Search for the associated production of the Higgs boson and a vector boson in proton-proton collisions at $\sqrt{s} = 13$ TeV via Higgs boson decays to $\tau$ leptons

The CMS Collaboration

Abstract

A search for the standard model Higgs boson, decaying to a pair of $\tau$ leptons and produced in association with a $W$ or a $Z$ boson is performed. A data sample of proton-proton collisions collected at $\sqrt{s} = 13$ TeV by the CMS experiment at the CERN LHC is used, corresponding to an integrated luminosity of 35.9 fb$^{-1}$. The signal strength is measured relative to the expectation for the standard model Higgs boson, yielding $\mu = 2.5^{+1.4}_{-1.3}$. These results are combined with earlier CMS measurements targeting Higgs boson decays to a pair of $\tau$ leptons, performed with the same data set in the gluon fusion and vector boson fusion production modes. The combined signal strength is $\mu = 1.24^{+0.29}_{-0.27}$ (1.00$^{+0.24}_{-0.23}$ expected), and the observed significance is 5.5 standard deviations (4.8 expected) for a Higgs boson mass of 125 GeV.

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1 Introduction

In the standard model (SM), the fermions receive mass via their Yukawa couplings to the Higgs boson [1–9], and measurements of the Higgs boson branching fractions to fermions directly probe these couplings. The Higgs boson decay to a $\tau$ lepton pair is particularly interesting because it has the largest branching fraction among the direct leptonic Higgs boson decays ($B(H \rightarrow \tau^+\tau^-) \simeq 6.3\%$). Many searches for the $H \rightarrow \tau^+\tau^-$ process have been performed by earlier experiments [10–15]. The ATLAS and CMS Collaborations each previously reported evidence for this particular Higgs boson decay process using data collected at center-of-mass energies of 7 and 8 TeV [16–18]. The $H \rightarrow \tau^+\tau^-$ process was measured targeting the gluon fusion and vector boson fusion production modes using data collected by the CMS Collaboration at a center-of-mass energy of 13 TeV [19] resulting in a cross section times branching fraction of $1.09^{+0.27}_{-0.26}$ relative to the SM expectation.

This paper reports on a search for the SM Higgs boson produced in association with a W or Z boson in proton-proton (pp) collisions at $\sqrt{s} = 13$ TeV, using a data set collected in 2016 by the CMS experiment corresponding to an integrated luminosity of 35.9 fb$^{-1}$. In this search, the Higgs boson is sought in its decay to a pair of $\tau$ leptons. The results are combined with results from the the CMS $H \rightarrow \tau^+\tau^-$ analysis performed with the same data set [19] providing dedicated signal regions covering the four leading Higgs boson production mechanisms.

For the ZH associated production channel, $Z \rightarrow \ell^+\ell^- (\ell = e, \mu)$ decays are considered, combined with four possible $\tau\tau$ final states from the Higgs boson decay: $e\tau_h^\text{b}, \mu\tau_h^\text{b}, e\mu$, and $\tau_h^\text{b}\tau_h^\text{b}$, where $\tau_h$ denotes $\tau$ leptons decaying hadronically. For the WH channel, four final states are considered, with the W boson decaying leptonically to a neutrino and an electron or a muon, and at least one $\tau_h$ from the decay of the Higgs boson: $\mu\mu\tau_h^\text{b}, e\mu\tau_h^\text{b}, e\tau_h^\text{b}\tau_h^\text{b}$, and $\mu\tau_h^\text{b}\tau_h^\text{b}$. The $ee\tau_h^\text{b}$ final state is not considered because of the lower acceptance and efficiency for electrons with respect to muons. Throughout the paper neutrinos are omitted from the notation of the final states.

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid 6 m in internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume there are: a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL). Each of these is composed of a barrel and two endcap sections. Forward hadron calorimeters extend the pseudorapidity ($\eta$) coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. Events are selected using a two-tiered trigger system [20]. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [21].

3 Simulated samples

The signal samples with a Higgs boson produced in association with a W or Z boson (WH or ZH) are generated at next-to-leading order (NLO) in perturbative quantum chromodynamics (QCD) with the POWHEG 2.0 [22–26] generator extended with the MiNLO procedure [27]. The set of parton distribution functions (PDFs) is NNPDF3.0 [28]. Because the analysis focuses on measuring the WH and ZH processes, the tth process is included as a background. The contribution from Higgs boson events produced via gluon fusion or vector boson fusion is
negligible. The transverse momentum ($p_T$) distribution of the Higgs boson in the POWHEG simulations is tuned to match closely the next-to-NLO (NNLO) plus next-to-next-to-leading-logarithmic prediction in the HERA generator [29, 30]. The production cross sections and branching fractions for the SM Higgs boson production and their corresponding uncertainties are taken from Refs. [31–33].

The $tt$, $WZ$, and $qq \rightarrow ZZ$ processes are generated at NLO with POWHEG, as are the $WH \rightarrow WWW$, $ZH \rightarrow ZWW$, and $H \rightarrow ZZ$ backgrounds. The $gg \rightarrow ZZ$ process is generated at leading order (LO) with MCFM [34]. The MadGraph5_aMC@NLO v2.3.3 generator is used for triboson, $ttW$, and $ttZ$ production, with the jet matching and merging scheme applied either at NLO with the FxFx algorithm [35] or at LO with the MLM algorithm [36]. The generators are interfaced with PYTHIA 8.212 [37] to model the parton showering and fragmentation, as well as the decay of the $\tau$ leptons. The PYTHIA parameters affecting the description of the underlying event are set to the CUETP8M1 tune [38].

Generated events are processed through a simulation of the CMS detector based on GEANT4 [39], and are reconstructed with the same algorithms that are used for data. The simulated samples include additional pp interactions per bunch crossing, referred to as pileup. The effect of pileup is taken into account by generating concurrent minimum-bias collision events. The simulated events are weighted such that the distribution of the number of additional pileup interactions matches closely with data. The pileup distribution in data is estimated from the measured instantaneous luminosity for each bunch crossing and results in an average of approximately 23 interactions per bunch crossing.

4 Event reconstruction

The reconstruction of observed and simulated events relies on the particle-flow (PF) algorithm [40]. This algorithm combines information from all subdetectors to identify and reconstruct the particles emerging from pp collisions: charged hadrons, neutral hadrons, photons, muons, and electrons. Combinations of these PF objects are used to reconstruct higher-level objects such as the missing transverse momentum ($\vec{p}_T$). The $\vec{p}_T$ is defined as the projection onto the plane perpendicular to the beam axis of the negative vectorial sum of the momenta of all reconstructed particle-flow objects in an event. Its magnitude is referred to as $p_T$. The reconstructed vertex with the largest value of summed physics-object $p_T$ is taken to be the primary pp interaction vertex. The physics objects are the objects constructed by a jet finding algorithm [41, 42] applied to all charged tracks associated with the vertex, including tracks from lepton candidates, and the corresponding associated missing transverse momentum.

