Constraints on anomalous HVV couplings in the production of Higgs bosons decaying to tau lepton pairs

The CMS Collaboration

Abstract

A study of anomalous HVV interactions of the Higgs boson and its CP properties is presented. The study uses Higgs boson candidates produced in vector boson fusion, WH and ZH processes and subsequently decaying to a pair of tau leptons. The data were recorded by the CMS experiment at the LHC at a center-of-mass energy of 13 TeV and correspond to an integrated luminosity of 35.9 fb\(^{-1}\). A matrix element technique is employed for optimal analysis of four types of anomalous interactions. Constraints are further improved by combination of the \(H \rightarrow \tau\tau\) and \(H \rightarrow 4\ell\) decay channels resulting in the most stringent constraints on anomalous Higgs boson couplings to date: 

\[
\begin{align*}
f_{a3} \cos(\phi_{a3}) &= (0.00 \pm 0.27) \times 10^{-3}, \\
f_{a2} \cos(\phi_{a2}) &= (0.08^{+1.04}_{-0.21}) \times 10^{-3}, \\
f_{\Lambda1} \cos(\phi_{\Lambda1}) &= (0.00^{+0.53}_{-0.09}) \times 10^{-3}, \text{ and } \\
f_{\Lambda1} \cos(\phi_{\Lambda1}^{Z\gamma}) &= (0.0^{+1.1}_{-1.3}) \times 10^{-3}.
\end{align*}
\]

These results are consistent with expectations of the standard model.
1 Introduction

The Higgs boson (H) discovered in 2012 at the LHC has been found to be consistent with expectations from the standard model (SM) [1–7]. Its spin-parity quantum numbers are consistent with $J^{PC} = 0^{++}$ following the studies by the CMS [8–14] and ATLAS [15–20] experiments. It is still to be determined if small anomalous couplings contribute to HVV or $Hff$ interactions, where V stands for the vector bosons and f for the fermions. Because exotic non-zero spin assignments of the Higgs boson have been excluded, we focus on the analysis of couplings of a spin-zero Higgs boson. Previous studies of anomalous HVV couplings were performed by both the CMS and ATLAS experiments using either decay-only information [8–10, 15, 16, 18], including associated production information [12–14, 17, 19, 20], or including off-shell Higgs boson production [11, 14]. In this note, we report a study of HVV couplings using associated production information with the $H \rightarrow \tau \tau$ process. These results are combined with the previous CMS measurements using both associated production and decay information in the $H \rightarrow ZZ \rightarrow 4\ell$ process [14].

The decays of Higgs bosons to pairs of tau leptons ($H \rightarrow \tau \tau$) have been analyzed and observed by the CMS experiment [21], with over 5$\sigma$ significance. The $H \rightarrow \tau \tau$ events can be used to study the quantum numbers of the Higgs boson, including its $CP$ properties, and more generally its anomalous couplings to SM particles. The correlations of the two jets in vector boson fusion (VBF), associated production with a weak vector boson (VH), or gluon fusion production in association with two jets are sensitive to anomalous $HZZ$, $HWW$, $HZ\gamma$, $H\gamma\gamma$, and $Hgg$ couplings, which are the focus of this note. These correlations lead to kinematic effects that can be observed in distributions of particles produced in association with the Higgs boson. To increase sensitivity to these effects, the matrix-element likelihood approach (MELA) is utilized to form optimal observations for the search for anomalous HVV couplings. The analysis is optimized for vector boson fusion production and is not additionally optimized for either VH or gluon fusion production. However, all three production mechanisms are included in the analysis, with a general anomalous coupling parameterization for each case. A study of anomalous $Hff$ couplings in $tH$ or $tqH$ production, and $H\tau \tau$ couplings in the correlation of decay products of two $\tau$ leptons are also possible using di-tau events. However, these are not studied here as more data are needed to reach sensitivity to anomalous Higgs boson decays.

The analysis utilizes the same data and follows closely the event selection and categorization used in [21], which are described in Sections 2 and 3. The phenomenological model and Monte Carlo (MC) simulation are described in Section 4. The kinematic information is extracted in the optimal way using the matrix-element techniques discussed in Section 5. The implementation of the likelihood fit using kinematic information in the events is presented in Section 6. The results are presented and discussed in Section 7 and 8, before the conclusions are drawn in Section 9.

2 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. Within the solenoid volume, there are 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. Forward calorimeters extend the pseudorapidity coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid.
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. [22].

The data samples used in this analysis correspond to an integrated luminosity of 35.9 fb$^{-1}$ collected in Run 2 of the LHC during 2016 at a center-of-mass energy of 13 TeV. The integrated luminosity is measured with an uncertainty of 2.5% using data from the CMS hadron forward calorimeter system and the pixel detector.

### 3 Event Reconstruction and Selection

The analysis uses the same data set, event reconstruction and selection criteria as those used in the analysis leading to the observation of the Higgs boson decay to a pair of $\tau$ leptons [21].

#### 3.1 Event Reconstruction

The reconstruction of observed and simulated events relies on the particle-flow (PF) algorithm [23], which combines the information from the CMS subdetectors to identify and reconstruct the particles emerging from pp collisions. Combinations of these PF objects are used to reconstruct higher-level objects such as jets, $\tau$ candidates, or missing transverse momentum. The vertex with the largest value of summed PF object transverse momentum squared $p_T^2$ is taken to be the primary pp interaction vertex.

Muons are identified with requirements on the quality of the track reconstruction and on the number of measurements in the tracker and the muon systems [24]. Electrons are identified with a multivariate discriminant combining several quantities describing the track quality, the shape of the energy deposits in the ECAL, and the compatibility of the measurements from the tracker and the ECAL [25]. To reject non-prompt or misidentified leptons, an isolation requirement is applied according to the criteria described in [21].

Jets are reconstructed with an anti-$k_T$ clustering algorithm implemented in the FASTJET library [26, 27]. It is based on the clustering of neutral and charged PF objects within a distance parameter of 0.4. Charged PF objects not associated with the primary vertex of the interaction are not considered when building jets. In this analysis, jets are required to have transverse momentum $p_T$ greater than 30 GeV and pseudorapidity, $|\eta|$, less than 4.7, and are separated from the selected leptons by a $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$ of at least 0.5. The combined secondary vertex (CSV) algorithm is used to identify jets that are likely to originate from a b quark ("b jets"). The algorithm exploits track-based lifetime information along with the secondary vertex of the jet to provide a likelihood ratio discriminator for b jet identification. The details of jet-energy and b tagging efficiency corrections are described in [21].

Hadronically decaying $\tau$ leptons are reconstructed with the hadron-plus-strips (HPS) algorithm [28, 29], which is seeded with anti-$k_T$ jets. The HPS algorithm reconstructs $\tau_h$ candidates based on the number of tracks and the number of ECAL strips with energy deposits within the associated $\eta$-$\phi$ plane. The HPS algorithm reconstructs 1-prong, 1-prong + $\pi^0$(s), and 3-prong decay modes. A multivariate (MVA) discriminator [30], including isolation and lifetime information, is used to reduce the rate for quark- and gluon-initiated jets to be identified as $\tau_h$ candidates. Electrons and muons misidentified as $\tau_h$ candidates are suppressed using dedicated criteria based on the consistency between the measurements in the tracker, the calorimeters, and the muon detectors [28, 29]. The $\tau_h$ energy scale as well as the rate and the energy scale of electrons and muons misidentified as $\tau_h$ candidates are corrected in simulation [21].

