Cross-section measurements of the Higgs boson decaying into a pair of τ-leptons in proton-proton collisions $\sqrt{s}$ at $=13$ TeV with the ATLAS detector

Aaboud, M.; The ATLAS Collaboration

DOI
10.1103/PhysRevD.99.072001

Publication date
2019

Document Version
Final published version

Published in
Physical Review D. Particles and Fields

License
CC BY

Citation for published version (APA):
Cross-section measurements of the Higgs boson decaying into a pair of $\tau$-leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

M. Aaboud et al.*
(ATLAS Collaboration)

(Received 22 November 2018; published 10 April 2019)

A measurement of production cross sections of the Higgs boson in proton-proton collisions is presented in the $H \rightarrow \tau\tau$ decay channel. The analysis is performed using 36.1 fb$^{-1}$ of data recorded by the ATLAS experiment at the Large Hadron Collider at a center-of-mass energy of $\sqrt{s} = 13$ TeV. All combinations of leptonic ($\tau \rightarrow \ell v\bar{v}$ with $\ell = e, \mu$) and hadronic ($\tau \rightarrow$ hadrons $v$) $\tau$ decays are considered. The $H \rightarrow \tau\tau$ signal over the expected background from other Standard Model processes is established with an observed (expected) significance of 4.4 (4.1) standard deviations. Combined with results obtained using data taken at 7 and 8 TeV center-of-mass energies, the observed (expected) significance amounts to 6.4 (5.4) standard deviations and constitutes an observation of $H \rightarrow \tau\tau$ decays. Using the data taken at $\sqrt{s} = 13$ TeV, the total cross section in the $H \rightarrow \tau\tau$ decay channel is measured to be $3.77^{+0.60}_{-0.59}$ (stat) $^{+0.87}_{-0.74}$ (syst) pb, for a Higgs boson of mass 125 GeV assuming the relative contributions of its production modes as predicted by the Standard Model. Total cross sections in the $H \rightarrow \tau\tau$ decay channel are determined separately for vector-boson-fusion production and gluon-gluon-fusion production to be $\sigma_{VBF}^{H\rightarrow\tau\tau} = 0.28 \pm 0.09$ (stat) $^{+0.11}_{-0.09}$ (syst) pb and $\sigma_{ggF}^{H\rightarrow\tau\tau} = 3.1 \pm 1.0$ (stat) $^{+1.6}_{-1.3}$ (syst) pb, respectively. Similarly, results of a fit are reported in the framework of simplified template cross sections. All measurements are in agreement with Standard Model expectations.

DOI: 10.1103/PhysRevD.99.072001

I. INTRODUCTION

The ATLAS and CMS Collaborations discovered [1,2] a particle consistent with the Standard Model (SM) [3–5] Higgs boson [6–10] in 2012. Several properties of this particle, such as its coupling strengths, spin and charge-parity (CP) quantum numbers, were studied with 7 and 8 TeV center-of-mass energy ($\sqrt{s}$) proton-proton collision data delivered by the Large Hadron Collider (LHC) in 2011 and 2012, respectively, referred to as “Run 1.” These results rely predominantly on studies of the bosonic decay modes [11–14] and have not shown any significant deviations from the SM expectations.

The coupling of the Higgs boson to the fermionic sector has been established with the observation of the $H \rightarrow \tau\tau$ decay mode with a signal significance of 5.5$\sigma$ from a combination of ATLAS and CMS results [15–17] using LHC Run-1 data. A measurement performed by the CMS Collaboration with Run-2 data at $\sqrt{s} = 13$ TeV reached a significance of 4.9$\sigma$ using 35.9 fb$^{-1}$ of integrated luminosity and 5.9$\sigma$ combined with data from Run 1 [18]. While the Higgs-boson coupling to other fermions such as top quarks [19,20] and bottom quarks [21,22] have been observed, only upper limits exist on its coupling to muons [23,24] and the $H \rightarrow \tau\tau$ decay mode has been the only accessible leptonic decay mode. It was also used to constrain CP violation in the production via vector-boson fusion (VBF) [25] and is unique in that it provides sensitivity to CP violation in the Higgs-boson coupling to leptons [26].

This paper presents cross-section times branching-fraction measurements of Higgs bosons that decay into a pair of $\tau$-leptons in proton-proton ($pp$) collisions at $\sqrt{s} = 13$ TeV using data collected by the ATLAS experiment in 2015 and 2016, corresponding to an integrated luminosity of 36.1 fb$^{-1}$. All combinations of leptonic ($\tau \rightarrow \ell v\bar{v}$ with $\ell = e, \mu$) and hadronic ($\tau \rightarrow$ hadrons $v$) $\tau$ decays are considered. The corresponding three analysis channels are denoted by $\tau_{\text{lep}}\tau_{\text{lep}}$, $\tau_{\text{lep}}\tau_{\text{had}}$, and $\tau_{\text{had}}\tau_{\text{had}}$ and are composed of.

*Full author list given at the end of the article.

Published by the American Physical Society under the terms of the Creative Commons Attribution 4.0 International license. Further distribution of this work must maintain attribution to the author(s) and the published article’s title, journal citation, and DOI. Funded by SCOAP3.

1Throughout this paper, the inclusion of charge-conjugate decay modes is implied. The symbol $\ell$ is used to denote electrons and muons, also referred to as “light leptons.”
different dominant backgrounds. While $Z \to \tau\tau$ is a dominant background in all channels, the relative contributions from other backgrounds from top-quark and other vector-boson decays, as well as from misidentified leptonic or hadronic $\tau$ decays, vary considerably between the channels. Two analysis categories are defined that are predominantly sensitive to Higgs bosons produced via VBF and gluon-gluon fusion ($gFg$, $ggF$). A maximum-likelihood fit is performed on data using distributions of the reconstructed di-$\tau$ mass in signal regions (SRs), simultaneously with event yields from control regions (CRs) that are included to constrain normalizations of major backgrounds estimated from simulation. The dominant and irreducible $Z \to \tau\tau$ background is estimated from simulation. This is different from the search for $H \to \tau\tau$ decays in Run 1 [15], which used the embedding technique [27]. A reliable modeling of this background is therefore of crucial importance for this analysis. Validation regions (VRs) based on $Z \to \ell\ell$ events are studied, but not included in the fit, to verify as precisely as possible the modeling of the $Z \to \tau\tau$ background.

The paper is organized as follows. Section II describes the ATLAS detector. This is followed in Sec. III by a description of the data set and Monte Carlo (MC) simulated samples employed by this measurement. Section IV details the reconstruction of particles and jets. The event selection for each channel and event category as well as signal, control and validation regions are discussed in Sec. V. Background estimation techniques and the systematic uncertainties of the analysis are described in Secs. VI and VII, respectively. The signal extraction procedure and the results of the Higgs cross-section measurements in the $H \to \tau\tau$ decay mode are presented in Sec. VIII. Section IX gives the conclusions.

II. THE ATLAS DETECTOR

The ATLAS experiment [28] at the LHC is a multipurpose particle detector with a forward-backward symmetric cylindrical geometry and a near-4$\pi$ coverage in solid angle.\footnote{The ATLAS Collaboration uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the z axis along the beam pipe. The x axis points from the IP to the center of the LHC ring, and the y axis points upwards. Cylindrical coordinates ($r$, $\phi$) are used in the transverse plane, $\phi$ being the azimuthal angle around the z axis. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln \tan (\theta/2)$. Angular distance is measured in units of $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$.} It consists of an inner tracking detector surrounded by a thin superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer. The inner tracking detector covers the pseudorapidity range $|\eta| < 2.5$, followed by a transition radiation straw-tube tracker covering $|\eta| < 2$. The inner tracking detector is immersed in a 2 T axial magnetic field provided by the solenoid. Lead/liquid-argon (LAr) sampling calorimeters provide electromagnetic (EM) energy measurements with high granularity. A hadron detector (steel/scintillator-tile) calorimeter covers the central pseudorapidity range ($|\eta| < 1.7$). The end-cap and forward regions are instrumented with LAr calorimeters for both the EM and hadronic energy measurements up to $|\eta| = 4.9$. The muon spectrometer surrounds the calorimeters and is based on three large air-core toroidal superconducting magnets with eight coils each. The field integral of the toroids ranges between 2.0 and 6.0 T m across most of the detector. The muon spectrometer includes a system of precision tracking chambers and fast detectors for triggering.

Events are selected using a two-level trigger system. The first-level trigger is implemented in hardware and uses a subset of the detector information to filter events that are then processed by a software-based high-level trigger. This further reduces the average recorded collision rate to approximately 1 kHz.

III. DATA AND SIMULATION SAMPLES

The data used in this analysis were taken from $pp$ collisions at the LHC where proton bunches are collided every 25 ns at $\sqrt{s} = 13$ TeV. A combination of several triggers for single light leptons, two light leptons and two hadronically decaying $\tau$-leptons were used to record the data for the analysis, depending on the analysis channel (see Sec. VA). After data quality requirements, the samples used for this measurement consist of 3.2 fb$^{-1}$ of data recorded in 2015, with an average of 14 interactions per bunch crossing, and 32.9 fb$^{-1}$ recorded in 2016, with an average of 25 interactions per bunch crossing.

Samples of signal and background processes were simulated using various MC generators as summarized in Table I. The signal contributions considered include the following four processes for Higgs-boson production at the LHC: $ggF$, VBF and associated production of a Higgs boson with a vector boson ($VH$) or with a top-antitop quark pair (ttH) where all decay modes for the $H \to \tau\tau$ process are included. Other Higgs production processes such as associated production with a bottom-antibottom quark pair and with a single top quark are found to be negligible. Higgs decays into WW are considered background and simulated similarly for these production processes. The mass of the Higgs boson was assumed to be 125 GeV [31].
processes were simulated at NLO accuracy in QCD using POWHEG-BOX with the MiNLO approach. The $t\bar{t}H$ production process was simulated with MADGRAPH5_aMC@NLO v2.2.2 [38] at NLO accuracy in QCD. For these signal samples, the simulation was interfaced to the PYTHIA 8.212 [39] model of parton showering, hadronization and underlying event (UEPS). To estimate the impact of UEPS uncertainties, the $ggF$, VBF and $VH$ samples were also simulated with the HERWIG 7.0.3 [40,41] UEPS model. The PDF4LHC15 [42] parametrization of the parton distribution functions (PDFs) was used for these production processes.

The overall normalization of the $ggF$ process is taken from a next-to-next-to-next-to-leading-order (N$^3$LO) QCD calculation with NLO EW corrections included [49–52]. Production by VBF is normalized to an approximate-NNLO QCD cross section calculated at NLO in QCD, with NLO EW corrections included [53–55]. The $VH$ samples are normalized to cross sections calculated at NNLO in QCD, with NLO EW corrections included [56–58]. The $t\bar{t}H$ process is normalized to a cross section calculated at NLO in QCD with NLO EW corrections applied [59–64].

Background samples of EW production of $W/Z$ bosons from VBF, $W/Z$-boson production with associated jets and diboson production processes were simulated with the SHERPA 2.2.1 [65] generator. Matrix elements were calculated using the Comix [66] and OpenLoops [67] matrix-element generators and merged with the SHERPA UEPS model [68] using the ME+PS@NLO prescription [69]. For $W$ and $Z$ production with associated jets the matrix elements were calculated for up to two partons at NLO and four partons at LO precision. Their inclusive cross sections are normalized to NNLO calculations from FEWZ [70,71].

In particular, the dominant $Z \rightarrow \tau\tau$ background is estimated using these simulations of $Z$-boson production. For diboson production, the matrix elements were calculated for up to one additional parton at NLO and up to three additional partons at LO precision. For all samples the NNPDF30NNLO [45] PDF set was used together with the SHERPA UEPS model.

The impact of UEPS uncertainties, and other modeling uncertainties such as LO/NLO precision comparison for leading jets, on the main background from $Z \rightarrow \tau\tau$ is studied in an alternative sample which was simulated using MADGRAPH5_aMC@NLO v2.2.2 [38] at leading order interfaced to the PYTHIA 8.186 UEPS model. The A14 set of tuned parameters [47] was used together with the NNPDF23LO PDF set [46].