Electrons are identified with a multivariate discriminant combining several quantities describing the track quality, the shape of the energy deposits in the ECAL, and the compatibility of the measurements from the tracker and the ECAL [43]. Muons are reconstructed by combining information from the inner tracker and the muon systems, using two algorithms [44]. One matches tracks in the silicon tracker to hits in the muon detectors, while the other one performs a track fit using hits in both the silicon tracker and the muon systems. To reject nonprompt or misidentified leptons, a relative lepton isolation is defined as:

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

In this expression, $\sum_{\text{charged}} P_T$ is the scalar sum of the transverse momenta of the charged particles originating from the primary vertex and located in a cone of size $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} =$
0.3 (0.4) centered on the electron (muon) direction, where \( \phi \) is the azimuthal angle in radians. The sum \( \sum_{\text{neutral}} \pT \) represents a similar quantity for neutral particles. The contribution of photons and neutral hadrons originating from pileup vertices is estimated from the scalar sum of the transverse momenta of charged hadrons in the cone originating from pileup vertices, \( \sum_{\text{charged, PU}} \pT \). This sum is multiplied by a factor of 1/2, which corresponds approximately to the ratio of neutral to charged hadron production in the hadronization process of inelastic pp collisions, as estimated from simulation. The expression \( \pT^l \) stands for the \( \pT \) of the lepton. Isolation requirements used in this analysis range from 0.10 to 0.25 depending on the lepton type and on the specific channel.

Jets are reconstructed with an anti-\( k_T \) clustering algorithm implemented in the FastJet library [42, 45]. It is based on the clustering of neutral and charged PF candidates with a distance parameter of 0.4. Charged PF candidates not associated with the primary vertex of the interaction are not considered when clustering. The combined secondary vertex (CSVv2) algorithm is used to identify jets that are likely to have originated from a bottom quark (“b jets”) [46]. The algorithm exploits the track-based lifetime information together with the secondary vertices associated with the jet using a multivariate technique to produce a discriminator for b jet identification. A set of \( \pT \)-dependent correction factors are applied to simulated events to account for differences in the b tagging efficiency between data and simulation [46]. The working point chosen in this analysis gives an identification efficiency for genuine b jets of about 70% and a misidentification probability for light flavor or gluon jets of about 1%. All events with a b-tagged jet are discarded from this analysis. This selection requirement suppresses the contributions of \( t\bar{t}, t\bar{t} + W, \) and \( t\bar{t} + Z \) with minimal impact to the signal selection efficiency.

Hadronically decaying \( \tau \) leptons are reconstructed with the hadron-plus-strips (HPS) algorithm [47, 48], which is seeded from anti-\( k_T \) jets. The HPS algorithm reconstructs \( \tau_h \) candidates on the basis of the number of tracks and on the number of ECAL strips with an energy deposit in the \( \eta-\phi \) plane, in the 1-prong, 1-prong + \( \pi^0 \), and 3-prong decay modes. A multivariate analysis (MVA) discriminator [49], including isolation and lifetime information, is used to reduce the rate for quark- and gluon-initiated jets to be identified as \( \tau_h \) candidates. The three working points used in this analysis have efficiencies of about 55, 60, and 65% for genuine \( \tau_h \) with about 1.0, 1.5, and 2.5% misidentification rates for quark- and gluon-initiated jets, within a \( \pT \) range typical of a \( \tau_h \) originating from a Z boson. The first working point is used in the \( \ell \tau_\ell \tau_\ell \) channels of WH for the \( \tau_h \) that has the same charge as the electron or muon. The second working point is used in the WH channels with exactly one \( \tau_h \), whereas the third working point is used in the ZH channels as well as for the \( \tau_h \) that has the opposite charge to the muon or electron in the WH channels with two \( \tau_h \) candidates. Electrons and muons misidentified as \( \tau_h \) candidates are suppressed using dedicated criteria based on the consistency between the measurements in the tracker, the calorimeters, and the muon detectors [47, 48]. The working points of these discriminators are specific to each decay channel. The \( \tau_h \) energy in simulation is corrected for each decay mode on the basis of a measurement of the \( \tau_h \) energy scale in \( Z \to \tau\tau \) events. The rate and the energy of electrons and muons misidentified as \( \tau_h \) candidates are also corrected in simulation on the basis of a “tag-and-probe” measurement [50] in \( Z \to \ell\ell \) events.

In all final states, the visible mass of the Higgs boson candidate, \( m_{\text{vis}} \), can be used to separate the \( H \to \tau\tau \) signal events from the large irreducible contribution of \( Z \to \tau\tau \) events. However, the neutrinos from the \( \tau \) lepton decays carry a large fraction of the \( \tau \) lepton energy and reduce the discriminating power of this variable. The svfit algorithm [51] combines \( \pT^{\text{miss}} \) with the four-vector momenta of both \( \tau \) candidates to estimate the mass of the parent boson, denoted as \( m_{\tau\tau} \). The resolution of \( m_{\tau\tau} \) is about 20%. The \( m_{\tau\tau} \) variable is used for the ZH channels, while \( m_{\text{vis}} \) is used for the WH channels because the svfit algorithm cannot account for the additional
\( \vec{p}_T^{\text{miss}} \) from the W boson decay.

### 5 Event selection

Events for the WH and ZH production channels are selected using single- or double-lepton triggers targeting leptonic decays of the W and Z bosons. The trigger and offline selection requirements for all possible decay modes are presented in Table 1. Leptons selected by the trigger must be matched to those selected in the analysis. The light leptons (electrons and muons) in the events are required to be separated from each other by \( \Delta R > 0.3 \), while the \( \tau_1 \) candidates must be separated from each other and from the other leptons by \( \Delta R > 0.5 \). The resulting event samples are made mutually exclusive by discarding events that have additional identified and isolated electrons or muons.