The missing transverse momentum, $\vec{p}_T^{\text{miss}}$, is defined as the negative vector sum of the trans-
verse momenta of all PF objects [31]. The details of the corrections to $\vec{p}_T^{\text{miss}}$ for the mis-modelling in the simulation of $Z + \text{jets}$, $W + \text{jets}$ and Higgs boson processes are described in Ref. [21].

Both the visible mass of the $\tau\tau$ system, $m_{\text{vis}}$, and the invariant mass of the $\tau\tau$ system, $m_{\tau\tau}$, are used. The observable $m_{\tau\tau}$ is reconstructed using the SVFIT [32] algorithm, which combines the $\vec{p}_T^{\text{miss}}$ and its uncertainty with the four-vectors of both $\tau$ candidates to calculate a more accurate estimate of the mass of the parent boson. The estimate of the four-momentum of the Higgs boson provided by SVFIT, is used to calculate the kinematic observables discussed in Section 5.

3. Event Reconstruction and Selection

Selected events are classified into four decay channels, $e\mu$, $e\tau_\nu$, $\mu\tau_\nu$ and $\tau_\nu\tau_\nu$, according to the number of selected electrons, muons, and $\tau_\nu$ candidates. The resulting event samples are made mutually exclusive by discarding events that have additional loosely identified and isolated muons or electrons.

Electrons, muons, and $\tau_\nu$ candidates 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. Electrons and muons must additionally satisfy $|d_{xy}| < 0.045\text{ cm}$ in the transverse plane from the primary vertex. The two leptons assigned to the Higgs boson decay are required to have opposite charge. The trigger requirements, geometrical acceptances and transverse momentum criteria are summarized in Table 1. The pseudorapidity thresholds come from trigger and object reconstruction constraints. The $p_T$ thresholds for the lepton selection are driven by the trigger requirements, except for the highest $p_T$ $\tau_\nu$ candidate in the $\tau_\nu\tau_\nu$ channel, the $\tau_\nu$ candidate in the $\mu\tau_\nu$ and $e\tau_\nu$ channels, and the muon in the $e\mu$ channel, where the thresholds have been optimized to increase the sensitivity to the $H \to \tau\tau$ signal.

Table 1: Kinematic selection criteria for the four decay channels. For the trigger threshold requirements, the numbers indicate the approximate trigger thresholds in GeV. The lepton selection criteria include transverse momentum threshold, pseudo-rapidity range as well as isolation criteria.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Trigger requirement</th>
<th>Lepton selection</th>
<th>Isolation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_\nu\tau_\nu$</td>
<td>$\tau_\nu(35)$ &amp; $\tau_\nu(35)$</td>
<td>$p_T^{\tau_\nu} &gt; 50$ &amp; $40$ &amp; $</td>
<td>\eta^{\tau_\nu}</td>
</tr>
<tr>
<td>$\mu\tau_\nu$</td>
<td>$\mu(22)$</td>
<td>$p_T^{\mu} &gt; 23$ &amp; $</td>
<td>\eta^{\mu}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$p_T^{\mu} &gt; 30$ &amp; $</td>
<td>\eta^{\mu}</td>
</tr>
<tr>
<td>$\mu(19)$ &amp; $&amp;$ &amp; $\tau_\nu(21)$</td>
<td>$20 &lt; p_T^{\mu} &lt; 23$ &amp; $</td>
<td>\eta^{\mu}</td>
<td>&lt; 2.1$ &amp; $I^{\mu} &lt; 0.15$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$p_T^{\mu} &gt; 30$ &amp; $</td>
<td>\eta^{\mu}</td>
</tr>
<tr>
<td>$e\tau_\nu$</td>
<td>$e(25)$</td>
<td>$p_T^{e} &gt; 26$ &amp; $</td>
<td>\eta^{e}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$p_T^{e} &gt; 30$ &amp; $</td>
<td>\eta^{e}</td>
</tr>
<tr>
<td>$e\mu$</td>
<td>$e(12)$ &amp; $&amp;$ &amp; $\mu(23)$</td>
<td>$p_T^{e} &gt; 13$ &amp; $</td>
<td>\eta^{e}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$p_T^{\mu} &gt; 24$ &amp; $</td>
<td>\eta^{\mu}</td>
</tr>
<tr>
<td>$e(23)$ &amp; $&amp;$ &amp; $\mu(8)$</td>
<td>$p_T^{e} &gt; 24$ &amp; $</td>
<td>\eta^{e}</td>
<td>&lt; 2.5$ &amp; $I^{e} &lt; 0.15$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$p_T^{\mu} &gt; 15$ &amp; $</td>
<td>\eta^{\mu}</td>
</tr>
</tbody>
</table>

In the $\ell\tau_\nu$ channels, the large $W + \text{jets}$ background is reduced by requiring the transverse mass, $m_T$, to be less than 50 GeV. It is defined as follows

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

(1)
where $p_T^\ell$ is the transverse momentum of the electron or muon, $\ell$, and $\Delta \phi$ is the azimuthal angle between the lepton and the $p_T^{\text{miss}}$ directions.

In the same way as in Ref. [21], the event samples are split into three mutually exclusive production categories, described in the following:

- **0-jet category**: This category targets Higgs boson events produced via gluon fusion. Simulations indicate that about 98% of signal events in the 0-jet category arise from the gluon fusion production mechanism.

- **VBF category**: This category targets Higgs boson events produced via the vector boson fusion (VBF) process. Events are selected with at least two (exactly two) jets with $p_T > 30$ GeV in the $\tau_\text{h} \tau_\text{h}$, $\mu \tau_\text{h}$, and $e \tau_\text{h}$ (em) channels. In the $\mu \tau_\text{h}$, $e \tau_\text{h}$, and em channels, the two leading jets are required to have an invariant mass, $m_{JJ}$, larger than 300 GeV. The variable $p_T^{\tau\tau}$, defined as the magnitude of the vector sum of the $p_T$ of the visible decay products of the $\tau$ leptons and $p_T^{\text{miss}}$, is required to be greater than 50 (100) GeV in the $\ell \tau_\text{h}$ ($\ell \tau_\text{h} \tau_\text{h}$) channels. In addition, the $p_T$ threshold on the $\tau_\text{h}$ candidate is raised to 40 GeV in the $\mu \tau_\text{h}$ channel, and the two leading jets in the $\tau_\text{h} \tau_\text{h}$ channel should be separated in pseudorapidity by $\Delta \eta > 2.5$. Integrating over the whole $m_{JJ}$ phase space, up to 57% of the signal events in the VBF category are produced in the VBF production mode. This fraction increases with $m_{JJ}$. Gluon fusion production makes 40-50% of the total signal while the VH contribution is less than 3%.

- **Boosted category**: This category contains all the events that do not enter one of the previous categories, namely events with one jet and events with several jets that fail the requirements of the VBF category. It contains gluon fusion events produced in association with one or more jets (78–80% of signal events), VBF events where one of the jets has escaped detection or has low $m_{JJ}$ (11–13%), as well as Higgs bosons produced in association with a W or a Z boson decaying hadronically (4–8%).

