jj}$</td>
<td>$32.9^{+17.7}_{-17.3}$</td>
<td>$47.5^{+1.80}_{-1.80}$</td>
</tr>
<tr>
<td>qqH BSM</td>
<td>$6.41^{+4.40}_{-4.17}$</td>
<td>$9.90^{+0.339}_{-0.339}$</td>
</tr>
<tr>
<td>ggH &gt; 1 jet</td>
<td>$19.0^{+251}_{-271}$</td>
<td>$306^{+70.3}_{-70.3}$</td>
</tr>
<tr>
<td>ggH $200 &lt; p_T^H &lt; 300$ GeV</td>
<td>$24.2^{+24.3}_{-24.5}$</td>
<td>$27.5^{+11.5}_{-11.5}$</td>
</tr>
<tr>
<td>ggH $p_T^H &gt; 300$ GeV</td>
<td>$13.0^{+7.90}_{-8.64}$</td>
<td>$7.19^{+3.36}_{-3.36}$</td>
</tr>
<tr>
<td>ggH 0 jet</td>
<td>$-964^{+792}_{-759}$</td>
<td>$1753^{+160}_{-160}$</td>
</tr>
<tr>
<td>ggH 1 jet low $p_T$</td>
<td>$-756^{+510}_{-510}$</td>
<td>$451^{+63.2}_{-63.2}$</td>
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<td>ggH 1 jet med $p_T$</td>
<td>$1010^{+264}_{-261}$</td>
<td>$288^{+40.9}_{-40.9}$</td>
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<tr>
<td>ggH 1 jet high $p_T$</td>
<td>$99.1^{+35.9}_{-47.1}$</td>
<td>$50.0^{+11.5}_{-11.5}$</td>
</tr>
</tbody>
</table>

Table 7: Product of the production cross section $\sigma$ and branching fraction $B(H \to \tau\tau)$ measured for the stage-1 processes in the topology-based merging scheme.

<table>
<thead>
<tr>
<th>Process</th>
<th>Measured (fb)</th>
<th>SM Prediction (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>qqH non-VBF topology</td>
<td>$374^{+252}_{-515}$</td>
<td>$209^{+6.11}_{-6.11}$</td>
</tr>
<tr>
<td>qqH medium $m_{jj}$</td>
<td>$-18.9^{+45.8}_{-46.0}$</td>
<td>$34.4^{+0.909}_{-0.909}$</td>
</tr>
<tr>
<td>qqH high $m_{jj}$</td>
<td>$32.9^{+17.7}_{-17.3}$</td>
<td>$47.5^{+1.80}_{-1.80}$</td>
</tr>
<tr>
<td>qqH BSM</td>
<td>$6.41^{+4.40}_{-4.17}$</td>
<td>$9.90^{+0.339}_{-0.339}$</td>
</tr>
<tr>
<td>ggH &gt; 1 jet</td>
<td>$19.0^{+251}_{-271}$</td>
<td>$306^{+70.3}_{-70.3}$</td>
</tr>
<tr>
<td>ggH $200 &lt; p_T^H &lt; 300$ GeV</td>
<td>$24.2^{+24.3}_{-24.5}$</td>
<td>$27.5^{+11.5}_{-11.5}$</td>
</tr>
<tr>
<td>ggH $p_T^H &gt; 300$ GeV</td>
<td>$13.0^{+7.90}_{-8.64}$</td>
<td>$7.19^{+3.36}_{-3.36}$</td>
</tr>
<tr>
<td>ggH 0 jet</td>
<td>$-964^{+792}_{-759}$</td>
<td>$1753^{+160}_{-160}$</td>
</tr>
<tr>
<td>ggH 1 jet low $p_T$</td>
<td>$-756^{+510}_{-510}$</td>
<td>$451^{+63.2}_{-63.2}$</td>
</tr>
<tr>
<td>ggH 1 jet med $p_T$</td>
<td>$1010^{+264}_{-261}$</td>
<td>$288^{+40.9}_{-40.9}$</td>
</tr>
<tr>
<td>ggH 1 jet high $p_T$</td>
<td>$99.1^{+35.9}_{-47.1}$</td>
<td>$50.0^{+11.5}_{-11.5}$</td>
</tr>
</tbody>
</table>

section and branching fraction is $\mu = 0.85^{+0.12}_{-0.11}$ times the standard model expectation, which corresponds to a significant improvement in precision with respect to previous measurements performed in the final state of two $\tau$ leptons. Cross sections and signal strengths have also been measured in the simplified template cross section framework, providing strong constraints and a good agreement with the standard model in topologies with jets and with Higgs bosons with a large transverse momentum.
Figure 13: Products of the cross section and branching fraction measured for the inclusive, stage-0, and stage-1 parameters. The top plot corresponds to the process-based stage-1 merging, and the bottom plot to the topology-based stage-1 merging. The ggH processes are indicated in blue while the qqH are indicated in yellow, the green squares can contain both ggH and qqH processes as they are solely based on topology.
Figure 14: Scan of the negative log-likelihood difference as a function of $\kappa_V$ and $\kappa_f$ (left) and the signal strengths for the ggF and VBF productions (right), for $m_H = 125.09$ GeV. All nuisance parameters are profiled for each point.
References


References


[54] CMS Collaboration, “Measurements of t$\bar{t}$H production and the CP structure of the Yukawa interaction between the higgs boson and top quark in the diphoton decay channel”, arXiv:2003.10866. Submitted to PRL.