Table 1: Kinematic selection requirements for WH and ZH events. The trigger requirement is defined by a combination of trigger candidates with \( p_T \) over a given threshold (in GeV), indicated inside parentheses. The \( |\eta| \) thresholds come from trigger and object reconstruction constraints. ZH events are selected with either a lower \( p_T \) threshold double lepton trigger or a higher \( p_T \) threshold single lepton trigger.

| Channel | Trigger \((p_T/|\eta|)\) | WH selection \(p_T^{\text{th}} > 20\) GeV, \(|\eta^{\text{th}}| < 2.3\), \(I^e < 0.1\), \(I^\mu < 0.15\), b veto | Lepton selection: \(p_T\) (GeV) | \(\tau_1\) selection: isolation |
|---------|-------------------|---------------------------------------------------------------|------------------|------------------|
| e\(\mu\) \(\tau_1\) | \(\mu(22/2.1)\) or \(e(25/2.1)\) | \(p_T^e > 15\) or \(26\), \(p_T^\mu > 23\) or \(15\) | MVA \(\tau_1\) (60% eff.) |
| \(\mu\mu\) \(\tau_1\) | \(\mu(22/2.1)\) | \(p_T^\mu > 23\), \(p_T^e > 15\) | MVA \(\tau_1\) (60% eff.) |
| e\(\tau_1\) \(\tau_1\) | \(e(25/2.1)\) | \(p_T^e > 26\) | MVA \(\tau_1\) (55 or 65% eff.) |
| \(\mu\tau_1\) \(\tau_1\) | \(\mu(22/2.1)\) | \(p_T^\mu > 23\) | MVA \(\tau_1\) (55 or 65% eff.) |

**ZH selection**

Z boson reconstructed from opposite charge, same-flavor light leptons, \(60 < m_{ee} < 120\) GeV, b veto

\(\tau_0\) baseline requirements: \(p_T^{\tau_0} > 20\), \(|\eta^{\tau_0}| < 2.3\), MVA \(\tau_0\) (65% efficiency)

\(e\) baseline requirements: \(p_T^e > 10\), \(|\eta^e| < 2.5\), MVA ID (90% efficiency)

\(\mu\) baseline requirements: \(p_T^\mu > 10\), \(|\eta^\mu| < 2.4\), MVA ID (> 99% efficiency), \(I^\mu < 0.25\)

| Channel | Trigger \((p_T/|\eta|)\) | Lepton selection: \(p_T\) (GeV) | Lepton selection: isolation |
|---------|-------------------|------------------|------------------|
| e\(ee\) \(\tau_1\) | \(e(23/2.5)\) & \(e(12/2.5)\) | \([p_T^e > 24 \& p_T^{e2} > 13]\) | \(I^e < 0.15\) |
| e\(ee\) \(\tau_1\) | or \(e(27/2.5)\) | \([p_T^e > 28]\) | e ID (80% eff.), \(I^e < 0.15\) |
| e\(ee\) \(ee\) | or \(e(27/2.5)\) | | baseline selection listed above |

\(\mu\mu\mu\) \(\tau_1\) | \([\mu(17/2.4) \& \mu(8/2.4)\] | \([p_T^{\mu1} > 18 \& p_T^{\mu2} > 10]\) | \(I^\mu < 0.15\) |

\(\mu\mu\) \(\tau_1\) \(\tau_1\) | or \(\mu(24/2.4)\) | \([p_T^{\mu1} > 25]\) | e ID (80% eff.), \(I^\mu < 0.15\) |

\(\mu\mu\mu\) \(\mu\mu\) | or \(\mu(24/2.4)\) | | baseline selection listed above |

In the \(e\mu\) \(\tau_1\) and \(\mu\mu\) \(\tau_1\) final states of the WH channel, the two light leptons are required to have the same charge to reduce the \(t\) and \(Z + \text{jets}\) backgrounds where one or more jets is misidentified as a \(\tau_1\) candidate. The \(\tau_1\) candidate must have opposite charge to the light leptons. The highest \(p_T\) light lepton is considered as coming from the W boson, while the Higgs boson candidate is formed from the \(\tau_1\) object and the subleading light lepton. The correct pairing is achieved in about 75% of events, according to simulation. The leading light lepton is required to pass a single-lepton trigger and to have a \(p_T\) that is 1 GeV above the online threshold, whereas the subleading light lepton must have \(p_T > 15\) GeV, as determined from optimizing for signal sensitivity. Selection criteria based on three variables have been found to improve the signal sensitivity in both channels:
• $L_T > 100 \text{ GeV}$, where $L_T$ is the scalar sum of $p_T$ of the light leptons and the $\tau_h$ candidate;
• $|\Delta\phi(\ell_1, H)| > 2.0$, where $\ell_1$ is the leading light lepton, and $H$ is the system formed by the subleading light lepton and the $\tau_h$ candidate;
• $|\Delta\eta(\ell_1, H)| < 2.0$.

In the $e\tau_h\tau_h$ and $\mu\tau_h\tau_h$ final states of the WH channel, the $\tau_h$ candidates are required to have opposite charge. The $\tau_h$ candidate that has the same charge as the light lepton must have $p_T > 35 \text{ GeV}$, while the other one is required to have $p_T > 20 \text{ GeV}$. This requirement is driven by the fact that the $\tau_h$ candidate with the same charge as the light lepton is often a jet misidentified as a $\tau_h$ from the SM background, and the jet misidentification rate strongly decreases as $p_T$ increases. Selection criteria based on three variables have been found to improve the results in the $e\tau_h\tau_h$ and $\mu\tau_h\tau_h$ final states:

• $L_T > 130 \text{ GeV}$, where $L_T$ is the scalar sum of $p_T$ of the light lepton and $\tau_h$ candidates;
• $|S_T^\tau| < 70 \text{ GeV}$, where $S_T^\tau$ is the vectorial sum of $p_T$ of the light lepton, $\tau_h$ candidates, and $\vec{p}_T^{\text{miss}}$;
• $|\Delta\eta(\tau_h, \tau_h)| < 2.0$.

In the ZH final states, the $Z$ boson is reconstructed from the opposite charge, same-flavor light lepton combination that has a mass closest to the $Z$ boson mass. A looser identification and isolation selection is applied to the leptons associated to the $Z$ boson to increase the signal acceptance, while a tighter selection is applied to the light leptons assigned to the Higgs boson to decrease the background contributions from $Z + \text{jets}$ and other reducible backgrounds. The leptons assigned to the Higgs boson are required to have opposite charge. The specific selections detailed in Table 1, including those chosen for the $\tau_h$ candidates, were optimized to obtain the best expected signal sensitivity.

Candidates for associated ZH production are also categorized depending on the value of $L^{\text{Higgs}}_T$, defined as the scalar sum of $p_T$ of the visible decay products of the Higgs boson. The large Higgs boson mass causes the decay products to have relatively high $p_T$ compared to the jets misidentified as leptons from the $Z + \text{jets}$ background process, which leads to a higher signal purity in the category with high $L^{\text{Higgs}}_T$. The thresholds to separate the high $L^{\text{Higgs}}_T$ and low $L^{\text{Higgs}}_T$ regions are optimized to maximize the expected signal sensitivity for each $H \rightarrow \tau\tau$ final state. The threshold is equal to 50 GeV in the $\ell\ell\mu\mu$ final states, 60 GeV in the $\ell\ell\tau_h$ and $\ell\ell\mu\tau_h$ final states, and 75 GeV in the $\ell\ell\tau_h\tau_h$ final state.