### 3.3 Systematic uncertainties

The systematic uncertainties are identical to those detailed in Ref. [21]. They are summarized in the following.

The uncertainties in the identification, isolation, and trigger efficiencies of muons and electrons amount to 2%. For genuine $\tau_\text{h}$ leptons, the uncertainty in the identification is 5%, whereas the uncertainty related to the trigger amounts to an additional 5% per $\tau_\text{h}$ candidate. In the 0-jet category, the relative contribution of $\tau_\text{h}$ in a given reconstructed decay mode is allowed to fluctuate by 3%. The $\tau_\text{h}$ identification leads to rate uncertainties of 25 and 12%, respectively for muons and electrons misidentified as $\tau_\text{h}$ candidates. Requirement of no b-tagged jets in events in the $e\mu$ decay channel results in up to 5% rate uncertainty for the tt background.

The uncertainties in the energy scale of muons, electrons, and genuine $\tau_\text{h}$ leptons amount to 1, 1–2.5, and 1.2%, respectively. This uncertainty increases to 1.5 and 3% respectively, for muons and electrons misidentified as $\tau_\text{h}$ candidates. For events where quark- or gluon-initiated jets are misidentified as $\tau_\text{h}$ candidates, a linear uncertainty that increases by 20% per 100 GeV in transverse momentum of the hadronically decaying tau lepton is taken into account. Uncertainties in the jet and $p_T^{\text{miss}}$ energy scales are determined event-by-event, and propagated through to the observables used in the analysis.

The uncertainty in the integrated luminosity is 2.5%. Per-bin uncertainties related to the finite
number of simulated events, or to the limited number of events in data control regions, are also taken into account.

The rate and acceptance uncertainties for the signal processes related to the theoretical calculations are due to uncertainties in the PDFs, variations of the QCD renormalization and factorization scales, and uncertainties in the modeling of parton showers. The magnitude of the rate uncertainty depends on the production process and on the event category. The theoretical uncertainty in the branching fraction of the Higgs boson to $\tau$ leptons is 2.1%.

An overall rate uncertainty of 3–10% affects the $Z \rightarrow \tau\tau$ background, depending on the category. Additional uncertainties dependent on $m_{jj}$ and $\Delta\Phi_{jj}$, reaching up to 20%, are taken into account. In addition to the uncertainties related to the $W + \text{jets}$ control regions in the $\mu\tau$ and $e\tau$ final states, the $W + \text{jets}$ background is affected by an uncertainty ranging between 5 and 10% to account for the extrapolation of the constraints from the high-$m_T$ to the low-$m_T$ regions. In the $e\mu$ and $\tau\tau$ final states, the uncertainty in the $W + \text{jets}$ background yield is 20 and 4%, respectively.

The uncertainty in the QCD multijet background yield in the $e\mu$ decay channel ranges from 10 to 20%, depending on the category. In the $\mu\tau$ and $e\tau$ decay channels, uncertainties from the fit of the control regions are considered for the QCD multijet background, together with an additional 20% uncertainty that accounts for the extrapolation from the relaxed-isolation control region to the isolated signal region. In the $\tau_h\tau_h$ decay channel, the uncertainty in the QCD multijet background yield is a combination of the uncertainties obtained from fitting the dedicated control regions with $\tau_h$ candidates passing relaxed isolation criteria, and of extrapolation uncertainties to the signal region ranging from 3 to 15% and accounting for residual differences between prediction and data in signal-free regions with various loose isolation criteria.

The uncertainty from the fit in the $t\bar{t}$ control region results in an uncertainty of about 5% on the $t\bar{t}$ cross section in the signal region. The combined systematic uncertainty in the background yield arising from diboson and single top quark production processes is taken to be 5%.

### 4 Phenomenology of Anomalous Couplings and Simulation

We follow the formalism used in the study of anomalous couplings in the earlier analyses by CMS [8–14]. The theoretical background is described in Refs. [33–45]. Anomalous interactions of a spin-zero Higgs boson with two spin-one gauge bosons $VV$, such as $ZZ$, $Z\gamma$, $\gamma\gamma$, $WW$, and $gg$ are parameterized by a scattering amplitude that includes three tensor structures with expansion of coefficients up to $(q^2/\Lambda^2)$:

$$A(HVV) \sim \left[ a_{1}^{VV} + \frac{\kappa_{1}^{VV} q_{1}^2 + \kappa_{2}^{VV} q_{2}^2}{(\Lambda_{1}^{VV})^2} \right] m_{V1} e_{V1}^* e_{V2}^* + a_{2}^{VV} f_{\mu\nu}^{(1)} f_{\mu\nu}^{(2)} + a_{3}^{VV} f_{\mu\nu}^{(1)} f_{\mu\nu}^{(2)} + \text{terms} \right),$$  \quad (2)

where $q_{1}, e_{V1}$, and $m_{V1}$ are the four-momentum, polarization vector, and pole mass of a gauge boson, the field strength tensor of a gauge boson is $f_{\mu\nu}^{(1)} = \epsilon^{\mu\nu\rho\sigma} f_{\rho\sigma}$, $f_{\mu\nu}^{(2)} = \frac{1}{2} \epsilon_{\mu\nu\rho\sigma} f_{\rho\sigma}$, $\Lambda_{1}$ is the scale of beyond the standard model (BSM) physics, and $a_{1}^{VV}$ and $\kappa_{1}^{VV}/(\Lambda_{1}^{VV})^2$ are parameters to be determined from data.

In Eq. (2), the SM contributions at tree-level are $a_{1}^{ZZ} = a_{1}^{WW} \neq 0$, where we assume custodial symmetry $a_{1}^{ZZ} = a_{1}^{WW}$. All other ZZ and WW couplings are considered anomalous contributions, which are either small contributions arising in the SM due to loop effects or new BSM contributions. Among the anomalous contributions, considerations of symmetry and gauge
invariance require \( \kappa^{ZZ}_{\gamma} = \kappa^{ZZ}_{\gamma} = -\exp(i\phi^{ZZ}_{\gamma}), \kappa^{\gamma\gamma}_{\gamma} = \kappa^{\gamma\gamma}_{\gamma} = 0, \kappa^{gg}_{g} = \kappa^{gg}_{g} = 0, \kappa^{Z\gamma}_{\gamma} = 0 \) and
\( \kappa^{Z\gamma}_{\gamma} = -\exp(i\phi^{Z\gamma}_{\gamma}), \) where \( \phi^{VV}_{\gamma} \) is the phase of the corresponding coupling. In the case of \( \gamma\gamma \) and \( gg \) couplings the only contributing terms are \( a^{\gamma\gamma}_{1} \) and \( a^{\gamma\gamma}_{3} \). The precision of the constraints on \( a^{\gamma\gamma}_{1} \) and \( a^{\gamma\gamma}_{3} \) is still not competitive with on-shell photon measurements in \( H \to Z\gamma \) and \( H \to \gamma\gamma \) [10]. We therefore omit those measurements in this note. The coupling \( a^{gg}_{3} \) refers to SM-like contribution in the gluon fusion process, and \( a^{gg}_{3} \) corresponds to a CP-odd anomalous contribution. There are four other anomalous couplings targeted in this analysis, two from the first term of Eq. (2), \( \Lambda^{ZZ}_{1} = \Lambda^{WW}_{1} = \Lambda_{1} \) and \( \Lambda^{Z\gamma}_{1} \), one coming from the second tensor, \( a^{ZZ}_{2} = a^{WW}_{2} = a_{2} \), and one coming from the third term, \( a^{ZZ}_{3} = a^{WW}_{3} = a_{3} \). As the event kinematics in the Higgs boson production in \( WW \) fusion and in \( ZZ \) fusion are very similar, they are analyzed together assuming \( a^{ZZ}_{1} = a^{WW}_{1} \). The results can be reinterpreted for any other relationship between the \( a^{ZZ}_{1} \) and \( a^{WW}_{1} \) couplings [14]. The \( a_{3} \) coupling corresponds to the CP-odd amplitude and its presence together with a CP-even amplitude would signify CP violation.