For the generation of $t\bar{t}$ production, the POWHEG-BOX v2 [32–34,72] generator with the CT10 PDF sets in the matrix element calculations was used. The predicted $t\bar{t}$ cross section was calculated with the Top++2.0 program to NNLO in perturbative QCD, including soft-gluon resummation to next-to-leading-log order [73]. Single top-quark production of $Wt$ was simulated using the POWHEG-BOX v1 [74,75] generator. This generator uses the four-flavor scheme for the NLO matrix-element calculations together with the fixed four-flavor PDF set CT10F4. For all top-quark production processes, top-quark spin correlations were preserved, using MadSpin [76] for the $t$-channel.

The parton shower, hadronization, and the underlying event were simulated using PYTHIA 6.428 [77] with the CTEQ6L1 PDF set and the corresponding Perugia 2012 set of tuned parameters [78]. The top mass was assumed to be 172.5 GeV. The EvtGen v.1.2.0 program [79] was used for the properties of $b$- and $c$-hadron decays.

For all samples, a full simulation of the ATLAS detector response [80] using the GEANT4 program [81] was performed. The effect of multiple $pp$ interactions in the same and neighboring bunch crossings (pileup) was included by overlaying minimum-bias events simulated with PYTHIA 8.186 using the MSTW2008LO PDF [82] and the A2 [83] set of tuned parameters on each generated signal and background event. The number of overlaid events was

chosen such that the distribution of the average number of interactions per $pp$ bunch crossing in the simulation matches that observed in data.

IV. OBJECT RECONSTRUCTION

Electron candidates are reconstructed from energy deposits in the electromagnetic calorimeter associated with a charged-particle track measured in the inner detector. The electron candidates are required to pass the “loose” likelihood-based identification selection of Refs. [84,85], to have transverse momentum $p_T > 15$ GeV and to be in the fiducial volume of the inner detector, $|η| < 2.47$. The transition region between the barrel and end-cap calorimeters (1.37 < $|η| < 1.52$) is excluded. The trigger efficiency for single electrons selected in the analysis ranges between 90% and 95% [86]. Electron candidates are ignored if they share their reconstructed track with a muon candidate defined below or if their angular distance from a jet is within $0.2 < ΔR < 0.4$.

Muon candidates are constructed by matching an inner detector track with a track reconstructed in the muon spectrometer [87]. The muon candidates are required to have $p_T > 10$ GeV and $|η| < 2.5$ and to pass the “loose” muon identification requirements of Ref. [87]. The trigger efficiency for single muons selected in the analysis is close to 80% (70%) in the barrel in the 2016 (2015) data set and 90% in the end caps [86]. Muon candidates are ignored if their angular distance from a jet is $ΔR < 0.4$ with the following exceptions: If $ΔR < 0.2$ or the muon track is associated with the jet, and if the jet has either less than three tracks or less than twice the transverse momentum of the muon candidate, the jet is removed instead. This recovers efficiency for muons that radiate a hard bremsstrahlung photon in the calorimeter.

In the $τ_{{lep}lep}$ and $τ_{{lep}had}$ signal regions, events are selected only if the selected electron and muon candidates satisfy their respective “medium” identification criteria. The reconstruction and identification efficiency for muons with the “medium” identification requirement has been measured in $Z → μμ$ events [87]. It is well above 98% over the full phase space, except for $|η| < 0.1$ where the reconstruction efficiency is about 70%. The combined identification and reconstruction efficiency for “medium” electrons ranges from 80% to 90% in the $p_T$ range of 10 GeV to 80 GeV as measured in $Z → ee$ events [85]. In addition, the electrons and muons must satisfy the “gradient” isolation criterion, which requires that there are no additional high-$p_T$ tracks in a cone around the track and no significant energy deposits in a cone around the calorimeter clusters of the object after correcting for pileup. The size of the respective cones depends on the $p_T$ of the light lepton. This isolation requirement rejects about 10% of light leptons for low $p_T$ and less than 1% for $p_T > 60$ GeV [85,87].

Jets are reconstructed from topological clusters in the calorimeter using the anti-$k_T$ algorithm [88,89], with a radius parameter value $R = 0.4$, and have $p_T > 20$ GeV and $|η| < 4.9$. To reject jets from pileup, a “Jet Vertex Tagger” (JVT) [90] algorithm is used for jets with $p_T < 50$ GeV and $|η| < 2.4$. It employs a multivariate technique that relies on jet-tracking and calorimeter-cluster-shape variables to determine the likelihood that the jet originates from pileup. Similarly, pileup jets in the forward region are suppressed with a forward JVT [91] algorithm, relying in this case only on calorimeter-cluster-shape variables, which is applied to all jets with $p_T < 50$ GeV and $|η| > 2.5$. In the pseudorapidity range $|η| < 2.5$, $b$-jets are selected using a multivariate algorithm [92,93]. A working point is chosen that corresponds to an efficiency of approximately 85% for $b$-jets and rejection factors of 2.8 and 28 for c-jets and light-flavor jets, respectively, in simulated $t\bar{t}$ events. A jet is ignored if it is within $ΔR = 0.2$ of an electron or hadronically decaying $τ$ candidate.

Leptonic $τ$ decays are reconstructed as electrons and muons. The reconstruction of the visible decay products of hadronic $τ$ decays ($τ_{had-vis}$) [94] starts with a reconstructed jet that has $p_T > 10$ GeV and $|η| < 2.5$. As in the case of electron reconstruction the transition region between the barrel and end-cap calorimeters is excluded. To discriminate $τ_{had-vis}$ from jets initiated by light-quarks or gluons, an identification algorithm using multivariate techniques is applied to $τ_{had-vis}$ candidates. They have to pass the “loose” identification requirement of Ref. [94]. In addition, the $τ_{had-vis}$ candidates are required to have $p_T > 20$ GeV, to have one or three associated tracks and an absolute electric charge of one. Their energy is reconstructed by multivariate regression techniques using information about the associated tracks and calorimeter clusters, as well as the average number of collisions recorded. The trigger efficiency per $τ_{had-vis}$ selected in the analysis is 95% and 85% for 1-prong and 3-prong $τ$-leptons, respectively [95]. The $τ_{had-vis}$ candidates are ignored if they are within $ΔR = 0.2$ of a muon or electron candidate or if they have a high likelihood score of being an electron [85]. The requirement on the likelihood score corresponds to a $τ_{had-vis}$ efficiency measured in $Z → ττ$ decays of 95% [94].

In the $τ_{{lep}lep}$ and $τ_{{lep}had}$ signal regions, events are selected only if the $τ_{had-vis}$ candidate passes the “medium” identification requirement, corresponding to an efficiency of 55% and 40% for real 1-prong and 3-prong $τ_{had-vis}$, respectively [94]. In addition, if a 1-prong $τ_{had-vis}$ candidate and an electron candidate are selected, a dedicated multivariate algorithm to reject electrons misidentified as $τ_{had-vis}$ is applied to suppress $Z → ee$ events. In the $τ_{{had}had}$ signal regions, both selected $τ_{had-vis}$ candidates have to fulfill the “tight” identification requirement, which corresponds to a selection efficiency of 45% for real 1-prong $τ_{had-vis}$ and 30% for real 3-prong $τ_{had-vis}$ [94].

The missing transverse momentum vector is calculated as the negative vectorial sum of the $p_T$ of the fully
calibrated and reconstructed physics objects [96]. This procedure includes a soft term, which is calculated from the inner detector tracks that originate from the vertex associated with the hard-scattering process and that are not associated with any of the reconstructed objects. The missing transverse momentum \( (E_T^{\text{miss}}) \) is defined as the magnitude of this vector.

The Higgs-boson candidate is reconstructed from the visible decay products of the \( \tau \)-leptons and from the \( E_T^{\text{miss}} \), which is assumed to originate from the final-state neutrinos. The \( \Delta\tau \) invariant mass \( (m_{\Delta\tau}^{\text{MMC}}) \) is determined using the missing-mass calculator (MMC) [97]. The standard deviation of the reconstructed \( \Delta\tau \) mass is 17.0, 15.3 and 14.7 GeV for signal events selected in the \( \tau_{\text{lep}} \), \( \tau_{\text{had}} \) and \( \tau_{\text{had-vis}} \) channels, respectively. The \( p_T \) of the Higgs-boson candidate \( (p_T^\tau) \) is computed as the vector sum of the transverse momenta of the visible decay products of the \( \tau \)-leptons and the missing transverse momentum vector.

V. EVENT SELECTION AND CATEGORIZATION

In addition to data quality criteria that ensure that the detector was functioning properly, events are rejected if they contain reconstructed jets associated with energy deposits that can arise from hardware problems, beam-halo events or cosmic-ray showers. Furthermore, events are required to have at least one reconstructed primary vertex with at least two associated tracks with \( p_T > 0.5 \) GeV, which rejects noncollision events originating from cosmic rays or beam-halo events. The primary vertex is chosen as the \( pp \) vertex candidate with the highest sum of the squared transverse momenta of all associated tracks.

The triggers and event selection for the three analysis channels are described in Sec. VA. Selected events are categorized into exclusive signal regions, with enhanced signal-to-background ratios. In addition, control regions are defined where a specific background is dominant, and thus a CR facilitates the adjustment of the simulated prediction of a background contribution to match the observed data. The signal and control regions are included in the fit described in Sec. VIII. They are described in Sec. V B together with validation regions (VRs) used to validate the simulation of the dominant \( Z \) + jets background.

A. Event selection

Depending on the trigger, transverse momentum requirements are applied to selected electron, muon, and \( \tau_{\text{had-vis}} \) candidates. They are summarized in Table II and their per-object efficiencies are given in Sec. IV. Due to the increasing luminosity and the different pileup conditions, the \( p_T \) thresholds of the triggers were increased during data-taking in 2016, which is taken into account in the \( p_T \) requirements of the event selection. In the \( \tau_{\text{lep}} \) channel, the triggers for multiple light leptons are used only if the highest-\( p_T \) light lepton does not pass the corresponding single-light-lepton trigger \( p_T \) requirement. This ensures that each trigger selects an exclusive set of events.

All channels require the exact number of identified “loose” leptons, i.e., electrons, muons and \( \tau_{\text{had-vis}} \), as defined in Sec. IV, corresponding to their respective final state. Events with additional “loose” leptons are rejected. The two leptons are required to be of opposite charge and they have to fulfill the \( p_T \) requirements of the respective trigger shown in Table II. The selected \( \tau_{\text{had-vis}} \) in the \( \tau_{\text{lep}} \) channel is required to have \( p_T > 30 \) GeV.