6 Background estimation

The irreducible backgrounds ($ZZ$, $t\bar{t}Z$, $WWZ$, $WZZ$, $ZZZ$, as well as $WZ$ and $t\bar{t}W$ in the WH channels) are estimated from simulation and scaled by their theoretical cross sections at the highest order available. Inclusive Higgs boson decays to $W$ or $Z$ boson pairs and the $t\bar{t}H$ associated production background processes are also estimated from simulation.

The reducible backgrounds, which have at least one jet misidentified as an electron, muon, or $\tau_h$ candidate, are estimated from data. The dominant reducible background contributions come from $t\bar{t}$ and $Z + \text{jets}$ in the WH channels and from $t\bar{t}$, $Z + \text{jets}$, and $WZ + \text{jets}$ in the ZH channels. The misidentification rates are estimated in control samples, and are used to reweight events with $\tau$ candidates (electrons, muons, or $\tau_h$) failing the identification criteria to estimate the contribution of processes with jets misidentified as $\tau$ candidates in the signal region.
In the WH analysis, the misidentification rate of jets as \( \tau \) candidates is measured in \( Z + \text{jets} \) events. After reconstructing the \( Z \rightarrow ee \) decay, the jet-to-muon misidentification rate is estimated as a function of the lepton \( p_T \) by applying the lepton identification algorithm to any additional jet in the event. Similarly, \( (Z \rightarrow \mu\mu) + \text{jets} \) events are used to estimate the jet-to-electron and jet-to-\( \tau_h \) misidentification rates. Events where the \( \tau \) candidates arise from genuine leptons and not jets, primarily from the WZ process, are estimated from simulation and subtracted from the data so that the misidentification rates are measured for jets only. The rates are measured in bins of lepton \( p_T \), and are separated by the reconstructed decay mode of the \( \tau_h \) candidates.

In the \( e\mu\tau_h \) and \( \mu\mu\tau_h \) final states, events that do not pass the identification conditions of either the subleading light lepton or the \( \tau_h \) are reweighted to estimate the reducible background contribution in the signal region. In particular, events with exactly one object failing the identification criteria receive a weight \( f/(1-f) \), where \( f \) is the misidentification rate for the particular type of object. Events with both objects failing the identification criteria receive a weight \( -f_1 f_2/[(1-f_1)(1-f_2)] \), where the negative sign removes the double counting of events with two jets. This method estimates the number of events for which the subleading light lepton or the \( \tau_h \) candidate corresponds to a jet. Such events are therefore removed from simulated samples to avoid double counting. However, events that have a jet misidentified as the leading lepton, but two genuine leptons for the subleading lepton and the \( \tau_h \), are not taken into account with the misidentification rate method and are therefore estimated from simulation. These events mostly arise from \( t\bar{t} \) and \( Z + \text{jets} \) processes, and account for less than 10% of the total expected background in the signal region. In the \( e\tau_h\tau_h \) and \( \mu\tau_h\tau_h \) final states of the WH channels, the method is essentially the same, except that the misidentification rate functions are applied only to events where the \( \tau_h \) candidate that has the same charge as the light lepton fails the identification criteria.

In the ZH analysis, a very similar method is used to estimate the contribution of jets misidentified as electrons, muons, or \( \tau_h \) candidates to the signal region. The misidentification rates are measured in a region with an opposite-charge same-flavor lepton pair compatible with a \( Z \) boson, and two additional objects. This region is dominated by \( Z + \text{jets} \) events with a small contribution from \( t\bar{t} \) events. In a procedure identical to that of the WH final states, the contribution from genuine leptons is estimated from simulation and is subtracted, and the rates are measured in bins of lepton \( p_T \) and are split between reconstructed decay modes for the \( \tau_h \) candidates. In the ZH analysis, events that pass the full signal region selection with the exception that either or both of the \( \tau \) candidates associated to the Higgs boson fail the identification criteria are weighted as a function of the misidentification rates. To avoid double counting, events with both \( \tau \) candidates failing the selection criteria have their weight subtracted from the events that have only a single object failing. This misidentification rate method is used to estimate only the yield of the reducible backgrounds. The \( m_{\tau\tau} \) distribution of the reducible background contribution is taken from data in a region with negligible signal and irreducible background contribution, defined similarly to the signal region but with same charge \( \tau \) candidates passing relaxed identification and isolation criteria.

## 7 Systematic uncertainties

The overall uncertainty in the \( \tau_h \) identification efficiency for genuine \( \tau_h \) leptons is 5% [48], which has been measured with a tag-and-probe method in \( Z \rightarrow \tau\tau \) events. An uncertainty of 1.2% in the visible energy of genuine \( \tau_h \) leptons affects both the distributions and yields of the signals and backgrounds. It is uncorrelated among the 1-prong, 1-prong + \( \pi^0 \), and 3-prong...
The uncertainties in the electron and muon identification, isolation, and trigger efficiencies lead to a rate uncertainty of 2% for both electrons and muons. The uncertainty in the electron energy, which amounts to 2.5% in the endcaps and 1% in the barrel, affects the final distributions and the rate. In all channels, the effect of the uncertainty in the muon energy is negligible.

The rate uncertainty related to discarding events with a b-tagged jet is 4.5% for processes with heavy-flavor jets, and 0.15% for processes with light-flavor jets.

Theoretical uncertainties associated with finite-order perturbative calculations, and with the choice of the PDF set, are taken into account for the ZZ and WZ background processes. The theoretical uncertainties are evaluated by varying renormalization and factorization scales by factors of 0.5 and 2.0, independently. The process leads to yield uncertainties of $\pm 3.2\%$ for the $qq \rightarrow ZZ$ process, and $\pm 3.2\%$ for the WZ process. The uncertainty from the PDF set is determined to be $\pm 3.1\%$ for the $qq \rightarrow ZZ$ process, and $\pm 4.5\%$ for the WZ process. In addition, a 10% uncertainty in the NLO $K$ factor used for the $gg \rightarrow ZZ$ prediction is used [52]. The uncertainties in the cross section of the rare $t\bar{t}W$ and $t\bar{t}Z$ processes amount to 25% [53].

The rate and acceptance uncertainties for the signal processes related to the theoretical calculations arise from uncertainties in the PDFs, variations of the QCD renormalization and factorization scales, and uncertainties in the modeling of parton showers. The magnitude of the rate uncertainty is estimated from simulation and depends on the production process. The inclusive uncertainties related to the PDFs amount to 1.9 and 1.6%, respectively, for the WH and ZH production modes [31]. The corresponding uncertainty for the variation of the renormalization and factorization scales is 0.7 and 3.8%, respectively [31].