It is convenient to measure the effective cross-section ratios \( f_{ai} \) rather than the anomalous couplings \( a_{i} \), themselves, as in the ratio most uncertainties cancel. Moreover, the effective fractions are conveniently bounded between 0 and 1, independently of the coupling convention. The effective fractional cross sections \( f_{ai} \) and phases \( \phi_{ai} \) are defined as follows:

\[
\begin{align*}
 f_{a3} &= \frac{|a_{3}|^{2} |\sigma_{3}|}{|a_{1}|^{2} |\sigma_{1}| + |a_{2}|^{2} |\sigma_{2}| + |a_{3}|^{2} |\sigma_{3}| + \tilde{\sigma}_{A1} / (\Lambda_{1})^{4} + \ldots}, & \phi_{a3} &= \arg \left( \frac{a_{3}}{a_{1}} \right), \\
 f_{a2} &= \frac{|a_{2}|^{2} |\sigma_{2}|}{|a_{1}|^{2} |\sigma_{1}| + |a_{2}|^{2} |\sigma_{2}| + |a_{3}|^{2} |\sigma_{3}| + \tilde{\sigma}_{A1} / (\Lambda_{1})^{4} + \ldots}, & \phi_{a2} &= \arg \left( \frac{a_{2}}{a_{1}} \right), \\
 f_{A1} &= \frac{\tilde{\sigma}_{A1} / (\Lambda_{1})^{4}}{|a_{1}|^{2} |\sigma_{1}| + |a_{2}|^{2} |\sigma_{2}| + |a_{3}|^{2} |\sigma_{3}| + \tilde{\sigma}_{A1} / (\Lambda_{1})^{4} + \ldots}, & \phi_{A1}, \\
 f^{Z\gamma}_{A1} &= \frac{\tilde{\sigma}_{A1} / (\Lambda_{1})^{4}}{|a_{1}|^{2} |\sigma_{1}'| + \tilde{\sigma}_{A1} / (\Lambda_{1})^{4} + \ldots}, & \phi_{A1}^{Z\gamma},
\end{align*}
\]

where \( \sigma_{i} \) is the cross section of the process corresponding to \( a_{i} = 1 \), and all other couplings are set to zero. The effective fractional cross section for the anomalous \( HZ\gamma \) coupling is defined with the requirement \( \sqrt{q_{Vi}^{2}} \geq 4 \text{ GeV} \) for all processes, including the \( ZZ \) tree-level process with \( a_{1} \), in which case the cross section is \( \sigma'_{1} \) for \( a_{1} = 1 \). This requirement on \( q_{Vi}^{2} \) is introduced to restrict the definition to a region without infrared divergence. Since the production cross sections depend on parton density functions, the definition with respect to the decay process is more convenient. The cross-section ratios defined in the \( H \to 2e2\mu \) decay analysis [9] are adopted. Their values are: \( \sigma_{1}/\sigma_{3} = 6.53, \sigma_{1}/\sigma_{2} = 2.77, (\sigma_{1}/\sigma_{A1}) \times \text{TeV}^{4} = 1.47 \times 10^{4}, \) and \( (\sigma_{1}'/\sigma_{A1}') \times \text{TeV}^{4} = 5.80 \times 10^{3} \), as calculated using JHUGEN 7.0.2 [37, 39, 42, 45].

Anomalous effects in the \( H \to \tau\tau \) decay and \( tH \) production are described by the \( Hff \) couplings of the Higgs boson to fermions, with generally two couplings \( \kappa_{f} \) and \( \kappa_{f} \), CP-even and CP-odd, respectively. Similarly, if the gluon fusion coupling \( Hg \) is dominated by the top quark loop, it can be described with the \( \kappa_{t} \) and \( \bar{\kappa}_{t} \) parameters. However, since other heavy states may contribute to the loop, we adopt a more general coupling parameterization given in Eq. (2). In particular, the effective cross section fraction in gluon fusion becomes

\[
f^{gH}_{a3} = \frac{|a_{3}^{gH}|^{2}}{|a_{2}^{gH}|^{2} + |a_{3}^{gH}|^{2}}.
\]
Experimentally observable effects resulting from the above anomalous couplings are discussed in the next section. In this note, anomalous HWW, HZZ, HZγ couplings are considered in VBF and VH production, and anomalous Hgg couplings in gluon fusion. Since CP-violating effects in electroweak (VBF and VH) and gluon fusion production modify the same kinematic distributions, both CP-violating parameters, \( f_{a3} \) and \( f_{gH}^{a3} \), are floated unconstrained simultaneously. It has been checked that potential CP violation in \( H \rightarrow \tau \tau \) decay does not affect these measurements.

Following the formalism discussed in this section, simulated samples of Higgs boson events produced via anomalous HVV couplings (VBF, VH, gluon fusion in association with two jets) are generated using the generator JHUGEN 7.0.2 [37, 39, 42, 45]. The associated production in gluon fusion with two jets is affected by anomalous interactions, while the kinematics of the production with zero or one jets are not affected. The latter events are generated with POWHEG [46–49]. For the kinematics relevant to this analysis in VBF and VH production, the effects that appear at next-to-leading order (NLO) in quantum chromodynamics (QCD) are well approximated by the leading order (LO) QCD matrix elements used in JHUGEN, combined with parton showering. The JHUGEN samples produced with the SM coupling are compared with the equivalent samples generated by the POWHEG event generator at NLO QCD, with parton showering applied in both cases, and the kinematic distributions are found to agree.

The generator PYTHIA 8.212 [50] is used to model the Higgs boson decay to \( \tau \) leptons, the decays of the \( \tau \) leptons, as well as parton showering and fragmentation. Both scalar and pseudoscalar \( H \rightarrow \tau \tau \) decays, and their interference, have been modeled to confirm that the analysis does not depend on the decay model. The default samples are generated with the scalar hypothesis in decay. The parton distribution functions (PDF) used in this note are NNPDF30 [51]. All MC samples are further processed through a dedicated simulation of the CMS detector based on GEANT4 [52].

To simulate processes with anomalous Higgs boson couplings, for each type of anomalous coupling we generate events with both the pure anomalous term and its interference with the SM contribution in the production HVV interaction. This allows extraction of various coupling components and their interference. The MELA package [37, 39, 42, 45, 53], based on JHUGEN matrix elements allows application of weights to events in any sample to model any other HVV or Hff couplings with the same production mechanism. Re-weighting allows one to increase statistics using all samples at once and to cover any model even if it has not been simulated. The MELA package also allows calculation of optimal discriminants for further analysis, as discussed in Section 5.