The event selection for the three analysis channels is summarized in Table III. Only events with \( E_T^{\text{miss}} > 20 \) GeV are selected to reject events without neutrinos. In the \( \tau_{\text{lep}} \) channel with two same-flavor (SF) light leptons this requirement is further tightened to suppress the large \( Z \to \ell^+\ell^- \) background. For the same reason, requirements are tightened on the invariant mass of two light leptons \( (m_{\ell\ell}) \) and a requirement is introduced on the \( E_T^{\text{miss}} \) calculated only from the physics objects without the soft track term \( (E_T^{\text{miss,hard}}) \). Requirements on the angular distance between the visible decay products of the two selected \( \tau \)-lepton decays \( (\Delta R_{\tau\tau}) \) and their pseudorapidity difference \( (|\Delta\eta_{\tau\tau}|) \) are applied in all channels to reject nonresonant background events. Requirements are applied to the fractions of the \( \tau \)-lepton momenta carried by each visible decay product \( x_i = p_i^{\text{vis}}/(p_i^{\text{vis}} + p_i^{\text{miss}}) \), where \( p_i^{\text{vis}} \) and \( p_i^{\text{miss}} \) are the visible and missing momenta of the \( i \)th \( \tau \) lepton, ordered in descending \( p_T \), calculated in the collinear approximation [98], to suppress events with \( E_T^{\text{miss}} \) that is incompatible with a \( \Delta\tau \) decay. Low transverse mass \( (m_T) \), calculated from \( E_T^{\text{miss}} \) and the momentum of the selected light lepton, is required in the \( \tau_{\text{lep}} \) channel to reject events with leptonic \( W \) decays. A requirement on the \( \Delta\tau \) mass calculated in the collinear approximation \( (m_{T}^{\text{coll}}) \) of \( m_{T}^{\text{coll}} > m_Z - 25 \) GeV is introduced in the \( \tau_{\text{lep}} \) channel suppress events from \( Z \to \ell^+\ell^- \) and to ensure orthogonality between this

<table>
<thead>
<tr>
<th>Analysis channel</th>
<th>Trigger</th>
<th>Analysis ( p_T ) requirement [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau_{\text{lep}} ) &amp; ( \tau_{\text{lep}} )</td>
<td>Single electron</td>
<td>25</td>
</tr>
<tr>
<td>( \tau_{\text{had}} ) &amp; ( \tau_{\text{had}} )</td>
<td>Single muon</td>
<td>21</td>
</tr>
<tr>
<td>( \tau_{\text{lep}} )</td>
<td>Di-lepton</td>
<td>15/15</td>
</tr>
<tr>
<td>Dimuon</td>
<td>19/10</td>
<td></td>
</tr>
<tr>
<td>Electron + muon</td>
<td>18/15</td>
<td></td>
</tr>
<tr>
<td>( \tau_{\text{had}} ) &amp; ( \tau_{\text{had}} )</td>
<td>Di-( \tau_{\text{had-vis}} )</td>
<td>40/30</td>
</tr>
</tbody>
</table>

TABLE II. Summary of the triggers used to select events for the three analysis channels during 2015 and 2016 data-taking and the corresponding \( p_T \) requirements applied in the analysis.
TABLE III. Summary of the event selection requirements for the three analysis channels that are applied in addition to the respective lepton $p_T$ requirements listed in Table II. $E_T^{\text{miss,hard}}$ is an alternative $E_T^{\text{miss}}$ calculated only from the physics objects without the soft-track term. The transverse mass ($m_T$) is calculated from $E_T^{\text{miss}}$ and the momentum of the selected light lepton. The visible momentum fractions $x_1$ and $x_2$ of the respective $\tau$-lepton and the collinear di-$\tau$ mass ($m_{\tau\tau}$) are calculated in the collinear approximation [98].

<table>
<thead>
<tr>
<th>$\tau_{\text{lep}}\tau_{\text{lep}}$</th>
<th>$\tau_{\text{lep}}\tau_{\text{had}}$</th>
<th>$\tau_{\text{had}}\tau_{\text{had}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e\mu/e\mu$</td>
<td>$e\mu$</td>
<td>$e\mu$</td>
</tr>
<tr>
<td>$N_{\text{loose}}^{e/\mu} = 2$, $N_{\text{loose}}^{\text{had-vis}} = 0$</td>
<td>$N_{\text{loose}}^{e/\mu} = 1$, $N_{\text{loose}}^{\text{had-vis}} = 1$</td>
<td>$N_{\text{loose}}^{e/\mu} = 0$, $N_{\text{loose}}^{\text{had-vis}} = 2$</td>
</tr>
<tr>
<td>$e/\mu$: Medium, gradient iso.</td>
<td>$e/\mu$: Medium, gradient iso.</td>
<td>$e/\mu$: Medium, gradient iso.</td>
</tr>
<tr>
<td>Opposite charge</td>
<td>Opposite charge</td>
<td>Opposite charge</td>
</tr>
<tr>
<td>$m_{\tau\tau}^{\text{coll}} &gt; m_Z - 25 \text{ GeV}$</td>
<td>$m_{\tau\tau}^{\text{coll}} &gt; m_Z - 25 \text{ GeV}$</td>
<td>$m_{\tau\tau}^{\text{coll}} &gt; m_Z - 25 \text{ GeV}$</td>
</tr>
<tr>
<td>$30 &lt; m_{\ell\ell} &lt; 75 \text{ GeV}$</td>
<td>$30 &lt; m_{\ell\ell} &lt; 100 \text{ GeV}$</td>
<td>$30 &lt; m_{\ell\ell} &lt; 100 \text{ GeV}$</td>
</tr>
<tr>
<td>$E_T^{\text{miss}} &gt; 55 \text{ GeV}$</td>
<td>$E_T^{\text{miss}} &gt; 55 \text{ GeV}$</td>
<td>$E_T^{\text{miss}} &gt; 55 \text{ GeV}$</td>
</tr>
<tr>
<td>$E_T^{\text{miss,hard}} &gt; 55 \text{ GeV}$</td>
<td>$E_T^{\text{miss,hard}} &gt; 55 \text{ GeV}$</td>
<td>$E_T^{\text{miss,hard}} &gt; 55 \text{ GeV}$</td>
</tr>
<tr>
<td>$\Delta \eta_{\tau\tau} &lt; 2.0$</td>
<td>$\Delta \eta_{\tau\tau} &lt; 2.0$</td>
<td>$0.8 &lt; \Delta \eta_{\tau\tau} &lt; 2.5$</td>
</tr>
<tr>
<td>$</td>
<td>\Delta \eta_{\tau\tau}</td>
<td>&lt; 1.5$</td>
</tr>
<tr>
<td>$0.1 &lt; x_1 &lt; 1.0$</td>
<td>$0.1 &lt; x_1 &lt; 1.4$</td>
<td>$0.1 &lt; x_1 &lt; 1.4$</td>
</tr>
<tr>
<td>$0.1 &lt; x_2 &lt; 1.0$</td>
<td>$0.1 &lt; x_2 &lt; 1.2$</td>
<td>$0.1 &lt; x_2 &lt; 1.4$</td>
</tr>
<tr>
<td>$p_T^j &gt; 40 \text{ GeV}$</td>
<td>$p_T^j &gt; 40 \text{ GeV}$</td>
<td>$p_T^j &gt; 70 \text{ GeV}$, $</td>
</tr>
<tr>
<td>$N_{\text{b-jets}} = 0$</td>
<td>$N_{\text{b-jets}} = 0$</td>
<td>$N_{\text{b-jets}} = 0$</td>
</tr>
</tbody>
</table>

measurement and the measurement of $H \to WW^* \to \ell\ell\nu\nu$, which has a similar final state.

All channels require at least one jet ($j_1$) with $p_T^j > 40 \text{ GeV}$ to select Higgs bosons produced by VBF and to suppress background from $Z \to \tau\tau$ events when selecting Higgs bosons produced through ggF. Since 2016 the di-$\tau$ $m_{\tau\tau}^{\text{had-vis}}$ first-level trigger requires a jet with $p_T > 25 \text{ GeV}$ calibrated at trigger level with $|\eta| < 3.2$ in addition to the two $m_{\tau\tau}^{\text{had-vis}}$ candidates. In the $\tau_{\text{had}}\tau_{\text{had}}$ channel the jet $p_T$ requirement is thus raised to $p_T^j > 70 \text{ GeV}$ to achieve uniform trigger selection efficiency as a function of $p_T^j$. The trigger efficiency for the additional jet ranges from 95% to 100% for these requirements. In the $\tau_{\text{lep}}\tau_{\text{lep}}$ and $\tau_{\text{lep}}\tau_{\text{had}}$ channels, the top-quark background is suppressed by requiring that no jet with $p_T > 25 \text{ GeV}$ is tagged as a $b$-jet.

B. Signal, control and validation regions

To exploit signal-sensitive event topologies, a “VBF” and a “boosted” analysis category are defined without any overlap in phase space. The VBF category targets events with a Higgs boson produced by VBF and is characterized by the presence of a second high-$p_T$ jet ($p_T^j > 30 \text{ GeV}$). In addition, the two jets are required to be in opposite hemispheres of the detector with a large pseudorapidity separation of $|\Delta \eta_{jj}| > 3$ and their invariant mass ($m_{jj}$) is required to be larger than 400 GeV. The selected leptons are required to have $\eta$-values that lie between those of the two jets (“central leptons”). Although this category is dominated by VBF production, it also includes significant contributions from ggF production, amounting to up to 30% of the total expected Higgs-boson signal.

The boosted category targets events with Higgs bosons produced through ggF with additional recoiling jets, which is motivated by the harder $p_T$-spectrum of the $H \to \tau\tau$ signal compared to the dominant background from $Z \to \tau\tau$. It contains all events with $p_T^j > 100 \text{ GeV}$ that do not pass the VBF selection. In addition to events from ggF, the boosted categories contain sizable contributions from VBF and VH production of 10–20% of the expected signal. Events that pass the event selection, detailed in Table III, but do not fall into the VBF or boosted categories, are not used in the analysis.

Using $p_T^j$, $\Delta \eta_{\tau\tau}$ and $m_{jj}$, the VBF and boosted categories, referred to as “inclusive” categories, are split further into 13 exclusive signal regions with different signal-to-background ratios to improve the sensitivity. Table IV summarizes the analysis categories and signal region definitions. Figure 1 illustrates the expected signal and background composition in the signal and control regions of all analysis channels. Figure 2 compares for each analysis channel the observed distributions with predictions, as resulting from the fit described in Sec. VIII, for $p_T^j$ in the boosted inclusive categories, and for $m_{jj}$ in the VBF inclusive categories. The observed data agree within the given uncertainties with the background expectation described in Sec. VI for all distributions.

Six control regions are defined to constrain the normalization of the dominant backgrounds in the regions of phase
space where their purity is high. Their definitions are summarized in Table V. Two \(Z \rightarrow \ell \ell\) CRs, which are both more than 90% pure in \(Z \rightarrow \ell \ell\) events, are defined by applying the same selection as for the SF \(\tau_{\text{lep}}\tau_{\text{lep}}\) VBF and boosted inclusive regions, respectively, but with the \(m_{\ell \ell}\) requirement modified to \(80 < m_{\ell \ell} < 100\) GeV. The

<table>
<thead>
<tr>
<th>Signal region</th>
<th>Inclusive</th>
<th>(\tau_{\text{lep}}\tau_{\text{lep}})</th>
<th>(\tau_{\text{lep}}\tau_{\text{had}})</th>
<th>(\tau_{\text{had}}\tau_{\text{had}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>VBF High-(p_T^{\ell})</td>
<td>(p_T^{\ell} &gt; 30) GeV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\Delta \eta_{jj} &gt; 3)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(m_{jj} &gt; 400) GeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\eta_j_1 \cdot \eta_j_2 &lt; 0)</td>
<td>Not VBF high-(p_T^{\ell}) and not VBF tight</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Central leptons</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tight</td>
<td>(m_{jj} &gt; 800) GeV</td>
<td>(m_{jj} &gt; 500) GeV</td>
<td>Not VBF high-(p_T^{\ell})</td>
<td></td>
</tr>
<tr>
<td>(p_T^{\ell} &gt; 100) GeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(m_{jj} &gt; (1550 - 250</td>
<td>\Delta \eta_{jj}</td>
<td>)) GeV</td>
<td></td>
</tr>
<tr>
<td>Loose</td>
<td>Not VBF tight</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Boosted High-(p_T^{\ell})</td>
<td>Not VBF</td>
<td></td>
<td>(p_T^{\ell} &gt; 140) GeV</td>
<td></td>
</tr>
<tr>
<td>(p_T^{\ell} &gt; 100) GeV</td>
<td></td>
<td>(\Delta R_{\tau \tau} &lt; 1.5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low-(p_T^{\ell})</td>
<td>Not boosted high-(p_T^{\ell})</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**ATLAS**

\(\sqrt{s} = 13\) TeV, 36.1 fb\(^{-1}\)

- \(H \rightarrow \tau \tau\)
- Top
- \(Z \rightarrow \tau \tau\)
- Other backgrounds
- \(Z \rightarrow \ell \ell\)
- Misidentified \(\tau\)

FIG. 1. Expected signal and background composition in 6 control regions (CRs) and the 13 signal regions (SRs) used in the analysis.
The top-quark background is characterized by the presence of b-jets. Four separate top CRs are defined by inverting the b-jet veto in the inclusive VBF and boosted categories for each of the $\tau_{lep,lep}$ and $\tau_{lep,had}$ channels. The top CRs in the $\tau_{lep,lep}$ channel are about 80% pure in top-quark events. For the top CRs in the $\tau_{lep,had}$ channel, the requirement of $m_T < 70$ GeV is replaced by $m_T > 40$ GeV to further enhance the purity to about 70% in the VBF top CR.