The reducible backgrounds are estimated by using the measured rates for jets to be misidentified as electron, muon, or $\tau_h$ candidates. In the WH channels, an uncertainty arises from potentially different misidentification rates in $Z +$ jets events, where the rates are measured, and in $W +$ jets or $t\bar{t}$ events, which constitute a large fraction of the reducible background in the signal region. This leads to a 20% yield uncertainty for the reducible background in each final state of the WH analysis. This 20% yield uncertainty also covers the measured differences in observed versus predicted reducible background yields in multiple dedicated control regions.

In the ZH final states a similar uncertainty is applied based on potential differences between the region where the misidentification rates are measured and the region where they are applied. These uncertainties are based on the results of closure tests comparing the differences in observed versus predicted reducible background yields. The uncertainty is taken to be the largest difference between simulation-based and data-based closure tests. The yield uncertainties are 50% in the $\ell\ell\tau_h$ final states, 25% in $\ell\ell\mu\tau_h$, 40% in $\ell\ell\tau_h\tau_h$, and 100% in $\ell\ell\mu\mu$. The large uncertainty in the $\ell\ell\mu\mu$ final states results from the very low expected reducible background yields, which makes the closure tests susceptible to large statistical fluctuations.

The misidentification rates are measured in different bins of lepton $p_T$, separately for the three reconstructed decay modes for the $\tau_h$ candidate. In the WH channels, where the shape of the reducible background is taken from the misidentification rate method, the statistical uncertainty in every bin is considered as an independent uncertainty and is propagated to the mass distributions and to the yields of the reducible background estimate. In contrast, in the ZH channels, the mass distribution of the reducible background is estimated from data in a region where the $\tau$ candidates have the same charge and pass relaxed isolation conditions. Therefore, the statistical uncertainties in the misidentification rates do not have an impact on the shape of the mass distribution in this channel. Additionally, their impact on the reducible background yields is
subleading compared to the closure-based uncertainties. In both the WH and ZH channels, an additional uncertainty in the misidentification rates arising from the subtraction of prompt leptons estimated from simulation is taken into account and propagated to the reducible background mass distributions.

The $p_T^{\text{miss}}$ scale uncertainties [54], which are computed event-by-event, affect the normalization of various processes through the event selection, as well as their distributions through the propagation of these uncertainties to the di-$\tau$ mass $m_{\tau\tau}$ in the ZH channels. The $p_T^{\text{miss}}$ scale uncertainties arising from unclustered energy deposits in the detector come from four independent sources related to the tracker, ECAL, HCAL, and forward calorimeters. Additionally, $p_T^{\text{miss}}$ scale uncertainties related to the uncertainties in the jet energy measurement, which affect the $p_T^{\text{miss}}$ calculation, are taken into account.

Uncertainties related to the finite number of simulated events, or to the limited number of events in data control regions, are taken into account. They are considered for all bins of the distributions used to extract the results. They are uncorrelated across different samples, and across bins of a single distribution. Finally, the uncertainty in the integrated luminosity amounts to 2.5% [55]. The systematic uncertainties considered in the analysis are summarized in Table 2.

Table 2: Sources of systematic uncertainty. The sign † marks the uncertainties that are both shape- and rate-based. Uncertainties that affect only the normalizations have no marker. For the shape and normalization uncertainties, the magnitude column lists the range of the associated change in normalization, which varies by process and final state. The last column specifies the processes affected by each source of uncertainty.

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<th>Source of uncertainty</th>
<th>Magnitude</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_h$ ID &amp; isolation</td>
<td>5%</td>
<td>All simulations</td>
</tr>
<tr>
<td>$\tau_h$ energy† (1.2% energy shift)</td>
<td>0.1–1.9%</td>
<td>All simulations</td>
</tr>
<tr>
<td>e ID &amp; isolation &amp; trigger</td>
<td>2%</td>
<td>All simulations</td>
</tr>
<tr>
<td>e energy† (1–2.5% energy shift)</td>
<td>0.3–1.4%</td>
<td>All simulations</td>
</tr>
<tr>
<td>$\mu$ ID &amp; isolation &amp; trigger</td>
<td>2%</td>
<td>All simulations</td>
</tr>
<tr>
<td>b veto</td>
<td>0.15–4.50%</td>
<td>All simulations</td>
</tr>
<tr>
<td>Diboson theoretical uncertainty</td>
<td>5%</td>
<td>WZ, ZZ</td>
</tr>
<tr>
<td>$gg \rightarrow ZZ$ NLO K factor</td>
<td>10%</td>
<td>$gg \rightarrow ZZ$</td>
</tr>
<tr>
<td>$t\bar{t} + W/Z$ theoretical uncertainty</td>
<td>25%</td>
<td>$t\bar{t} + W/Z$</td>
</tr>
<tr>
<td>Signal theoretical uncertainty</td>
<td>Up to 4%, see text</td>
<td>Signal</td>
</tr>
<tr>
<td>Reducible background uncertainties:</td>
<td></td>
<td>Reducible bkg.</td>
</tr>
<tr>
<td>WH statistical error propagation†</td>
<td>1–2%</td>
<td></td>
</tr>
<tr>
<td>WH prompt lepton normalization†</td>
<td>2.6% in $e\mu\tau_h$, 4% in $\mu\mu\tau_h$</td>
<td></td>
</tr>
<tr>
<td>ZH prompt lepton normalization†</td>
<td>20% in $\ell\ell\mu$, &lt;1% elsewhere</td>
<td></td>
</tr>
<tr>
<td>WH normalization</td>
<td>20%</td>
<td></td>
</tr>
<tr>
<td>ZH normalization</td>
<td>25–100%</td>
<td></td>
</tr>
<tr>
<td>$p_T^{\text{miss}}$ energy†</td>
<td>Up to 1.5% in WH, &lt;1% in ZH</td>
<td>All simulations</td>
</tr>
<tr>
<td>Limited number of events</td>
<td>Stat. uncertainty per bin</td>
<td>All</td>
</tr>
<tr>
<td>Integrated luminosity</td>
<td>2.5%</td>
<td>All</td>
</tr>
</tbody>
</table>

8 Results

The results of the analysis are extracted with a global maximum likelihood fit based on the reconstructed Higgs boson mass distributions in the eight ZH and four WH signal regions. In
the ZH channels, the $m_{\tau\tau}$ distribution is used. The $m_{\tau\tau}$ distributions are shown in Fig. 1 for each of the four $H \rightarrow \tau\tau$ final states, and in Fig. 2 for all eight ZH channels combined together. The low $L_T^{\text{Higgs}}$ and high $L_T^{\text{Higgs}}$ regions are plotted side-by-side. The eight ZH channels are each fit as separate distributions in the global fit; combining them together is for visualization purposes only. The WH and ZH signal yields correspond to their best fit signal strength value of 2.5. The distributions are shown after the fit and include both statistical and systematic uncertainties. The signal and background predicted yields, as well as the number of observed events, are given for each of the four $H \rightarrow \tau\tau$ final states of the ZH channel in Table 3.