Simulated samples for the modeling of background processes and of the Higgs signal processes with SM couplings are the same as those used for the observation of the Higgs boson decay to a pair of \( \tau \) leptons [21].

### 5 Discriminant Distributions

Full kinematic information for both production and decay of the H boson can be extracted for each event. This note focuses on the production process, illustrated in Fig. 1.

The kinematic distributions of associated particles in VBF and VH production provide sensitivity to the quantum numbers and anomalous couplings of the Higgs boson. A set of observables could be defined in associated production, such as \( \bar{\Omega} = \{ \theta_1, \theta_2, \Phi, \phi^*, \Phi_1, \eta_1^2, q_1^2 \} \) for the VBF or VH process with the angles illustrated in Fig. 1 and the \( q_1^2 \) and \( q_2^2 \) discussed in reference to
Figure 1: Illustrations of H production in strong $qq' \rightarrow gg(qq') \rightarrow H(qq') \rightarrow \tau\tau(qq')$ or weak vector boson fusion $qq' \rightarrow V^*V^*(qq') \rightarrow H(qq') \rightarrow \tau\tau(qq')$ (left) and $qq' \rightarrow V^* \rightarrow VH \rightarrow qq'\tau\tau$ (right). The decay $H \rightarrow \tau\tau$ is shown without further illustrating the $\tau$ decay chain. Angles and invariant masses fully characterize the orientation of the production and two-body decay chain and are defined in suitable rest frames [37, 42].

Eq. (2), as described in detail in Ref. [42]. It is, however, a challenging task to perform an optimal analysis in a multidimensional space of observables. Here, the matrix element likelihood approach (MELA) is applied. The MELA approach is designed to reduce the number of observables to the minimum, while retaining all essential information. Two types of discriminants are used. One type of discriminant is designed to separate the process with anomalous couplings, denoted as BSM, from the SM signal process:

$$D_{BSM} = \frac{P_{SM}(\hat{\Omega})}{P_{SM}(\hat{\Omega}) + P_{BSM}(\hat{\Omega})}. \quad (5)$$

This discriminant is denoted as $D_{0-}$, $D_{0h}$, $D_{A1}$, or $D_{Z1}^{Z}$, depending on the targeted anomalous coupling $a_3$, $a_2$, $A_1$ or $Z_1^{Z}$ respectively.

The second type of discriminant isolates the interference contribution:

$$D_{int} = \frac{P_{int}^{SM-BSM}(\hat{\Omega})}{P_{SM}(\hat{\Omega}) + P_{BSM}(\hat{\Omega})} \quad (6)$$

where this discriminant is only used for the CP-odd amplitude analysis with $f_3$ and is then denoted $D_{CP}$ in the rest of the note. In the cases of $f_3$ and $f_3^{Z1}$, the interference discriminants do not carry additional information due to their high correlation with the $D_{A1}$ and $D_{Z1}^{Z}$ discriminants. The $f_2$ interference discriminant is not used in this analysis either, as it only becomes important for measurements of smaller couplings with larger data samples and because of the limited statistics available for background parameterization. The discriminant $D_{CP}$ is used with consideration of symmetry as discussed below. In the above, $P$ is the probability for the process (either SM or BSM signal, or background), $P_{int}^{SM-BSM}$ is the interference probability distribution for a mixture of the SM and BSM contributions. The probabilities are normalized such that the matrix elements give the same cross sections for $f_3 = 0$ or 1 in the relevant phase space of each process. Such normalization leads to an optimal population of events in the range between 0 and 1 of the $D_{BSM}$ discriminants.
6. Analysis Implementation

The two observables in Eqs. (5) and (6) rely only on signal matrix elements and are well-defined. One can apply the Neyman-Pearson lemma to prove that these are the minimal and complete set of optimal observables [42, 45] for the measurement of the $f_{a3}$ parameters.

Kinematic distributions of associated particles in gluon fusion production are also sensitive to the quantum numbers of the Higgs boson and to anomalous Hgg couplings. A set of observables, $\Omega^{\text{assoc}}$, identical to those from the VBF process also describes this process. In this analysis, the focus is on the VBF-enhanced phase space in which the selection efficiency for the gluon fusion process is relatively small. The optimal VBF observables used in this analysis are also found to provide smaller separation between $CP$-even and $CP$-odd components of Higgs boson couplings in gluon fusion production compared to the MELA discriminants dedicated to the gluon fusion process. Nonetheless, both parameters sensitive to $CP$ violation, $f_{a3}$ and $f_{a3}^{ggH}$, are included in a simultaneous fit to avoid any possible bias.

It is worth noting that while the correlation of the two jets and the Higgs boson provides the primary information about $CP$ violation and anomalous couplings in electroweak production (VBF and VH), there are other kinematic features that facilitate this analysis. For example, even in cases where both jets lie outside of the detector acceptance, the distribution of the transverse momentum of the Higgs boson is different between the SM and BSM scenarios of electroweak production. This leads to different event populations across the three tagging categories and to a different distribution of the $p_T$ observable in the boosted category. For example, the fraction of signal events is much smaller in the 0-jet category and the $p_T$ distribution is significantly higher in the boosted category for pseudoscalar Higgs boson production than it is for the SM case. Such effects are, however, negligible in gluon fusion production, where both scalar and pseudoscalar Hgg couplings are generated by higher-dimension operators.

Other observables, such as $\Delta \Phi_{JJ}$ [33] defined as the azimuthal difference between the two associated jets, have been suggested for the study of $CP$ effects. While they do provide sensitivity to $CP$ measurements, they are not as sensitive as the discriminant variables for VBF production used in this analysis. Nonetheless, as an alternative to the optimal VBF analysis, we have also performed a cross-check analysis where the $\Delta \Phi_{JJ}$ observable is used in place of the MELA discriminants discussed above. It has been verified that the expected precision on $f_{a3}$ is indeed lower than in the optimal VBF analysis. On the other hand, the sensitivity of the $\Delta \Phi_{JJ}$ observable to the $f_{a3}^{ggH}$ parameter is better than that of the VBF-discriminants, and it is close but not as high as with the optimal MELA observables targeting gluon fusion topology in association with two jets. Both results are discussed in Section 7.

6 Analysis Implementation

Four anomalous HVV coupling parameters defined in Section 4 are studied: $f_{a3}$, $f_{a2}$, $f_{\Lambda 1}$, and $f_{\Lambda 1}^{Z \gamma}$, describing anomalous couplings in VBF and VH production. Anomalous couplings in other production mechanisms and in the $H \rightarrow \tau\tau$ decay do not affect these measurements, as the distributions studied here are either insensitive to such effects or, in the case of gluon fusion production, $CP$ violation effects are studied jointly.