### TABLE V

Definitions of the six control regions (CRs) used to constrain the $Z \rightarrow \ell\ell$ and top backgrounds to the event yield in data in the $\tau_{lep,lep}$ and $\tau_{lep,had}$ channels. “SF” denotes a selection of same-flavor light leptons.

<table>
<thead>
<tr>
<th>Region</th>
<th>Selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_{lep,lep}$ VBF</td>
<td>$Z \rightarrow \ell\ell$ CR</td>
</tr>
<tr>
<td>$\tau_{lep,lep}$</td>
<td>boosted $Z \rightarrow \ell\ell$ CR</td>
</tr>
<tr>
<td>$\tau_{lep,lep}$ VBF</td>
<td>top CR</td>
</tr>
<tr>
<td>$\tau_{lep,lep}$</td>
<td>boosted top CR</td>
</tr>
<tr>
<td>$\tau_{lep,had}$ VBF</td>
<td>top CR</td>
</tr>
<tr>
<td>$\tau_{lep,had}$</td>
<td>boosted top CR</td>
</tr>
</tbody>
</table>

---

FIG. 2. Comparisons between data and predictions as computed by the fit of (top) the $p_T$ of the Higgs-boson candidate ($p_T^{H}$) in the boosted inclusive category and (bottom) the invariant mass of the two highest-$p_T$ jets ($m_{jj}$) in the VBF inclusive category for (left) the $\tau_{lep,lep}$ channel, (center) the $\tau_{lep,had}$ channel and (right) the $\tau_{had,had}$ channel. The ratios of the data to the background model are shown in the lower panels. The observed Higgs-boson signal ($\mu = 1.09$) is shown with the solid red line. Entries with values that would exceed the x-axis range are shown in the last bin of each distribution. The size of the combined statistical, experimental and theoretical uncertainties in the background is indicated by the hatched bands.
and about 60% in the boosted top CR. No such control regions are defined for the \( \tau_{\text{had}} \tau_{\text{had}} \) channel since the top and \( Z \rightarrow \ell \ell \) backgrounds are negligible in this case.

One validation region is defined for each signal region ("Z → ττ VRs") to validate the event yields and kinematic distributions of simulated \( Z \rightarrow \tau \tau \) events. The \( Z \rightarrow \tau \tau \) VRs are composed of \( Z \rightarrow \ell \ell \) events with kinematics similar to the \( Z \rightarrow \tau \tau \) background in the respective signal regions. This is achieved by starting with an event selection that is based on the SF \( \tau_{\text{lep}} \tau_{\text{lep}} \) channel preselection with the following differences that account for the selection of light leptons instead of decay products from \( \tau \)-leptons:

- The \( m_{\tau \tau} \), \( E_{\text{T}}^{\text{miss}} \) and \( E_{\text{T}}^{\text{miss,hard}} \) requirements are dropped and the \( m_{\ell \ell} \) requirement is inverted to \( m_{\ell \ell} > 80 \text{ GeV} \). The other requirements on \( \tau \)-lepton decays are replaced with requirements on the two light leptons. In particular, the requirements on \( p_{T}^{\ell} \) are substituted by the \( p_{T} \) of the \( Z \) boson computed from the \( p_{T} \) of the light leptons (\( p_{T}^{\ell} \)). Requirements on jets are unchanged since they define the shape of most kinematic distributions for \( Z \)-boson production similarly in the SRs and the \( Z \rightarrow \tau \tau \) VRs. More than 99% of the selected events are from \( Z \rightarrow \ell \ell \) in all \( Z \rightarrow \tau \tau \) VRs.

### VI. BACKGROUND ESTIMATION

The final-state topologies of the three analysis channels have different background compositions, which necessitates different strategies for the background estimation. In each SR, the expected number of background events and the associated kinematic distributions are derived from a mixture of data-driven methods and simulation.

Background contributions with \( \tau_{\text{had-vis}} \), with prompt light leptons and with light leptons from \( \tau \)-lepton decays are estimated from simulation. If their contribution is significant, their normalization is constrained using data in the fit, including all statistical and systematic uncertainties described in Sec. VII, but without uncertainties in total simulated cross sections extrapolated to the selected phase space. Systematic uncertainties are the dominant contribution to the normalization factor uncertainties. Also shown are the analysis channels to which the normalization factors are applied.

<table>
<thead>
<tr>
<th>Background Channel</th>
<th>Normalization factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Z \rightarrow \ell \ell ) (CR)</td>
<td>( \tau_{\text{lep}} \tau_{\text{lep}} ), ( 0.88^{+0.34}_{-0.30} )</td>
</tr>
<tr>
<td>Top (CR)</td>
<td>( \tau_{\text{lep}} \tau_{\text{lep}} ), ( 1.19 \pm 0.09 )</td>
</tr>
<tr>
<td>Top (CR)</td>
<td>( \tau_{\text{lep}} \tau_{\text{had}} ), ( 1.53^{+0.30}_{-0.27} )</td>
</tr>
<tr>
<td>Fake-( \tau_{\text{had-vis}} ) (data-driven)</td>
<td>( \tau_{\text{had}} \tau_{\text{had}} ), ( 1.12 \pm 0.12 )</td>
</tr>
<tr>
<td>( Z \rightarrow \tau \tau ) (fit in each SR)</td>
<td>( \tau_{\text{lep}} \tau_{\text{lep}}, \tau_{\text{lep}} \tau_{\text{had}}, \tau_{\text{had}} \tau_{\text{had}} ), ( 1.04^{+0.10}_{-0.09} )</td>
</tr>
</tbody>
</table>

A. \( Z \rightarrow \tau \tau \) background validation

The Drell-Yan process \( pp \rightarrow Z/\gamma^{*} \rightarrow \tau \tau \) is a dominant irreducible background in all analysis categories and contributes between 50% and 90% of the total background depending on the signal region. The separation between the Drell-Yan and the \( H \rightarrow \tau \tau \) signal processes is limited by the \( m_{\tau \tau}^{\text{MMC}} \) resolution.

The modeling of this important background is validated using \( Z \rightarrow \tau \tau \) VRs that consist of \( Z \rightarrow \ell \ell \) events. In Fig. 3, the observed distributions of several variables are compared with simulation normalized to the event yield in data. The selected observables correspond to either \( \tau \)-boson variables \( m_{\tau \tau}^{\text{MMC}} \) or \( p_{T}^{\ell} \), \( \Delta R_{\ell \ell} \), \( \Delta R_{jj} \), \( \Delta m_{jj} \), or to variables which differ in the simulation in each decay channel (\( p_{T}^{\ell} \)). Generally, the SHERPA simulation describes the shape of data distributions within the experimental and theoretical uncertainties (see Sec. VII), with the exception of a slight trend in the ratio of data to simulation as a function of \( \Delta m_{jj} \) shown in Fig. 3. These trends have no impact on the modeling of \( m_{\tau \tau}^{\text{MMC}} \). Reweights the simulation with the observed \( m_{jj} \) distribution, which is an important variable for VBF categorization, has a negligible impact on the measurement. In the fit, the normalization of the \( Z \rightarrow \tau \tau \) background is correlated across the decay channels and constrained by data in the \( m_{\tau \tau}^{\text{MMC}} \) distributions of the signal regions associated with the boosted and VBF.
FIG. 3. Observed and expected distributions in the $Z \rightarrow \tau \tau$ validation regions (VRs) corresponding to (a)–(d) the $r_{lep} \tau_{had}$ VBF inclusive category and (e)–(i) the $r_{lep} \tau_{had}$ boosted inclusive category. Shown are, in the respective region: (a) the pseudorapidity separation ($|\Delta \eta_{jj}|$) and (b) the invariant mass ($m_{jj}$) of the two highest-$p_T$ jets; (c) and (e) the $p_T$ of the di-lepton system ($p_T^{\ell \ell}$); (d) and (g) the $p_T$ of the highest-$p_T$ jet ($p_T^j$); (i) the angular distance between the light leptons ($\Delta R_{\tau \tau}$); (h) the $p_T$ of the highest-$p_T$ light lepton ($p_T^{\ell}$); and (i) the $p_T$ of the second-highest-$p_T$ light lepton ($p_T^{\ell'}$). The predictions in these validation regions are not computed by the fit, but are simply normalized to the event yield in data. The size of the combined statistical, experimental and theoretical uncertainties is indicated by the hatched bands. The ratios of the data to the background model are shown in the lower panels together with the theoretical uncertainties in the SHERPA simulation of $Z \rightarrow \ell \ell$, which are indicated by the blue lines.
FIG. 4. For the control regions (CRs) defined in Sec. V, comparisons between data and predictions as computed by the fit for the reconstructed di-lepton invariant mass ($m_{\ell\ell}^{\text{MMC}}$). Shown are (a) the $t_{\text{lep}}t_{\text{lep}}$ VBF $Z \to \ell\ell$ control region (CR), (b) the $t_{\text{lep}}$ boosted top CR and (c) the $t_{\text{lep}}t_{\text{had}}$ VBF top CR. Entries with values that would exceed the x-axis range are shown in the last bin of each distribution. The size of the combined statistical, experimental and theoretical uncertainties in the background is indicated by the hatched bands. The ratios of the data to the background model are shown in the lower panels.

categories, independently. As shown in Table VI, it is constrained to \(\pm 5\%\) in the boosted category and to \(\pm 9\%\) in the VBF category. The relative acceptance of events among the signal regions within a category is validated by applying the corresponding event-selection criteria to each individual channel. Entries with values that would exceed the x-axis range are shown in the last bin of each distribution. The size of the combined statistical, experimental and theoretical uncertainties in the background is indicated by the hatched bands. The ratios of the data to the background model are shown in the lower panels.

A. \(Z\rightarrow \ell\ell\) background

Decays of \(Z\) bosons into light leptons are a significant background for the \(t_{\text{lep}}t_{\text{lep}}\) and \(t_{\text{lep}}t_{\text{had}}\) channels, where mismeasured \(E_T^{\text{miss}}\) can bias the reconstructed \(m_{\ell\ell}^{\text{MMC}}\) of light-lepton pairs towards values similar to those expected for the signal. The observed event yields in the \(Z\rightarrow \ell\ell\) CRs constrain the normalization of simulated \(Z\rightarrow \ell\ell\) events in the \(t_{\text{lep}}t_{\text{lep}}\) channel to \(\pm 40\%\) in the VBF category and to \(\pm 25\%\) in the boosted category, as shown in Table VI. The good modeling of the \(m_{\ell\ell}^{\text{MMC}}\) distribution in the \(t_{\text{lep}}t_{\text{lep}}\) VBF \(Z\rightarrow \ell\ell\) CR is shown in Fig. 4(a). In other channels, the contribution from \(Z\rightarrow \ell\ell\) events is normalized to its theoretical cross section. In the \(t_{\text{lep}}t_{\text{had}}\) channel, \(Z\rightarrow \ell\ell\) background contributes primarily through \(Z\rightarrow ee\) decays where an electron is misidentified as a \(t_{\text{had-vis}}\) candidate. Due to the dedicated electron veto algorithm applied to selected 1-prong \(t_{\text{had-vis}}\) candidates (see Sec. VA), this background is small. This and other backgrounds from light leptons misidentified as \(t_{\text{had-vis}}\) in this channel are estimated from simulation, with the probability for electrons misidentified as \(t_{\text{had-vis}}\) candidates scaled to match that observed in data [94].