![Figure 1](image-url)

**Figure 1**: The post-fit $m_{\tau\tau}$ distributions used to extract the signal shown for (upper left) $\ell\ell\tau\tau$, (upper right) $\ell\ell\mu\tau\tau$, (lower left) $\ell\ell\tau\tau\tau\tau$, and (lower right) $\ell\ell\mu\mu$. The uncertainties include both statistical and systematic components. The left half of each distribution is the low $L_T^{\text{Higgs}}$ region, while the right half of each distribution is the high $L_T^{\text{Higgs}}$ region. The WH and ZH, $H \rightarrow \tau\tau$ signal processes are summed together and shown as VH, $H \rightarrow \tau\tau$ with a best fit $\mu = 2.5$. VH, $H \rightarrow \tau\tau$ is shown both as a stacked filled histogram and an open overlaid histogram. The contribution from “Other” includes events from triboson, $t\bar{t} + W/Z$, $t\bar{t}H$ production, and all production modes leading to $H \rightarrow WW$ and $H \rightarrow ZZ$ decays. In these distributions the ZH, $H \rightarrow \tau\tau$ process contributes more than 99% of the total of VH, $H \rightarrow \tau\tau$.

The results in the WH channels are obtained from the distributions of the visible mass of the
Figure 2: The post-fit $m_{\tau\tau}$ distributions used to extract the signal, shown for all 8 ZH channels combined. The uncertainties include both statistical and systematic components. The left half of the distribution is the low $L_T^{\text{Higgs}}$ region, while the right half corresponds to the high $L_T^{\text{Higgs}}$ region. The definitions of the $L_T^{\text{Higgs}}$ regions in this distribution are the same as those used in Fig. 1 and are final state dependent. The WH and ZH, $H \rightarrow \tau\tau$ signal processes are summed together and shown as VH, $H \rightarrow \tau\tau$ with a best fit $\mu = 2.5$. VH, $H \rightarrow \tau\tau$ is shown both as a stacked filled histogram and an open overlaid histogram. The contribution from “Other” includes events from triboson, $t\bar{t} + W/Z, t\bar{t}H$ production, and all production modes leading to $H \rightarrow WW$ and $H \rightarrow ZZ$ decays. In this distribution the ZH, $H \rightarrow \tau\tau$ process contributes more than 99% of the total of VH, $H \rightarrow \tau\tau$ decays.

$t_1$ candidate pairs in the $\ell_1\ell_2\ell_3$, $t\bar{t}_3$, channels, and of the visible mass of the $t_1$, and subleading light lepton in the $\ell_1\ell_3\ell_3$ final states. The mass distributions are shown in Fig. 3 for the semileptonic and hadronic channels. Figure 4 shows all four WH channels combined together. The signal and background predicted yields, as well as the number of observed events, are given for each final state for the WH channel in Table 4.

Events from all final states are combined as a function of their decimal logarithm of the ratio of the signal ($S$) to signal-plus-background ($S + B$) in each bin, as shown in Fig. 5. Most of the ZH and WH final states contribute to the most sensitive bin in this distribution. The sensitive bins in the mass distributions correspond to those that include the peak of the signal from approximately 70–110 GeV in the $m_{\text{vis}}$ distributions from the WH channels and 100–160 GeV in the $m_{\tau\tau}$ distributions from the ZH channels. The least sensitive bins in Fig. 5 include background events from all channels away from the signal peak and especially in the low $L_T^{\text{Higgs}}$ region for the ZH channels. An excess of observed events with respect to the SM background expectation is visible in the most sensitive bins of the analysis.

The maximum likelihood fit to the WH and ZH associated production event distributions yields a signal strength $\mu = 2.5^{+1.4}_{-1.3} (1.0^{+1.1}_{-1.0}$ expected) for a significance of 2.3 standard devi-
Table 3: Background and signal expectations for the ZH channels, together with the numbers of observed events, for the post-fit signal region distributions. The ZH final states are each grouped according to the Higgs boson decay products. The $\ell\ell$ notation covers both $Z \rightarrow \mu\mu$ and $Z \rightarrow ee$ events. The signal yields are the numbers of expected signal events for a Higgs boson with a mass $m_H = 125$ GeV. The background uncertainty accounts for all sources of background uncertainty, systematic as well as statistical, after the global fit. The contribution from “Other” includes events from triboson, $t\bar{t}W/Z$, $t\bar{t}H$ production, and all production modes leading to $H \rightarrow WW$ and $H \rightarrow ZZ$ decays.

<table>
<thead>
<tr>
<th>Process</th>
<th>$\ell\ell\tau_h$</th>
<th>$\ell\ell\tau_h$</th>
<th>$\ell\ell\tau_h\tau_h$</th>
<th>$\ell\ell\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZZ</td>
<td>14.40 ± 0.36</td>
<td>26.91 ± 0.55</td>
<td>25.58 ± 1.05</td>
<td>9.52 ± 1.18</td>
</tr>
<tr>
<td>Reducible</td>
<td>14.01 ± 1.55</td>
<td>17.58 ± 1.17</td>
<td>58.05 ± 2.87</td>
<td>3.66 ± 4.60</td>
</tr>
<tr>
<td>Other</td>
<td>0.62 ± 0.08</td>
<td>1.54 ± 0.61</td>
<td>0.81 ± 0.42</td>
<td>3.02 ± 0.23</td>
</tr>
<tr>
<td>Total backgrounds</td>
<td>29.03 ± 1.59</td>
<td>46.03 ± 1.43</td>
<td>84.44 ± 3.08</td>
<td>16.10 ± 4.61</td>
</tr>
<tr>
<td>WH, $H \rightarrow \tau\tau$</td>
<td>0.008 ± 0.002</td>
<td>0.010 ± 0.003</td>
<td>0.016 ± 0.005</td>
<td>0.002 ± 0.001</td>
</tr>
<tr>
<td>ZH, $H \rightarrow \tau\tau$</td>
<td>2.83 ± 0.39</td>
<td>5.31 ± 0.70</td>
<td>5.29 ± 1.17</td>
<td>1.62 ± 0.20</td>
</tr>
<tr>
<td>Total signal</td>
<td>2.84 ± 0.39</td>
<td>5.32 ± 0.70</td>
<td>5.31 ± 1.17</td>
<td>1.62 ± 0.20</td>
</tr>
<tr>
<td>Observed</td>
<td>33</td>
<td>53</td>
<td>87</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 4: Background and signal expectations for the WH channels, together with the numbers of observed events, for the post-fit signal region distributions. The signal yields are the numbers of expected signal events for a Higgs boson with a mass $m_H = 125$ GeV. The background uncertainty accounts for all sources of background uncertainty, systematic as well as statistical, after the global fit. The contributions from triboson, $t\bar{t}W/Z$, $t\bar{t}H$ production, and all production modes leading to $H \rightarrow WW$ and $H \rightarrow ZZ$ decays are included in the category labeled “Other”.