The data, represented by a set of observables $\bar{x}$, is used to set constraints on anomalous coupling parameters. The coupling parameters are discussed in detail in Section 4, and in the case of a $CP$ study these are $f_{a3}$ and $\phi_{a3}$. We also consider the scalar anomalous couplings described by $f_{a2}$ and $\phi_{a2}$; $f_{\Lambda 1}$ and $\phi_{\Lambda 1}$; $f_{\Lambda 1}^{Z \gamma}$ and $\phi_{\Lambda 1}^{Z \gamma}$. Since only real couplings are considered, we fit for the product $f_{a3} \cos \phi_{a3}$ with $\cos \phi_{a3} = \pm 1$, $f_{a2} \cos \phi_{a2}$ with $\cos \phi_{a2} = \pm 1$, $f_{\Lambda 1} \cos \phi_{\Lambda 1}$ with
\[ \cos \phi_{A1} = \pm 1, \text{ and } f_{A1}^Z \cos \phi_{A1}^Z \text{ with } \cos \phi_{A1}^Z = \pm 1. \]

### 6.1 Observable distributions

For each event \( j \) in category \( k \) observables \( \vec{x}_k^j \) are defined. In the 0-jet and boosted categories, which are dominated by the gluon fusion production mechanism, the observables are identical to those used in Ref. [21]. There are no dedicated observables sensitive to anomalous couplings in these categories, as it is not possible to construct them in the absence of a correlated jet pair.

In Figs. 2 and 3 the distributions of \( m_{\text{vis}} \) and \( m_{\tau\tau} \) are displayed for selected events in the 0-jet category, and the transverse momentum distribution of the Higgs boson is shown for the boosted category. Anomalous couplings result in higher transverse momentum of the Higgs boson and, unlike SM production, cause the events to preferentially populate the boosted category instead of the one with no jets in the final state. In Figs. 2 and 3, the contribution from the \( e\mu \) channel is omitted because of different binning and low sensitivity. The normalization of the predicted background distributions corresponds to the result of the global fit as described in the following. In all production modes in Figs. 2 and 3, the \( H \rightarrow \tau\tau \) process is normalized to its best fit signal strength and couplings, and is stacked on the background histograms. The background components labeled in the figures as “Others” include events from diboson and single top quark production, as well as Higgs boson decays to W boson pairs. The uncertainty band accounts for all sources of uncertainty. The SM prediction for the VBF \( H \rightarrow \tau\tau \) signal, multiplied by a factor 5000 (300) in Fig. 2 (Fig. 3), is shown as a red open overlaid histogram. The black open overlaid histogram represents a BSM hypothesis for the VBF \( H \rightarrow \tau\tau \) signal, normalized to 5000 (300) times the predicted SM cross section in Fig. 2 (Fig. 3).

In Figs. 4 – 8 the discriminant distributions in the VBF category are displayed. In the VBF category, a three- or four-dimensional analysis is performed for each of the four parameters. The observables \( \vec{x}_j^{\text{VBF}} = \{ m_{JJ}, m_{\tau\tau}, D_{0\pm}, D_{CP} \} \) are used to determine the \( f_{a3} \) parameter, \( \vec{x}_j^{\text{VBF}} = \{ m_{JJ}, m_{\tau\tau}, D_{0h+} \} \) for the \( f_{a2} \) parameter, \( \vec{x}_j^{\text{VBF}} = \{ m_{JJ}, m_{\tau\tau}, D_{A1} \} \) for the \( f_{A1} \) parameter, and \( \vec{x}_j^{\text{VBF}} = \{ m_{JJ}, m_{\tau\tau}, D_{A1}^{Z\gamma} \} \) for the \( f_{Z\gamma}^A \) parameter, as defined in Eqs. (5) and (6). In order to keep the background and signal templates sufficiently populated, a smaller number of bins is chosen for \( m_{JJ} \) and \( m_{\tau\tau} \) compared to Ref. [21]. It was found that four bins in \( D_{0\pm} \), \( D_{0h+} \), \( D_{A1} \), and \( D_{A1}^{Z\gamma} \) are sufficient for close-to-optimal performance. At the same time, we adopt two bins in \( D_{CP} \) with \( D_{CP} < 0 \) and \( D_{CP} > 0 \). This choice does not lead to the need for additional bins in the templates because all distributions, except the interference component, are symmetric in \( D_{CP} \) and this symmetry is enforced in the templates. A forward-backward asymmetry in \( D_{CP} \) would be a clear indication of \( CP \) violation and is present only in the signal interference template. Since this symmetry consideration is not possible in the \( f_{a2} \) analysis and there is a limit on the number of bins that we can use, the \( f_{a2} \) interference discriminant is not used in this analysis. Interference will become more important when smaller couplings are tested using larger data samples.
Figure 2: The distribution of \( m_{\text{vis}} \) and \( m_{\tau\tau} \) in the 0-jet category of the \( \mu\tau_h + e\tau_h \) (left) and \( \tau_h\tau_h \) (right) decay channels. The BSM hypothesis corresponds to \( f_{a3} \cos \phi_{a3} = 1 \).

Figure 3: The distribution of transverse momentum of the Higgs boson in the boosted category of the \( \mu\tau_h + e\tau_h + \mu \) (left) and \( \tau_h\tau_h \) (right) decay channels. The BSM hypothesis corresponds to \( f_{a3} \cos \phi_{a3} = 1 \).
Figure 4: The distributions of $D_{0-}$, $D_{CP}$, $D_{0h+}$, $D_{\Lambda 1}$, and $D^{Z\gamma}_{\Lambda 1}$ in the VBF category. In these figures, all four decay channels, $\tau_\ell\tau_\ell$, $\mu\tau_\ell$, $e\tau_\ell$, $e\mu$, are summed. The BSM hypothesis depends on the variable shown: it corresponds to $f_{\beta \delta} \cos \phi_{\beta \delta} = 1$ for the $D_{0-}$ (top left) distributions, the maximal mixing (“BSM mix“) in VBF production for the $D_{CP}$ distribution (top right), $f_{\alpha 2} \cos \phi_{\alpha 2} = 1$ for the $D_{0h+}$ distribution (center left), $f_{\Lambda 1} \cos \phi_{\Lambda 1} = 1$ for the $D_{\Lambda 1}$ distribution (center right), and $f^{Z\gamma}_{\Lambda 1} \cos \phi^{Z\gamma}_{\Lambda 1} = 1$ for the $D^{Z\gamma}_{\Lambda 1}$ distribution (bottom).
Figure 5: Observed and expected distributions in the VBF category in bins of $m_{\tau\tau}$, $m_{jj}$ and $D_{0-}$ for the $\mu\tau_1^+\tau_1^-\tau_2^-\mu$ (top) and $\tau_1^+\tau_1^-$ (middle and bottom) decay channels.
Figure 6: Observed and expected distributions in the VBF category in bins of $m_{\tau\tau}$, $m_{jj}$ and $D_{0h^+}$ for the $\mu\tau_h + e\tau_h + e\mu$ (top) and $\tau_h\tau_h$ (middle and bottom) decay channels.
Figure 7: Observed and expected distributions in the VBF category in bins of $m_{\tau\tau}$, $m_{jj}$ and $D_{A1}$ for the $\mu\tau\tau$ and $\tau\tau$ (top) and $\tau\tau$ (middle and bottom) decay channels.
Figure 8: Observed and expected distributions in the VBF category in bins of $m_{\tau\tau}$, $m_{jj}$ and $D_{A1}^{Z\gamma}$ for the $\mu\tau_b+e\tau_b+\mu\mu$ (top) and $\tau\tau_b$ (middle and bottom) decay channels.
6.2 Likelihood parameterization