C. Top-quark background

The production of \(t\bar{t}\) pairs or single top quarks is a significant background ("top background") for the \(t_{\text{lep}}t_{\text{lep}}\) and \(t_{\text{lep}}t_{\text{had}}\) channels, due to the production of prompt light leptons with associated \(E_T^{\text{miss}}\) in the top-quark decay chain \(t\rightarrow Wb, W\rightarrow \ell\nu, \tau\nu\). Events where a selected \(\tau\)-lepton decay product is misidentified, are estimated using data-driven methods that are discussed in Sec. VID. The remaining top background is estimated from simulation. In the \(t_{\text{lep}}t_{\text{lep}}\) and \(t_{\text{lep}}t_{\text{had}}\) channels the normalization of simulated top background is additionally constrained by the absolute event yields in their respective top CRs to \(\pm 30\%\) in the \(t_{\text{lep}}t_{\text{had}}\) VBF top CR and less than \(\pm 10\%\) in the other top CRs, as shown in Table VI. Figures 4(b) and 4(c) show \(m_{\ell\ell}^{\text{MMC}}\) distributions in the \(t_{\text{lep}}t_{\text{lep}}\) boosted top CR and the \(t_{\text{lep}}t_{\text{had}}\) VBF top CR, respectively.

D. Backgrounds from misidentified \(\tau\)

Apart from the small contribution from light leptons misidentified as \(t_{\text{had-vis}}\) described in Sec. VI B, hadronic jets can be misidentified as \(t_{\text{had-vis}}\), electrons and muons. These sources of background contribute up to half of the total background, depending on the signal region, and are estimated with data-driven techniques. Since the background sources depend on the event topology, specific methods are applied to each individual channel. In the \(t_{\text{lep}}t_{\text{lep}}\) channel, the main sources of the fake-\(\ell\) background are multijets, \(W\) bosons in association with jets, and semileptonically decaying \(t\bar{t}\) events. All these background sources are treated together. Fake-\(\ell\) regions are defined in data by requiring that the light lepton with the
second-highest $p_T$ does not satisfy the “gradient” isolation criterion. This is referred to as “inverted” isolation. In addition, if the light lepton is an electron, its identification criteria are relaxed to “loose.” Fake-$\ell$ templates are created from these samples by subtracting top and $Z \rightarrow \ell\ell$ backgrounds that produce real light leptons, estimated from simulation. The normalization of each template is then scaled by a factor that corrects for the inverted-isolation requirement. These correction factors are computed for each combination of lepton flavor from events that pass the $\tau_{lep}\tau_{lep}$ selection but have same-charge light leptons, subtracting simulated top and $Z \rightarrow \ell\ell$ backgrounds. Fake-$\ell$ background in the top-quark CRs is estimated following the procedure.

Systematic uncertainties in the shape and normalization of the fake-$\ell$ background in the $\tau_{lep}\tau_{lep}$ channel depend on the $p_T$ of the second-highest-$p_T$ lepton and are estimated as follows. A closure test of the background estimate is performed using events where the leptons are required to have the same charge and yields an uncertainty ranging between 20% and 65%. An uncertainty in the heavy-flavor content is estimated by using isolation correction factors that are computed from samples selected with inverted $b$-jet requirements. This uncertainty is as large as 50%. Minor contributions come from the uncertainty in the fractional composition of the fake-$\ell$ background in top-quark decays, multijet events and $W$-boson production.

In the $\tau_{lep}\tau_{had}$ channel, a “fake-factor” method is used to derive estimates for fake-$\tau_{had-vis}$ events, composed mainly of multijet events and $W$-boson production in association with jets. A fake-factor is defined as the ratio of the number of events where the highest-$p_T$ jet is identified as a “medium” $\tau_{had-vis}$ candidate to the number of events with a highest-$p_T$ jet that passes a very loose $\tau_{had-vis}$ identification but fails the “medium” one. Fake-factors depend on the $p_T$ and track multiplicity of the $\tau_{had-vis}$ candidate and on the type of parton initiating the jet. Therefore, they are computed depending on the $p_T$ and the track multiplicity, in both quark-jet-dominated “$W$-enhanced” and gluon-jet-dominated “multijet-enhanced” regions. The $W$-enhanced regions are defined by inverting the $m_T < 70$ GeV requirement and the multijet-enhanced regions are defined by inverting the light-lepton isolation, relative to the inclusive boosted and VBF selections. Backgrounds from $Z$-boson production with associated jets and semileptonically decaying $t\bar{t}$ have fake-factors similar to those found in backgrounds from $W$ bosons, and their contributions are negligible. The fake-factors are in the range 0.15–0.25 for 1-prong and 0.01–0.04 for 3-prong $\tau_{had-vis}$. To obtain the fake-$\tau_{had-vis}$ background estimate for the signal regions, these fake-factors are first weighted by the multijets-to-$W$ fraction. The weighted fake-factors are then applied to events in regions defined by the selections of the corresponding signal regions, except that the highest-$p_T$ $\tau_{had-vis}$ candidate passes a very loose $\tau_{had-vis}$ identification and fails the “medium” one (“anti-ID” regions). The relative multijet contribution in each anti-ID region is estimated from the yield of events that fail the light-lepton isolation requirement, multiplied by a factor that corrects for this requirement. The multijet contribution varies by more than 50% and depends on the $p_T$ and on the $\Delta\phi$ between $\tau_{had-vis}$ and $E_T^{miss}$. The good agreement between data and background estimates is shown in Fig. 5(a) for the main discriminant of the analysis, $m_T^{MMC}$, in the boosted $W$-enhanced region.

The dominant contribution to the uncertainties in the fake-$\tau_{had-vis}$ background in the $\tau_{lep}\tau_{had}$ channel originates from the statistical uncertainty in the individual fake-factors of up to 10% in the boosted signal regions and up to 35% in the VBF signal regions. Minor contributions originate from

FIG. 5. Observed distributions and predictions computed by the fit for (a) $m_T^{MMC}$ in the $W$-enhanced region of the $\tau_{lep}\tau_{had}$ boosted inclusive category, and (b) $\Delta\eta$ between the two $\tau_{had-vis}$, for events in the boosted low-$p_T^{\tau}$ signal region (SR) of the $\tau_{had}\tau_{had}$ channel. Entries with values that would exceed the x-axis range are shown in the last bin of each distribution. The size of the combined statistical, experimental and theoretical uncertainties in the background is indicated by the hatched bands. The ratios of the data to the background model are shown in the lower panels.
the statistical uncertainty in the anti-ID regions and uncertainties in the fractional size of the multijet contribution to the fake-r_{had-vis} background.

In the r_{had}r_{had} channel, the multijet background is modeled using a template extracted from data that pass the signal-region selections, but where the r_{had-vis} candidates are allowed to have two tracks and required to fail the opposite-charge requirement (nOC region). The contribution of events with true r-leptons from other SM processes is subtracted from this template using simulation. The template is then reweighted using scale factors dependent on the difference in \phi between the r_{had-vis} candidates (Δ\phi_{\tau\tau}). These scale factors are derived by comparing the template from an nOC selection with a region obtained by requiring the r_{had-vis} pair to have opposite charge and the second-highest-p_{T} r_{had-vis} to fail the “tight” but pass the “medium” identification requirements. As the yield of events that pass these identification requirements is small, the scale factors are derived from events that pass the r_{had}r_{had} selection with looser Δ\phi_{\tau\tau} and ΔR_{\tau\tau} requirements to gain statistical power. The normalization of the multijet background is constrained in the fit by data in the m_{\tau\tau}^{MMC} distribution in the signal regions. For this, a normalization factor is defined and it is correlated across all r_{had}r_{had} signal regions. Figure 5(b) shows good agreement between data and background predictions in the distribution of ΔH between the two r_{had-vis}, which has a quite different shape for the multijets than for the Z \rightarrow \tau\tau process. In this figure, events are selected that pass the r_{had}r_{had} boosted low-p_{T} selection. Contributions from other backgrounds, such as W with associated jets, range from 2% to 5% in the r_{had}r_{had} SRs.

The event yield of the multijet background in the r_{had}r_{had} channel is constrained by data to \pm 15% in the signal regions as shown in Table VI. The dominant contribution to the uncertainties that affect the m_{\tau\tau}^{MMC} shape originates from the statistical uncertainties in the Δ\phi_{\tau\tau} scale factors and amounts to 8%. The systematic uncertainty in these scale factors is estimated by comparing them with scale factors computed from the nOC region and a CR defined by requiring opposite-charge r_{had-vis} to pass “loose” but not “medium” identification. Minor contributions arise from the uncertainty in the extrapolation from the nOC requirement and the uncertainty from the subtraction of simulated backgrounds. The combination of these uncertainties leads to a total variation in the m_{\tau\tau}^{MMC} template shape by at most 10% between bins.

VII. SYSTEMATIC UNCERTAINTIES

The expected signal and background yields in the various signal and control regions as well as the shape of the m_{\tau\tau}^{MMC} distributions in the signal regions are affected by systematic uncertainties. These are discussed below, grouped into three categories: theoretical uncertainties in signal, theoretical uncertainties in background, and experimental uncertainties. The uncertainties in backgrounds from misidentified r-leptons, which are estimated using data-driven techniques, are discussed in Sec. VID. The effects of all uncertainties are included in the fit model described in Sec. VIII.

A. Theoretical uncertainties in signal

The procedures to estimate the uncertainty in the Higgs production cross sections follow the recommendations by the LHC Higgs Cross Section Working Group [100]. They are briefly summarized below. Uncertainties are evaluated separately for their impact on the total cross section, their impact on the acceptance in different SRs, and on the shape of the m_{\tau\tau}^{MMC} distribution in each SR.

The cross section of ggF production in association with an exclusive number of additional jets has large uncertainties from higher-order QCD corrections [101]. In this analysis, the boosted and VBF categories almost exclusively select ggF events with one and two additional jets, respectively. To take this effect into account, nine uncertainty sources are included. Four sources account for uncertainties in the jet multiplicities due to missing higher-order corrections: Two sources account for yield uncertainties and two sources account for migration uncertainties of zero to one jets and one to at least two jets in the event, respectively, using the STWZ [102] and BLPTW [102–104] predictions as an input. Three uncertainty sources parametrize modeling uncertainties in the Higgs-boson p_{T}, two of which encapsulate the migration uncertainty between the intermediate and high-p_{T} regions of events with at least one jet, and one which encapsulates the treatment of the top-quark mass in the loop corrections, where the difference between the LO and NLO predictions is taken as an uncertainty due to missing higher-order corrections. Two sources account for the acceptance uncertainties of ggF production in the VBF phase space from selecting exactly two and at least three jets, respectively. Their size is estimated using an extension of the Stewart–Tackmann method [105,106]. The resulting acceptance uncertainties from these nine sources range from 1% to 10%, with the dominant uncertainties due to the modeling of the Higgs p_{T} distribution in all SRs, to the scale variations in the boosted SRs, and to the acceptance uncertainties in the VBF signal regions.

For VBF and VH production cross sections, the uncertainties due to missing higher-order QCD corrections are estimated by varying the factorization and renormalization scales by factors of two around the nominal scale. The resulting uncertainties in the total cross section are below 1% for VBF and WH production and below 5% for ZH production. The uncertainties in the acceptance in the different SRs are about 1% for VBF production in all categories. For VH production the relative acceptance uncertainty ranges between −10% and +20% in VBF SRs. It is below 10% in boosted SRs.
Uncertainties related to the simulation of the underlying event, hadronization and parton shower for all signal samples are estimated by comparing the acceptance when using the default UEPS model from PYTHIA 8.212 with an alternative UEPS model from HERWIG 7.0.3. The resulting acceptance uncertainties range from 2% to 26% for ggF production and from 2% to 18% for VBF production, depending on the signal region. The PDF uncertainties are estimated using 30 eigenvector variations and two $\alpha_s$ variations that are evaluated independently relative to the default PDF set PDF4LHC15 [42]. The total uncertainty due to these variations is 5% or less depending on the SR and the Higgs production mode. Finally, an uncertainty in the $H \rightarrow \tau\tau$ decay branching ratio of 1% [100] affects the signal rates. All sources of theoretical uncertainties in the signal expectation are correlated across SRs.