<table>
<thead>
<tr>
<th>Process</th>
<th>$e\mu\tau_h$</th>
<th>$\mu\mu\tau_h$</th>
<th>$e\tau_h\tau_h$</th>
<th>$\mu\tau_h\tau_h$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZZ</td>
<td>1.56 ± 0.05</td>
<td>0.93 ± 0.03</td>
<td>0.82 ± 0.04</td>
<td>1.18 ± 0.05</td>
</tr>
<tr>
<td>WZ</td>
<td>7.92 ± 0.28</td>
<td>6.69 ± 0.24</td>
<td>4.83 ± 0.25</td>
<td>8.38 ± 0.42</td>
</tr>
<tr>
<td>Reducible</td>
<td>10.09 ± 1.61</td>
<td>12.19 ± 1.72</td>
<td>10.68 ± 1.27</td>
<td>19.80 ± 1.87</td>
</tr>
<tr>
<td>Other</td>
<td>2.28 ± 0.61</td>
<td>3.77 ± 0.84</td>
<td>1.71 ± 1.08</td>
<td>1.76 ± 0.90</td>
</tr>
<tr>
<td>Total backgrounds</td>
<td>21.85 ± 1.75</td>
<td>23.58 ± 1.93</td>
<td>18.04 ± 1.69</td>
<td>31.12 ± 2.12</td>
</tr>
<tr>
<td>WH, $H \rightarrow \tau\tau$</td>
<td>4.28 ± 0.72</td>
<td>4.25 ± 0.73</td>
<td>3.51 ± 0.62</td>
<td>5.45 ± 0.97</td>
</tr>
<tr>
<td>ZH, $H \rightarrow \tau\tau$</td>
<td>0.42 ± 0.07</td>
<td>0.40 ± 0.08</td>
<td>0.33 ± 0.07</td>
<td>0.44 ± 0.10</td>
</tr>
<tr>
<td>Total signal</td>
<td>4.70 ± 0.72</td>
<td>4.65 ± 0.73</td>
<td>3.84 ± 0.62</td>
<td>5.89 ± 0.98</td>
</tr>
<tr>
<td>Observed</td>
<td>28</td>
<td>29</td>
<td>23</td>
<td>38</td>
</tr>
</tbody>
</table>
Figure 3: Post-fit mass distributions in the $e\mu t\bar{t}$ (upper left), $\mu\mu t\bar{t}$ (upper right), $e\tau \tau$ (lower left), and $\mu \tau \tau$ (lower right) final states. The uncertainties include both statistical and systematic components. The WH and ZH, $H \rightarrow \tau\tau$ signal processes are summed together and shown as $VH, H \rightarrow \tau\tau$ with a best fit $\mu = 2.5$. $VH, H \rightarrow \tau\tau$ is shown both as a stacked filled histogram and an open overlaid histogram. The contribution from “Other” includes events from triboson, $t\bar{t} + W/Z$, $t\bar{t}H$ production, and all production modes leading to $H \rightarrow WW$ and $H \rightarrow ZZ$ decays. In these distribution the WH, $H \rightarrow \tau\tau$ processes contributes 91–93% of the total of VH, $H \rightarrow \tau\tau$.

The large $\mu$ value is driven by the WH channels, where the observation significantly exceeds the expectations from the SM including the Higgs boson. The constraints from the combined global fit are used to extract the individual best fit signal strengths for WH and ZH: $\mu_{WH} = 3.6^{+1.8}_{-1.6}$ (1.0 expected), and $\mu_{ZH} = 1.4^{+1.6}_{-1.5}$ (1.0 ± 1.3 expected).

The results of this dedicated WH and ZH associated production analysis are combined with the prior $H \rightarrow \tau\tau$ analysis that targeted the gluon fusion and vector boson fusion production modes using the same data set and dilepton final states [19]. The signal regions in both analyses are orthogonal by design because events with extra leptons are removed from the gluon fusion and vector boson fusion targeted dilepton final states. Changes in the gluon fusion signal modeling and uncertainties were made between the publication of Ref. [19] and the combination presented here, to take advantage of the most accurate, available simulations of
the gluon fusion process. The gluon fusion simulation used in Ref. [19] was computed with next-to-leading order matrix elements merged with the parton shower (NLO + PS) accuracy. These NLO + PS gluon fusion samples were reweighed to match the Higgs boson $p_T$ spectrum from the NNLQPS generator [56]. Additionally, the gluon fusion cross section uncertainty scheme has been updated to the one proposed in Ref. [31]. This uncertainty scheme includes 9 nuisance parameters accounting for the uncertainties in the cross section prediction for exclusive jet bins, the 2-jet and 3-jet VBF phase space regions, different Higgs boson $p_T$ regions, and the uncertainty in the Higgs boson $p_T$ distribution due to missing higher-order corrections relating to the treatment of the top quark mass.

After applying the mentioned changes to the gluon fusion modeling, the gluon fusion and VBF targeted analysis results in a best fit signal strength for $H \rightarrow \tau \tau$ of $\mu = 1.17^{+0.27}_{-0.25}$ ($1.00^{+0.25}_{-0.23}$ expected).

With combined results, the significance, signal strengths, and Higgs boson couplings can be measured with better precision than with either analysis alone. The combination leads to an observed significance of 5.5 standard deviations (4.8 expected). The best fit signal strength for the combination is $\mu = 1.24^{+0.27}_{-0.25}$ ($1.00^{+0.25}_{-0.23}$ expected). The signal regions used in the combination target the four leading Higgs boson production mechanisms allowing extraction of the Higgs boson signal strength per production mechanism. The production mode specific signal strength measurements are shown in Fig. 6.
Figure 5: Distribution of the decimal logarithm of the ratio between the expected signal and the sum of the expected signal and background. The signal, corresponding to the best fit value $\mu = 2.5$, and expected background in each bin of the mass distributions used to extract the results, in all final states are combined. The background contributions are separated based on the analysis channel, WH or ZH. The inset shows the corresponding difference between the data and expected background distributions divided by the background expectation, as well as the signal expectation divided by the background expectation.