The extended likelihood function is defined for candidate events \( j \) as

\[
\mathcal{L} = \exp \left( -\sum_{i} n_{i_{\text{sig}}}^{i} - \sum_{i} n_{i_{\text{bkg}}}^{i} \right) \prod_{k} \prod_{j} \left( \sum_{i} n_{i_{\text{sig}}}^{i} \times \mathcal{P}_{i_{\text{sig}}}^{j}(\vec{x}_{j}^{k}) + \sum_{i} n_{i_{\text{bkg}}}^{i} \times \mathcal{P}_{i_{\text{bkg}}}^{j}(\vec{x}_{j}^{k}) \right),
\]

(7)

where \( n_{i_{\text{sig}}}^{i} \) and \( n_{i_{\text{bkg}}}^{i} \) are the number of signal and background events for each signal and background process \( i \). The probability density functions (pdf) \( \mathcal{P}_{i_{\text{sig}}}^{j}(\vec{x}_{j}^{k}) \) and \( \mathcal{P}_{i_{\text{bkg}}}^{j}(\vec{x}_{j}^{k}) \) are binned templates and are defined in each category \( k \). For the VBF, VH, or gluon fusion production mechanisms, the pdf is defined as

\[
\mathcal{P}_{i_{\text{sig}}}^{j}(\vec{x}) = \left( 1 - f_{\text{an}}^{\text{prod}} \right) \mathcal{T}_{a_{1}}^{i_{\text{an}}}(\vec{x}) + f_{\text{an}}^{\text{prod}} \mathcal{T}_{a_{1}}^{i_{\text{an}}}(\vec{x}) + \sqrt{f_{\text{an}}^{\text{prod}}} \left( 1 - f_{\text{an}}^{\text{prod}} \right) \mathcal{T}_{a_{1}}^{i_{\text{an}}}(\vec{x}) \cos \phi_{\text{an}},
\]

(8)

where \( \mathcal{T}_{a_{1}}^{i_{\text{an}}} \) is the template probability of a pure anomalous coupling \( a_{1} \) term and \( \mathcal{T}_{a_{1}}^{i_{\text{an}}} \) describes the interference between the anomalous coupling and SM term \( a_{1} \). The parameter \( f_{\text{an}}^{\text{prod}} \) is defined in Eq. (3) with cross sections \( \sigma_{n} \) defined for the appropriate production mechanism and corrected for acceptance. It has a one-to-one relationship to the unique \( f_{\text{an}} \) defined for decay, which is used to report the results. Here \( f_{\text{an}} \) stands for either \( f_{a3}, f_{a2}, f_{A1}, \) or \( f_{Z_{1}}^{2} \). Each term in Eq. (8) is extracted from a dedicated simulation.

For the actual fit, instead of the signal yields \( n_{i_{\text{sig}}}^{i} \) given in Eq. (7), the signal strength parameters \( \mu_{V} \) and \( \mu_{f} \) are introduced as two parameters of interest. They scale the yields in the VBF-VH and gluon fusion production processes, respectively. They are defined in such a way that for \( f_{\text{an}} = 0 \) they are equal to the ratio of the measured cross section and the one expected in the SM, incorporating all the best known corrections. The likelihood in Eq. (7) is maximized with respect to the anomalous coupling \( (f_{\text{an}} \cos \phi_{\text{an}}, f_{a3}^{\text{H}}) \) and yield \( \mu_{V}, \mu_{F} \) parameters and with respect to the nuisance parameters, which include the constrained parameters describing the systematic uncertainties. All parameters except \( f_{\text{an}} \cos \phi_{\text{an}} \) are profiled. The confidence intervals are determined from profile likelihood scans of the respective parameters. The allowed 68% and 95% CL intervals are defined using the profile likelihood function, \(-2 \Delta \ln \mathcal{L} = 1.00 \) and 3.84, for which exact coverage is expected in the asymptotic limit [54]. The approximate coverage has been tested with generated samples.

The additional \( D_{0-}, D_{0h+}, D_{A1} \) and \( D_{L}^{\text{Z}_{1}} \) observables do not change the procedure of estimating systematic uncertainty, as any mis-modeling due to detector effects is estimated with the same procedure as for any other distribution. As none of the systematic uncertainties would introduce \( CP \) violation, variations in the \( D_{CP} \) dimension are not considered.

7 Results

The four parameters describing anomalous HVV couplings, as defined in Eqs. (2) and (3), are tested against the data according to the likelihood defined in Eqs. (7) and (8). The results of the likelihood scans are shown in Fig. 9 and listed in Table 2. In each fit, the values of the other three anomalous coupling parameters are set to zero. All other parameters, including the signal strength parameters \( \mu_{V} \) and \( \mu_{F} \), are profiled. The results are presented for the product of \( f_{a1} \) and \( \cos(\phi_{a1}) \), the latter being the sign of the real \( a_{1}/a_{0} \) ratio of couplings. In this approach, the \( f_{a1} \) parameter is constrained to be in the physical range \( f_{a1} \geq 0 \). Therefore, in the SM it is likely for the best fit value to be at the physical boundary \( f_{a1} = 0 \).
The constraints on $f_{ai}$ appear relatively tight compared to similar constraints utilizing Higgs boson decays for example [14]. This is because the cross section in VBF and VH production increases quickly with $f_{ai}$. The definition of $f_{ai}$ in Eq. (3) uses the cross-section ratios defined in the $H \to 2e2\mu$ decay, as the common convention across various measurements. Because of the relative difference in cross-section increase with $f_{ai}$ in production and decay, the relatively small values of $f_{ai}$ lead to a substantial anomalous contribution to the production cross section. This leads to the plateau in the $-2 \ln (\mathcal{L} / \mathcal{L}_{\text{max}})$ distributions for larger values of $f_{ai}$ in Fig. 9. Should we have used the cross-section ratios in the VBF production in $f_{ai}$ definition in Eq. (3) for example, the plateau would not be as pronounced. The observed maximum value of $-2 \ln (\mathcal{L} / \mathcal{L}_{\text{max}})$ is somewhat different in the four analyses, mostly due to statistical fluctuations in the distribution of events across the dedicated discriminants, leading to different significance of the observed signal driven by VBF and VH production. In particular, the best fitted $(\mu_\nu, \mu_F)$ values in the four analyses under the assumption that $f_{ai} = 0$ are: $(0.55 \pm 0.48, 1.03^{+0.45}_{-0.40})$ at $f_{a3} = 0$, $(0.72^{+0.48}_{-0.40}, 0.89^{+0.43}_{-0.37})$ at $f_{a2} = 0$, $(0.92^{+0.44}_{-0.45}, 0.82^{+0.46}_{-0.38})$ at $f_{A_1} = 0$, and $(0.94^{+0.48}_{-0.46}, 0.79 \pm 0.40)$ at $f_{Z_1} = 0$. The expected signal significance and the maximum value of $-2 \ln (\mathcal{L} / \mathcal{L}_{\text{max}})$ are similar in all four analyses.