B. Theoretical uncertainties in backgrounds

Uncertainties from missing higher-order corrections, the PDF parametrization and the UEPS modelling are also considered for the dominant $Z \rightarrow \tau\tau$ background. The UEPS modelling uncertainties are estimated by comparing with an alternative $Z \rightarrow \tau\tau$ sample as described in Sec. III. Since its overall normalization is constrained separately in the VBF and boosted SRs, variations due to these uncertainties are considered in the event migration within an analysis channel, in the $m_{\tau\tau}^{\text{MMC}}$ shape and in the relative change in acceptance between the three analysis channels. These variations are treated as uncorrelated between the VBF and boosted SRs. In addition, the first two types of variations are treated as uncorrelated among the three analysis channels. This treatment accounts for the differences in the corresponding event selections. The largest uncertainties are due to the CKKW matching [107] and are evaluated as a function of the number of true jets and the Z-boson $p_T$. They vary between 1% and 5% depending on the SR. The uncertainty in the measured cross section for electroweak $Z$ production with two associated jets [108] is found to be small compared to the other uncertainties in $Z$-boson production.

The top-quark background normalization in the $\tau_{\text{lep}} \tau_{\text{lep}}$ and $\tau_{\text{lep}} \tau_{\text{had}}$ channels as well as the $Z \rightarrow \ell\ell$ background normalization in the $\tau_{\text{lep}} \tau_{\text{lep}}$ channel are constrained by data in dedicated CRs. All other simulated background contributions are normalized to their Monte Carlo prediction. For all simulated background contributions, other than $Z \rightarrow \tau\tau$, no theoretical uncertainties are considered, as their impact is small compared to the uncertainties in the dominant backgrounds from $Z \rightarrow \tau\tau$ and misidentified leptons.

C. Experimental uncertainties

Experimental systematic uncertainties result from uncertainties in efficiencies for triggering, object reconstruction and identification, as well as from uncertainties in the energy scale and resolution of jets, $\tau_{\text{had-vis}}$, light leptons and $E_T^{\text{miss}}$. These uncertainties affect both the event yields and the shape of the $m_{\tau\tau}^{\text{MMC}}$. The dominant experimental uncertainties in the final result are related to jet and $\tau_{\text{had-vis}}$ reconstruction. The impact of the electron- and muon-related uncertainties [86,87,109] on the measurement are small. Uncertainties in the integrated luminosity affect the number of predicted signal and background events, with the exception of processes that are normalized to data, see Table VI. This uncertainty is 2.1% for the combined 2015 + 2016 data set. It is derived using a methodology similar to that detailed in Ref. [110], and using the LUCID-2 detector for the baseline luminosity measurements [111], from a calibration of the luminosity scale using $x$-$y$ beam-separation scans.

The uncertainties of the $\tau_{\text{had-vis}}$ identification efficiency are in the range of 2–4.5% for the reconstruction efficiency [112], 3–14% for the trigger efficiency (depending on the $\tau_{\text{had-vis}}$ $p_T$), 5–6% for the identification efficiency and 3–14% for the rate at which an electron is misidentified as $\tau_{\text{had-vis}}$ (depending on the $\tau_{\text{had-vis}}$ $\eta$) [94]. The uncertainties of the $b$-tagging efficiencies are measured in dedicated calibration analyses [92] and are decomposed into uncorrelated components. Uncertainties in the efficiency to pass the JVT and forward JVT requirements are also considered [91,113]. Simulated events are corrected for differences in these efficiencies between data and simulation and the associated uncertainties are propagated through the analysis.

The uncertainties of the $\tau_{\text{had-vis}}$ energy scale [94] are determined by fitting the $Z$-boson mass in $Z \rightarrow \tau\tau$ events, reconstructed using the visible $\tau$ decay products. The precision amounts to 2–3%, which is dominated by the uncertainty of background modeling. Additional uncertainties based on the modeling of the calorimeter response to single particles are added for $\tau_{\text{had-vis}}$ with $p_T > 50$ GeV [114]. The jet energy scale and its uncertainty are derived by combining information from test-beam data, LHC collision data and simulation [115]. The uncertainties from these measurements are factorized into eight principal components. Additional uncertainties that are considered are related to jet flavor, pileup corrections, $\eta$-dependence, and high-$p_T$ jets, yielding a total of 20 independent sources. The uncertainties amount to 1–6% per jet, depending on the jet $p_T$. The jet energy resolution uncertainties [116] are divided into 11 independent components and amount to 1–6%.

Since systematic uncertainties of the energy scales of all objects affect the reconstructed $E_T^{\text{miss}}$, this is recalculated after each variation is applied. The scale uncertainty of $E_T^{\text{miss}}$ due to the energy in the calorimeter cells not associated with physics objects is also taken into account [96]. The uncertainty of the resolution of $E_T^{\text{miss}}$ arises from the energy resolution uncertainties of each of the $E_T^{\text{miss}}$ terms and the modeling of pileup and its effects on the soft term (see Sec. IV).
VIII. RESULTS

Maximum-likelihood fits are performed on data to extract parameters of interest that probe $H \rightarrow \tau\tau$ production with increasing granularity. Firstly, a single parameter is fitted to measure the total cross section of the $H \rightarrow \tau\tau$ production processes. Then, a two-parameter cross-section fit is presented separating the $ggF$ and VBF production processes. Finally, a three-parameter fit is performed to measure $ggF$ production cross sections in two exclusive regions of phase space. For the small contribution from $H \rightarrow WW^*$ decays, the measurements assume the SM predictions for production cross section and branching ratio.

A probability model is constructed that describes the $m_{\tau\tau}^{\text{MMC}}$ distributions in the 13 signal regions and the event yields in 6 control regions. The latter are included to constrain the normalizations of the dominant backgrounds. Each signal region is modeled by a product of Poisson distributions, where each such distribution describes the expected event count in intervals of $m_{\tau\tau}^{\text{MMC}}$. Each control region is modeled by a single Poisson distribution that describes the total expected event count in that region. Signal and background predictions depend on systematic uncertainties, which are parametrized as nuisance parameters and are constrained using Gaussian or log-normal probability distributions. The latter are used for normalization factors (see Table VI) to ensure that they are always positive. The dependence of the predictions on nuisance parameters related to systematic uncertainties is modeled with an interpolation approach between yields obtained at different fixed systematic uncertainty settings. A smoothing procedure is applied to remove occasional large local fluctuations in the $m_{\tau\tau}^{\text{MMC}}$ distribution templates, which encode systematic uncertainties of some background processes in certain regions. For the measurements, all theoretical uncertainties are included, except those related to the respective measured signal cross sections, and are correlated as described in Sec. VII A. The experimental uncertainties are fully correlated across categories and the background modeling uncertainties are generally uncorrelated, with the exception of the normalization factors as described in Sec. VI. Estimates of the parameters of interest and the confidence intervals are calculated with the profile likelihood ratio [117] test statistic, whereas the test statistic $\hat{q}_0$ [117] is used to compute the significances of the deviations from the background-only hypothesis.

The observed (expected) significance of the signal excess relative to the background-only hypothesis computed from the likelihood fit is 4.4 (4.1) standard deviations, compatible with a SM Higgs boson with a mass $m_H = 125$ GeV. This result is combined with the result of the search for $H \rightarrow \tau\tau$ using data at 7 and 8 TeV center-of-mass energies [15]. The combined observed (expected) significance amounts to 6.4 (5.4) standard deviations. In this combination, all nuisance parameters are treated as uncorrelated between the two analyses. In particular, the dominant $Z \rightarrow \tau\tau$ background is estimated differently, as mentioned in Sec. I.

The parameter $\sigma_{H \rightarrow \tau\tau} \equiv \sigma_H \cdot \mathcal{B}(H \rightarrow \tau\tau)$ is fitted, where $\sigma_H$ is the total cross section of the considered Higgs-boson production processes $ggF$, VBF, VH and $t\bar{t}H$, and where $\mathcal{B}(H \rightarrow \tau\tau)$ is the $H \rightarrow \tau\tau$ branching fraction. For this measurement, the relative contributions from the various Higgs production processes are assumed as predicted by the SM and the uncertainties related to the predicted total signal cross section are excluded. The measured value of $\sigma_{H \rightarrow \tau\tau}$ is $3.77^{+0.60}_{-0.59}$ (stat) $^{+0.87}_{-0.74}$ (syst) pb, consistent with the SM prediction, $\sigma_{H \rightarrow \tau\tau}^{\text{SM}} = 3.46 \pm 0.13$ pb [100]. The signal

### TABLE VII. Observed event yields and predictions as computed by the fit in the $\tau\text{lep}\tau\text{lep}$ signal regions. Uncertainties include statistical and systematic components.

<table>
<thead>
<tr>
<th>$\tau\text{lep}\tau\text{lep}$ VBF</th>
<th>$\tau\text{lep}\tau\text{lep}$ boosted</th>
<th>$\tau\text{lep}\tau\text{lep}$ boosted</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low-$p_T^{\tau\ell\ell}$</td>
<td>High-$p_T^{\tau\ell\ell}$</td>
</tr>
<tr>
<td>$Z \rightarrow \tau\tau$</td>
<td>151 ± 13</td>
<td>5977 ± 90</td>
</tr>
<tr>
<td>$Z \rightarrow \ell\ell'$</td>
<td>15.1 ± 4.9</td>
<td>20.3 ± 6.6</td>
</tr>
<tr>
<td>Top</td>
<td>33.0 ± 6.4</td>
<td>25.1 ± 4.5</td>
</tr>
<tr>
<td>$VV$</td>
<td>11.8 ± 2.2</td>
<td>10.7 ± 1.5</td>
</tr>
<tr>
<td>Misidentified $\tau$</td>
<td>18.3 ± 9.6</td>
<td>9.6 ± 4.8</td>
</tr>
<tr>
<td>$ggF, H \rightarrow WW^*$</td>
<td>1.2 ± 0.2</td>
<td>1.4 ± 0.3</td>
</tr>
<tr>
<td>VBF, $H \rightarrow WW^*$</td>
<td>1.7 ± 0.2</td>
<td>4.1 ± 0.5</td>
</tr>
<tr>
<td>$ggF, H \rightarrow \tau\tau$</td>
<td>2.6 ± 0.9</td>
<td>1.8 ± 0.9</td>
</tr>
<tr>
<td>VBF, $H \rightarrow \tau\tau$</td>
<td>5.3 ± 1.5</td>
<td>11.3 ± 3.0</td>
</tr>
<tr>
<td>$WH, H \rightarrow \tau\tau$</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>$ZH, H \rightarrow \tau\tau$</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>$t\bar{t}H, H \rightarrow \tau\tau$</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>Total background</td>
<td>232 ± 13</td>
<td>178 ± 12</td>
</tr>
<tr>
<td>Total signal</td>
<td>8.0 ± 2.2</td>
<td>13.2 ± 3.5</td>
</tr>
<tr>
<td>Data</td>
<td>237</td>
<td>188</td>
</tr>
</tbody>
</table>

TABLE VIII. Observed event yields and predictions as computed by the fit in the $\tau_{lep}\tau_{had}$ signal regions. Uncertainties include statistical and systematic components.