Table 2: Summary of allowed 68% CL (central values with uncertainties) and 95% CL (in square brackets) intervals on anomalous coupling parameters using the $H \to \tau\tau$ decay.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Observed/$10^{-3}$</th>
<th>Expected/$10^{-3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>68% CL</td>
<td>95% CL</td>
</tr>
<tr>
<td>$f_{a3} \cos(\phi_{a3})$</td>
<td>$0.00^{+0.93}_{-0.43}$</td>
<td>$[−1000, 1000]$</td>
</tr>
<tr>
<td>$f_{a2} \cos(\phi_{a2})$</td>
<td>$0.0^{+1.2}_{-0.4}$</td>
<td>$[−1000, 1000]$</td>
</tr>
<tr>
<td>$f_{A_1} \cos(\phi_{A_1})$</td>
<td>$0.00^{+0.39}_{-0.10}$</td>
<td>$[−0.4, 1.8]$</td>
</tr>
<tr>
<td>$f_{Z_1} \cos(\phi_{Z_1})$</td>
<td>$0.0^{+1.2}_{-1.3}$</td>
<td>$[−7.4, 5.6]$</td>
</tr>
</tbody>
</table>

In the $f_{a3}$ analysis, a simultaneous measurement of $f_{a3}$ and $f_{a3}^{g\phi H}$ is performed. These are the parameters sensitive to CP in the VBF and gluon fusion processes, respectively. Both the observed and expected exclusion from the null hypothesis for any $g\phi H$ BSM scenario with either MELA or $\Delta \Phi_{\gamma\gamma}$ observable are below $1\sigma$. 

7. Results

Figure 9: Observed (solid) and expected (dashed) likelihood scans of $f_{a3} \cos(\phi_{a3})$ (a), $f_{a2} \cos(\phi_{a2})$ (b), $f_{\Lambda 1} \cos(\phi_{\Lambda 1})$ (c), and $f_{\Lambda 1}^{Z} \cos(\phi_{\Lambda 1}^{Z})$ (d).
8 Combination of results with other channels

The precision of the coupling measurements can be improved by combining the results in the H → ττ channel, presented here, with those of other H boson decay channels. A combination is possible only with those channels where anomalous couplings in the VH, VBF, and gluon fusion processes are taken into account in the fit in a consistent way. For example, it is not possible to combine with a SM-like fit because the kinematics of the associated jets and transverse momentum of the Higgs boson would not be modeled correctly for a non-SM value of the f_{ai} or f_{s3} parameters.

In the example of the CP fit, in the stand-alone fit with the H → ττ channel, the parameters of interest are f_{s3}, f_{s3}^{g3H}, μ_{V}^{HT}, and μ_{F}^{HT}. When reporting one parameter, all other parameters are profiled. In a combined fit of the H → ττ and H → VV channels, such as in Ref. [14], in principle there are four signal strength parameters in the two channels (μ_{V}^{HT}, μ_{F}^{HT}, μ_{V}^{HV}, μ_{F}^{HV}). However, this can be reduced to three parameters because the ratio between the VBF+VH and gluon fusion cross sections is expected to be the same in each of the two channels, that is μ_{V}^{HT}/μ_{F}^{HT} = μ_{V}^{HV}/μ_{F}^{HV}. Therefore, the three signal strength parameters are chosen as μ_{V}, μ_{F}, and η_{ττ}, the latter being the relative strength of the Higgs boson to the tau leptons. We should note that, as discussed earlier, the HWW couplings are analyzed together with the HZZ couplings assuming a_{i}^{ZZ} = a_{i}^{WW}. The results can be reinterpreted for a different assumption of the a_{i}^{ZZ}/a_{i}^{WW} ratio. In the combined likelihood fit, all common systematic uncertainties are correlated between the channels, both theoretical uncertainties, such as those due to the PDFs, and experimental uncertainties, such as jet energy calibration.

The results using the H → ττ decay are combined with those presented in Ref. [14] using the H → 4ℓ decay. The latter employs analysis of the data from Run 1 (from 2011 and 2012) and Run 2 (from 2015, 2016, and 2017) corresponding to an integrated luminosity of 5.1, 19.7 fb^{-1}, and 80.2 fb^{-1} at 7, 8, and 13 TeV, respectively. In this analysis, information about the HVV anomalous couplings both in VBF+VH production and in H → VV → 4ℓ decay is used. In all cases, the signal strength parameters are profiled, and the parameters common to the two analyses are correlated. The combined 68% CL and 95% CL intervals are presented in Table 3 and the likelihood scans are shown in Fig. 10. While the large confidence levels and large values of f_{ai} are predominantly constrained by the decay information in the H → VV analysis, the constraints in the narrow range of f_{ai} are dominated by the production information where the H → ττ channel dominates over the H → 4ℓ, which results in the most stringent limits on anomalous HVV couplings.

Table 3: Summary of allowed 68% CL (central values with uncertainties) and 95% CL (in square brackets) intervals on anomalous coupling parameters using combination of the H → ττ and H → 4ℓ [14] decay channels.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Observed / (10^{-3})</th>
<th>Expected / (10^{-3})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>68% CL</td>
<td>95% CL</td>
</tr>
<tr>
<td>f_{s3} cos(ϕ_{s3})</td>
<td>0.00 ± 0.27</td>
<td></td>
</tr>
<tr>
<td>f_{s2} cos(ϕ_{s2})</td>
<td>0.08^{+1.04}_{-0.21}</td>
<td>0.00^{+1.13}_{-1.1}</td>
</tr>
<tr>
<td>f_{A1} cos(ϕ_{A1})</td>
<td>0.00^{+0.53}_{-0.09}</td>
<td>0.00^{+0.48}_{-0.12}</td>
</tr>
<tr>
<td>f_{Z}^{g} cos(ϕ_{Z}^{g})</td>
<td>0.0^{+1.1}_{-1.3}</td>
<td>0.0^{+2.6}_{-3.6}</td>
</tr>
</tbody>
</table>
9. Summary

A study of anomalous HVV interactions of the Higgs boson, including CP violation, has been presented, using its associated production with two quark jets in vector boson fusion and VH with subsequent decay to a pair of tau leptons. Constraints on the CP-violating parameter $a_3$ and on the CP-conserving parameters $a_2$, $a_1$, and $f^{Z\gamma}_{A_1}$ are set using matrix element techniques. The observed and expected limits on parameters are summarized in Table 2. The 68% CL constraints are generally tighter than those from previous measurements using either production or decay information. Further constraints are obtained in the combination of the $H \rightarrow \tau\tau$ and $H \rightarrow 4\ell$ decay channels and are summarized in Table 3. This results in the most stringent constraints on anomalous Higgs boson couplings: $f_{a_3}\cos(\phi_{a_3}) = (0.00 \pm 0.27) \times 10^{-3}$, $f_{a_2}\cos(\phi_{a_2}) = (0.08^{+1.24}_{-0.21}) \times 10^{-3}$, $f_{A_1}\cos(\phi_{A_1}) = (0.00^{+0.55}_{-0.05}) \times 10^{-3}$, and $f^{Z\gamma}_{A_1}\cos(\phi^{Z\gamma}_{A_1}) = (0.0^{+1.1}_{-0.2}) \times 10^{-3}$. The results are consistent with expectations for the standard model Higgs boson.
References