<table>
<thead>
<tr>
<th>$\tau_{lep}\tau_{had}$</th>
<th>VBF</th>
<th>$\tau_{lep}\tau_{had}$ boosted</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Z \rightarrow \tau\tau$</td>
<td>178 $\pm$ 18</td>
<td>323 $\pm$ 21</td>
</tr>
<tr>
<td>$Z \rightarrow \ell\ell$</td>
<td>10.0 $\pm$ 3.0</td>
<td>12.7 $\pm$ 3.1</td>
</tr>
<tr>
<td>Top</td>
<td>5.8 $\pm$ 1.6</td>
<td>17.9 $\pm$ 4.6</td>
</tr>
<tr>
<td>Misidentified $\tau$</td>
<td>103 $\pm$ 16</td>
<td>101 $\pm$ 15</td>
</tr>
<tr>
<td>Other backgrounds</td>
<td>4.0 $\pm$ 1.6</td>
<td>9.3 $\pm$ 1.9</td>
</tr>
<tr>
<td>$ggF, H \rightarrow \tau\tau$</td>
<td>3.8 $\pm$ 1.1</td>
<td>7.1 $\pm$ 1.9</td>
</tr>
<tr>
<td>VBF, $H \rightarrow \tau\tau$</td>
<td>7.6 $\pm$ 2.2</td>
<td>24.7 $\pm$ 6.8</td>
</tr>
<tr>
<td>$WH, H \rightarrow \tau\tau$</td>
<td>$&lt; 0.1$</td>
<td>0.1 $\pm$ 0.0</td>
</tr>
<tr>
<td>$ZH, H \rightarrow \tau\tau$</td>
<td>$&lt; 0.1$</td>
<td>$&lt; 0.1$</td>
</tr>
<tr>
<td>$t\bar{t}H, H \rightarrow \tau\tau$</td>
<td>$&lt; 0.1$</td>
<td>$&lt; 0.1$</td>
</tr>
<tr>
<td>Total background</td>
<td>301 $\pm$ 17</td>
<td>463 $\pm$ 21</td>
</tr>
<tr>
<td>Total signal</td>
<td>11.5 $\pm$ 3.2</td>
<td>32.0 $\pm$ 8.2</td>
</tr>
<tr>
<td>Data</td>
<td>318</td>
<td>496</td>
</tr>
</tbody>
</table>

TABLE IX. Observed event yields and predictions as computed by the fit in the $\tau_{had}\tau_{had}$ signal regions. Uncertainties include statistical and systematic components.

<table>
<thead>
<tr>
<th>$\tau_{had}\tau_{had}$</th>
<th>VBF</th>
<th>$\tau_{had}\tau_{had}$ boosted</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Z \rightarrow \tau\tau$</td>
<td>67.3 $\pm$ 9.2</td>
<td>100 $\pm$ 12</td>
</tr>
<tr>
<td>Misidentified $\tau$</td>
<td>45.0 $\pm$ 5.4</td>
<td>96.4 $\pm$ 9.2</td>
</tr>
<tr>
<td>Other backgrounds</td>
<td>4.4 $\pm$ 1.4</td>
<td>11.6 $\pm$ 1.7</td>
</tr>
<tr>
<td>$ggF, H \rightarrow \tau\tau$</td>
<td>1.1 $\pm$ 0.4</td>
<td>2.0 $\pm$ 0.7</td>
</tr>
<tr>
<td>VBF, $H \rightarrow \tau\tau$</td>
<td>1.4 $\pm$ 0.5</td>
<td>6.4 $\pm$ 1.8</td>
</tr>
<tr>
<td>$WH, H \rightarrow \tau\tau$</td>
<td>$&lt; 0.1$</td>
<td>$&lt; 0.1$</td>
</tr>
<tr>
<td>$ZH, H \rightarrow \tau\tau$</td>
<td>$&lt; 0.1$</td>
<td>$&lt; 0.1$</td>
</tr>
<tr>
<td>$t\bar{t}H, H \rightarrow \tau\tau$</td>
<td>$&lt; 0.1$</td>
<td>$&lt; 0.1$</td>
</tr>
<tr>
<td>Total background</td>
<td>116.7 $\pm$ 9.4</td>
<td>208 $\pm$ 12</td>
</tr>
<tr>
<td>Total signal</td>
<td>2.6 $\pm$ 0.8</td>
<td>8.6 $\pm$ 2.4</td>
</tr>
<tr>
<td>Data</td>
<td>121</td>
<td>220</td>
</tr>
</tbody>
</table>

The strength $\mu_{H \rightarrow \tau\tau}$ is defined as the ratio of the measured signal yield to the Standard Model expectation. It is computed by the fit described above, including uncertainties in the predicted signal cross section, and is evaluated to be 1.09 $^{+0.16}_{-0.17}$ (stat) $^{+0.28}_{-0.22}$ (syst) $^{+0.16}_{-0.11}$ (theory syst).

Tables VII–IX summarize the expected signal and background yields computed by the fit in each signal region for the $\sigma_{H \rightarrow \tau\tau}$ measurement. The signal event yields are given separately for each production process of relevance. Within the uncertainties, good agreement is observed between the data and the predicted sum of signal and background contributions, for a SM Higgs boson of mass $m_H = 125$ GeV with the measured value of $\sigma_{H \rightarrow \tau\tau}$ reported above.

Table X shows a summary of the dominant uncertainties in $\sigma_{H \rightarrow \tau\tau}$, grouped by their respective sources. Figure 6 shows the systematic uncertainties with the largest impact, together with a comparison with their nominal values used as input to the fit. In both the table and the figure the shown uncertainties are ranked by their fractional impact on the measurement of $\sigma_{H \rightarrow \tau\tau}$. To compute the impact for each nuisance parameter, a separate fit is performed again with the parameter fixed to its fitted value, and the resulting uncertainty in $\sigma_{H \rightarrow \tau\tau}$ is subtracted from the uncertainty obtained in the original fit via variance subtraction. The dominant uncertainties are related to the limited number of events in the simulated samples, the missing higher-order QCD corrections to the signal process cross sections, the jet energy resolution, the $\tau_{had}$ identification and the normalizations of the $Z \rightarrow \tau\tau$ and $Z \rightarrow \ell\ell$ backgrounds. Figure 6 also shows that in most cases the fitted parameters are in agreement with the nominal values, except for the uncertainties related to jet energy resolution and scale.
In the case of real di-τ events, the distribution of $m_{\tau\tau}^{\text{MMC}}$ is sensitive to the jet-related uncertainties because selected di-τ events in the VBF and boosted categories are characterized by one or more high-$p_T$ jets that recoil against the two τ-leptons. The main contributions to $E_T^{\text{miss}}$ are thus the neutrinos in the τ-lepton decays and the impact of the jet energy resolution when projected onto the $E_T^{\text{miss}}$ direction. Applying both the jet energy resolution and scale uncertainties causes a shift in the mean jet $p_T$, which therefore translates directly into a shift of the reconstructed $E_T^{\text{miss}}$. This, in turn, translates into a shift of the reconstructed $m_{\tau\tau}^{\text{MMC}}$ that is constrained by data in the region of the $Z \rightarrow \tau\tau$ mass peak.

Results of the fit when only the data of an individual channel or of an individual category are used, are shown in Fig. 7. Also shown is the result from the fit and the uncertainty in $\sigma_{H \rightarrow \tau\tau}^{\text{SM}}$. All results are consistent with the SM expectations. The simple combination of the individual fit results does not agree exactly with the result of the combined fit because the values of the nuisance parameters are different. The $m_{\tau\tau}^{\text{MMC}}$ distributions in all signal regions with background predictions adjusted by the likelihood fit are shown in Figs. 12 and 13 in the Appendix. The $m_{\tau\tau}^{\text{MMC}}$ distributions for the predicted signal plus background are compared with the data in Fig. 8, separately for the combined signal regions of $\tau_{\text{had}}\tau_{\text{had}}$, $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{lep}}\tau_{\text{lep}}$ analysis channels, and in Fig. 9, separately for the combined VBF and the combined boosted signal regions. A weighted combination of the $m_{\tau\tau}^{\text{MMC}}$ distributions in all signal regions is shown in Fig. 10. The events are weighted by a factor of $\ln(1+S/B)$ which enhances the events compatible with the signal hypothesis. Here, $S/B$ is the expected signal-to-background ratio in the corresponding signal region.
provide good sensitivity, respectively, to VBF and the fermion-mediated separating the vector-boson-mediated VBF process from other Higgs production processes are set to their predicted SM values. The two-dimensional 68% and from other backgrounds is indicated by the hatched bands. The signal and background predictions are determined in the likelihood fit. The size of the combined statistical, experimental and theoretical uncertainties in the background is indicated by the hatched bands.

Figure 7 illustrates that the VBF and boosted categories provide good sensitivity, respectively, to VBF and ggF Higgs-boson production. A two-parameter fit is therefore performed to determine the cross sections of these production processes by exploiting the sensitivity offered by the use of the event categories in the analysis of the three channels. Two cross-section parameters $\sigma_{H^{\rightarrow}\tau\tau}^{\text{VBF}}$ and $\sigma_{H^{\rightarrow}\tau\tau}^{\text{ggF}}$ are introduced and the data are fitted to these parameters, separating the vector-boson-mediated VBF process from the fermion-mediated ggF process, while the contributions from other Higgs production processes are set to their predicted SM values. The two-dimensional 68% and 95% confidence level (C.L.) contours in the plane of $\sigma_{H^{\rightarrow}\tau\tau}^{\text{VBF}}$ and $\sigma_{H^{\rightarrow}\tau\tau}^{\text{ggF}}$ are shown in Fig. 11. The best-fit values are $\sigma_{H^{\rightarrow}\tau\tau}^{\text{VBF}} = 0.28 \pm 0.09(\text{stat}) \pm 0.11(\text{syst})$ pb and $\sigma_{H^{\rightarrow}\tau\tau}^{\text{ggF}} = 3.1 \pm 1.0(\text{stat}) \pm 1.6(\text{syst})$ pb, in agreement with the predictions from the Standard Model of $\sigma_{H^{\rightarrow}\tau\tau}^{\text{SM}} = 0.237 \pm 0.006$ pb and $\sigma_{H^{\rightarrow}\tau\tau}^{\text{SM}} = 3.05 \pm 0.13$ pb [100]. The two results are strongly anti-correlated (correlation coefficient of $-52\%$), as can be seen in Fig. 11.

The ggF signal provides enough events to measure ggF cross sections in mutually exclusive regions of the ggF phase space. Two ggF regions are defined by particle-level events with at least one jet where a jet is required to have $p_T > 30$ GeV: events with a Higgs-boson $p_T$ of $60 < p_T^{H} < 120$ GeV and events with $p_T^{H} > 120$ GeV. A cross-section parameter for each of the two ggF regions is introduced, along with a parameter for VBF production in an inclusive region, and a combined three-parameter fit is performed using the event categories in the analysis of the
three channels. The particle-level definitions of all three phase-space regions closely follow the framework of simplified template cross sections [101] where the Higgs-boson rapidity $y_H$ is required to satisfy $|y_H| < 2.5$. The $ggF$ and VBF production cross sections outside the respective particle-level region requirements are set to the measured values reported above. Cross sections of other Higgs-boson production processes are set to their SM values. Table XI shows the resulting cross sections along with the SM

![Graph](image)

FIG. 9. Distribution of the reconstructed di-$\tau$ invariant mass ($m_{\tau\tau}^{\text{MMC}}$) for the sum of (a) all VBF and (b) all boosted signal regions (SRs). The bottom panels show the differences between observed data events and expected background events (black points). The observed Higgs-boson signal ($\mu = 1.09$) is shown with the solid red line. Entries with values that would exceed the x-axis range are shown in the last bin of each distribution. The signal and background predictions are determined in the likelihood fit. The size of the combined statistical, experimental and theoretical uncertainties in the background is indicated by the hatched bands.

![Graph](image)

FIG. 10. Distribution of the reconstructed di-$\tau$ invariant mass ($m_{\tau\tau}^{\text{MMC}}$) for the sum of all signal regions (SRs). The contributions of the different SRs are weighted by a factor of $\ln(1 + S/B)$, where $S$ and $B$ are the expected numbers of signal and background events in that region, respectively. The bottom panel shows the differences between observed data events and expected background events after applying the same weights (black points). The observed Higgs-boson signal ($\mu = 1.09$) is shown with the solid red line. Entries with values that would exceed the x-axis range are shown in the last bin of each distribution. The signal and background predictions are determined in the likelihood fit. The size of the combined statistical, experimental and theoretical uncertainties in the background is indicated by the hatched bands.

![Graph](image)

FIG. 11. Likelihood contours for the combination of all channels in the $(\sigma_{ggF}^{H\rightarrow\tau\tau}, \sigma_{VBF}^{H\rightarrow\tau\tau})$ plane. The 68% and 95% C.L. contours are shown as dashed and solid lines, respectively, for $m_H = 125$ GeV. The SM expectation is indicated by a plus symbol and the best fit to the data is shown as a star.
predictions in the respective particle-level region. The measurements in all regions have a precision similar to that of the inclusive ggF and VBF measurements reported above.

### IX. CONCLUSIONS

A measurement of total production cross sections of the Higgs boson in proton-proton collisions is presented in the $H \to \tau\tau$ decay channel. The analysis was performed using 36.1 fb$^{-1}$ of data recorded by the ATLAS experiment at the LHC at a center-of-mass energy of $\sqrt{s} = 13$ TeV. All combinations of leptonic and hadronic $\tau$ decays were considered. An excess of events over the expected background from other Standard Model processes was found with an observed (expected) significance of 4.4 (4.1) standard deviations. Combined with results using data taken at $\sqrt{s}$ of 7 and 8 TeV, the observed (expected) significance amounts to 6.4 (5.4) standard deviations and constitutes an observation of $H \to \tau\tau$ decays by the ATLAS experiment. Using the data taken at $\sqrt{s} = 13$ TeV, the $pp \to H \to \tau\tau$ total cross section is measured to be $3.77^{+0.60}_{-0.59} \text{stat} \pm 0.37 \text{syst}$ pb, for a Higgs boson of mass 125 GeV. A two-dimensional fit was performed to separate the vector-boson-mediated VBF process from the fermion-mediated ggF process. The cross sections of the Higgs boson decaying into two $\tau$ leptons are measured to be $\sigma^{VBF}_{H \to \tau\tau} = 0.28 \pm 0.09 \text{(stat)} \pm 0.11 \text{syst}$ pb and $\sigma^{ggF}_{H \to \tau\tau} = 3.1 \pm 1.0 \text{(stat)} \pm 1.3 \text{(syst)}$ pb, respectively, for the two production processes. Similarly, a three-dimensional fit was performed in the framework of simplified template cross sections. Results are reported for the VBF cross section in an inclusive phase space and ggF cross sections in two exclusive regions of phase space defined by particle-level requirements on the Higgs boson $p_T$. All measurements are consistent with SM predictions.

### ACKNOWLEDGMENTS

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently. We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF and DNSRC, Denmark; IN2P3-CNRS, CEA-DRF/IRFU, France; GRICES, FPA and MCT, Greece; RFBR, Russia; INFN, Italy; BMBF, HGF, and MPG, Germany; GSRT; Greece; RGC, Hong Kong SAR, China; ISF and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRS, Morocco; NWO, Netherlands; RCN, Norway; MNISW and NCN, Poland; FCT, Portugal; MNE/IFA, Romania; MES of Russia and NRC KI, Russian Federation; JINR; MESTD, Serbia; MSSR, Slovakia; AARS and MIZS, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TAEK, Turkey; STFC, United Kingdom; DOE and NSF, United States of America. In addition, individual groups and members have received support from BCKDF, CANARIE, CRC and Compute Canada, Canada; COST, ERC, ERDF, Horizon 2020, and Marie Skłodowska-Curie Actions, European Union; Investissements d’Avenir Labex and Idex, ANR, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF, Greece; BSF-NSF and GIF, Israel; CERCA Programme Generalitat de Catalunya, Spain; The Royal Society and Leverhulme Trust, United Kingdom. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [118].

### APPENDIX: DISTRIBUTIONS OF $m_{\tau\tau}^{\text{MMC}}$ IN SIGNAL REGIONS

Figures 12 and 13 show the $m_{\tau\tau}^{\text{MMC}}$ distributions in all signal regions with background predictions adjusted by the likelihood fit.
FIG. 12. Observed and expected $m_{\text{MMC}}$ distributions as used in the fit in all signal regions (SRs) in the VBF category for the $\tau_{\text{lep}}\tau_{\text{lep}}$ (left), $\tau_{\text{lep}}\tau_{\text{had}}$ (middle) and $\tau_{\text{had}}\tau_{\text{had}}$ (right) analysis channels. The bottom panels show the ratio of observed data events to expected background events (black points). The observed Higgs-boson signal ($\mu = 1.09$) is shown with the solid red line. Entries with values that would exceed the $x$-axis range are shown in the last bin of each distribution. The signal and background predictions are determined in the likelihood fit. The size of the combined statistical, experimental and theoretical uncertainties in the background is indicated by the hatched bands.
FIG. 13. Observed and expected \( m_{\tau\tau}^{\text{MMC}} \) distributions as used in the fit in all signal regions (SRs) in the boosted category for the \( \tau\tau\tau\tau \) (left), \( \tau\tau\tau\tau \) (middle) and \( \tau\tau\tau\tau \) (right) analysis channels. The bottom panels show the ratio of observed data events to expected background events (black points). The observed Higgs-boson signal (\( \mu = 1.09 \)) is shown with the solid red line. Entries with values that would exceed the x-axis range are shown in the last bin of each distribution. The signal and background predictions are determined in the likelihood fit. The size of the combined statistical, experimental and theoretical uncertainties in the background is indicated by the hatched bands.


[61] S. Dawson, L. Orr, L. Reina, and D. Wackeroth, Next-to-leading order QCD corrections to $pp \rightarrow t\bar{t}h$ at the CERN Large Hadron Collider, Phys. Rev. D 67, 071503 (2003).


(ATLAS Collaboration)

1Department of Physics, University of Adelaide, Adelaide, Australia
2Physics Department, SUNY Albany, Albany, New York, USA
3Department of Physics, University of Alberta, Edmonton, Alberta, Canada
4aDepartment of Physics, Ankara University, Ankara, Turkey
4bIstanbul Aydin University, Istanbul, Turkey
4cDivision of Physics, TOBB University of Economics and Technology, Ankara, Turkey
5LAPP, Université Grenoble Alpes, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy, France
6High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois, USA
7Department of Physics, University of Arizona, Tucson, Arizona, USA
8Department of Physics, University of Texas at Arlington, Arlington, Texas, USA
9Physics Department, National and Kapodistrian University of Athens, Athens, Greece
10Physics Department, National Technical University of Athens, Zografou, Greece
11Department of Physics, University of Texas at Austin, Austin, Texas, USA
12Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey
12bIstanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey
12cDepartment of Physics, Bogazici University, Istanbul, Turkey
12dDepartment of Physics Engineering, Gaziantep University, Gaziantep, Turkey
13Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
14Institut de Física d’Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona, Spain
15aInstitute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
15bPhysics Department, Tsinghua University, Beijing, China
15cDepartment of Physics, Nanjing University, Nanjing, China
15dUniversity of Chinese Academy of Science (UCAS), Beijing, China
15eInstitute of Physics, University of Belgrade, Belgrade, Serbia
16Department for Physics and Technology, University of Bergen, Bergen, Norway
17Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, California, USA
18Institut für Physik, Humboldt Universität zu Berlin, Berlin, Germany
19Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
20School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
21Centro de Investigación y de Física, Universidad Antonio Nariño, Bogotá, Colombia
22Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
23bINFN Sezione di Bologna, Bologna, Italy
24Physikalisches Institut, Universität Bonn, Bonn, Germany
25Department of Physics, Boston University, Boston, Massachusetts, USA
26Department of Physics, Brandeis University, Waltham, Massachusetts, USA
27Transilvania University of Brasov, Brasov, Romania
28Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania
29Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi, Romania
29aNational Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca, Romania
29bUniversity Politehnica Bucharest, Bucharest, Romania
29cWest University in Timisoara, Timisoara, Romania
29dFaculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovak Republic
29eDepartment of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
29fPhysics Department, Brookhaven National Laboratory, Upton, New York, USA
30Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
31Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
32aDepartment of Physics, University of Cape Town, Cape Town, South Africa
32bDepartment of Mechanical Engineering Science, University of Johannesburg, Johannesburg, South Africa
32cSchool of Physics, University of the Witwatersrand, Johannesburg, South Africa
33Department of Physics, Carleton University, Ottawa, Ontario, Canada
34Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Énergies—Université Hassan II, Casablanca, Morocco

072001-34
117 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
118 Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
119 Department of Physics, Northern Illinois University, DeKalb, Illinois, USA
120 Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
120 Novosibirsk State University Novosibirsk, Russia
121 Department of Physics, New York University, New York, New York, USA
122 Ohio State University, Columbus, Ohio, USA
123 Faculty of Science, Okayama University, Okayama, Japan
124 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA
125 Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA
126 Palacký University, RCPTM, Joint Laboratory of Optics, Olomouc, Czech Republic
127 Center for High Energy Physics, University of Oregon, Eugene, Oregon, USA
128 LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
129 Graduate School of Science, Osaka University, Osaka, Japan
130 Department of Physics, University of Oslo, Oslo, Norway
131 Department of Physics, Oxford University, Oxford, United Kingdom
132 LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France
133 Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA
134 Konstantinov Nuclear Physics Institute of National Research Centre “Kurchatov Institute”, PNPI, St. Petersburg, Russia
135 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA
136 Laboratório de Instrumentação e Física Experimental de Partículas—LIP, Lisboa, Portugal
137 Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal
138 Centro de Física Nuclear da Universidade de Lisboa, Lisboa, Portugal
139 Departamento de Física, Universidade do Minho, Braga, Portugal
140 Departamento de Física Teorica y del Cosmos, Universidad de Granada, Granada (Spain), Spain
141 Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile
142 Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
143 Department of Physics, University of Washington, Seattle, Washington, USA
144 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
145 Department of Physics, Shinshu University, Nagano, Japan
146 Department Physik, Universität Siegen, Siegen, Germany
147 Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada
148 SLAC National Accelerator Laboratory, Stanford, California, USA
149 Physics Department, Royal Institute of Technology, Stockholm, Sweden
150 Departments of Physics and Astronomy, Stony Brook University, Stony Brook, New York, USA
151 School of Physics, University of Sydney, Sydney, Australia
152 E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia
153 High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
154 Department of Physics, Technion, Haifa, Israel
155 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
156 International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo, Japan
157 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
158
Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
Tomsk State University, Tomsk, Russia
Department of Physics, University of Toronto, Toronto, Ontario, Canada
TRIUMF, Vancouver, British Columbia, Canada
Department of Physics and Astronomy, York University, Toronto, Ontario, Canada
Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA
Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA
Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
Department of Physics, University of Illinois, Urbana, Illinois, USA
Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia—CSIC, Valencia, Spain
Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada
Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada
Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg, Germany
Department of Physics, University of Warwick, Coventry, United Kingdom
Waseda University, Tokyo, Japan
Department of Particle Physics, Weizmann Institute of Science, Rehovot, Israel
Department of Physics, University of Wisconsin, Madison, Wisconsin, USA
Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany
Department of Physics, Yale University, New Haven, Connecticut, USA
Yerevan Physics Institute, Yerevan, Armenia

Also at Department of Physics, King’s College London, London, United Kingdom.
Also at Istanbul University, Dept. of Physics, Istanbul, Turkey.
Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
Also at TRIUMF, Vancouver, British Columbia, Canada.
Also at Department of Physics and Astronomy, University of Louisville, Louisville, Kentucky, USA.
Also at Department of Physics, California State University, Fresno, California, USA.
Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.
Also at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain.
Also at Tomsk State University, Tomsk, and Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China.
Also at Università di Napoli Parthenope, Napoli, Italy.
Also at Institute of Particle Physics (IPP), Canada.
Also at II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany.
Also at Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy.
Also at Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania.
Also at CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France.
Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.
Also at Borough of Manhattan Community College, City University of New York, New York, USA.
Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.
Also at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town, South Africa.
Also at Louisiana Tech University, Ruston, Louisiana, USA.
Also at California State University, East Bay, California, USA.
Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.
Also at Department of Physics, University of Michigan, Ann Arbor, Michigan, USA.
Also at LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France.
Also at Graduate School of Science, Osaka University, Osaka, Japan.
Also at Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany.
Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands.
Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.
Also at CERN, Geneva, Switzerland.
Also at Department of Physics, Stanford University, Stanford, California, USA.
Also at Manhattan College, New York, New York, USA.
Also at Hellenic Open University, Patras, Greece.
Also at LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France.