This combination places a tighter constraint on the $\text{H} \rightarrow \tau\tau$ process in the $(\kappa_V, \kappa_I)$ parameter space than previous analyses targeting exclusively the $\text{H} \rightarrow \tau\tau$ decay process. A likelihood scan is performed for $m_H = 125\text{GeV}$ in the $(\kappa_V, \kappa_I)$ parameter space, where $\kappa_V$ and $\kappa_I$ quantify, respectively, the ratio between the measured and the SM expected values for the couplings of the Higgs boson to vector bosons and to fermions, with the methods described in Ref. [18]. For this scan only, Higgs boson decays to pairs of $W$ or $Z$ bosons, $\text{H} \rightarrow \text{WW}$ or $\text{H} \rightarrow \text{ZZ}$, are considered as part of the signal. All nuisance parameters are profiled for each point of the scan. As shown in Fig. 7, the observed likelihood contour is consistent with the SM expectations of $\kappa_V$ and $\kappa_I$ equal to unity providing increased confidence that the Higgs boson couples to $\tau$ leptons through a Yukawa coupling as predicted in the SM. The addition of the WH and ZH targeted final states brings roughly a 10% reduction in the maximum extent of the 68% CL for $\kappa_V$ compared to the gluon fusion and vector boson fusion targeted analysis.

9 Summary

A search is presented for the standard model (SM) Higgs boson in WH and ZH associated production processes, based on data collected in proton-proton collisions by the CMS detector in 2016 at a center-of-mass energy of 13 TeV. Event categories are defined by three-lepton final states targeting WH production, and four-lepton final states targeting ZH production. The best fit signal strength is $\mu = 2.5^{+1.4}_{-1.3} (1.0^{+1.1}_{-1.0}$ expected) for a significance of 2.3 standard deviations.
Figure 6: Best fit signal strength per Higgs boson production process, for $m_H = 125$ GeV, using a combination of the WH and ZH targeted analysis detailed in this paper with the CMS analysis performed in the same data set for the same decay mode but targeting the gluon fusion and vector boson fusion production mechanisms [19]. The constraints from the combined global fit are used to extract each of the individual best fit signal strengths. The combined best fit signal strength is $\mu = 1.24^{+0.29}_{-0.27}$. (1.0 expected).

The results of this analysis are combined with those of the CMS analysis targeting gluon fusion and vector boson fusion production, also performed at a center-of-mass energy of 13 TeV, and constraints on the $H \rightarrow \tau\tau$ decay rate are set. The best fit signal strength is $\mu = 1.24^{+0.29}_{-0.27}$ (1.00$^{+0.24}_{-0.23}$ expected), and the observed significance is 5.5 standard deviations (4.8 expected) for a Higgs boson mass of 125 GeV. This combination further constrains the coupling of the Higgs boson to vector bosons, resulting in measured couplings that are consistent with SM predictions within one standard deviation, providing increased confidence that the Higgs boson couples to $\tau$ leptons through a Yukawa coupling as predicted in the SM. The combination allows for extraction of the signal strengths for the four leading Higgs boson production processes using exclusively $H \rightarrow \tau\tau$ targeted final states, the results of which are largely consistent with the SM. The measurements of the Higgs boson production mechanisms using $H \rightarrow \tau\tau$ decays are the best results to date for the WH and ZH associated production mechanisms using the $H \rightarrow \tau\tau$ process.

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We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully
Figure 7: Scans of the negative log-likelihood difference as a function of $\kappa_V$ and $\kappa_f$, for $m_H = 125$ GeV. Contours corresponding to confidence levels (CL) of 68 and 95% are shown. All nuisance parameters are profiled for each point. The scan labeled as “Combined” is a combination of the WH and ZH targeted analysis detailed in this paper with the CMS analysis performed in the same data set for the same decay mode but targeting the gluon fusion and vector boson fusion production mechanisms [19]. The results for the gluon fusion and vector boson fusion analysis are represented by the dashed lines and are labeled as “ggH + VBF”. For these scans, the included $H \rightarrow WW$ and $H \rightarrow ZZ$ processes are treated as signal.

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References


A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik, Wien, Austria

Institute for Nuclear Problems, Minsk, Belarus
V. Chekhovsky, V. Mossolov, J. Suarez Gonzalez

Universität Antwerpen, Antwerpen, Belgium

Vrije Universiteit Brussel, Brussel, Belgium

Université Libre de Bruxelles, Bruxelles, Belgium

Ghent University, Ghent, Belgium

Université Catholique de Louvain, Louvain-la-Neuve, Belgium

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

Universidade Estadual Paulista \textsuperscript{a}, Universidade Federal do ABC \textsuperscript{b}, São Paulo, Brazil
S. Ahuja\textsuperscript{a}, C.A. Bernardes\textsuperscript{a}, L. Calligaris\textsuperscript{a}, T.R. Fernandez Perez Tomei\textsuperscript{a}, E.M. Gregores\textsuperscript{b}, P.G. Mercadante\textsuperscript{b}, S.F. Novaes\textsuperscript{a}, SandraS. Padula\textsuperscript{a}

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia,
Bulgaria
A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, A. Marinov, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov

University of Sofia, Sofia, Bulgaria
A. Dimitrov, L. Litov, B. Pavlov, P. Petkov

Beihang University, Beijing, China
W. Fang\textsuperscript{5}, X. Gao\textsuperscript{5}, L. Yuan

Institute of High Energy Physics, Beijing, China

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
Y. Ban, G. Chen, A. Levin, J. Li, L. Li, Q. Li, Y. Mao, S.J. Qian, D. Wang, Z. Xu

Tsinghua University, Beijing, China
Y. Wang

Universidad de Los Andes, Bogota, Colombia
C. Avila, A. Cabrera, C.A. Carrillo Montoya, L.F. Chaparro Sierra, C. Florez, C.F. González Hernández, M.A. Segura Delgado

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
B. Courbon, N. Godinovic, D. Lelas, I. Puljak, T. Sculac

University of Split, Faculty of Science, Split, Croatia
Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, D. Ferencek, K. Kadija, B. Mesic, A. Starodumov\textsuperscript{7}, T. Susa

University of Cyprus, Nicosia, Cyprus

Charles University, Prague, Czech Republic
M. Finger\textsuperscript{8}, M. Finger Jr.\textsuperscript{9}

Escuela Politecnica Nacional, Quito, Ecuador
E. Ayala

Universidad San Francisco de Quito, Quito, Ecuador
E. Carrera Jarrin

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
H. Abdalla\textsuperscript{9}, A.A. Abdelalim\textsuperscript{10,11}, E. Salama\textsuperscript{12,13}

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
S. Bhowmik, A. Carvalho Antunes De Oliveira, R.K. Dewanjee, K. Ehataht, M. Kadastik, M. Raidal, C. Veelken
Department of Physics, University of Helsinki, Helsinki, Finland
P. Eerola, H. Kirschenmann, J. Pekkanen, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland

Lappeenranta University of Technology, Lappeenranta, Finland
T. Tuuva

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France

Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, Université Paris-Saclay, Palaiseau, France

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France

Centre de Calcul de l’Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France
S. Gadrat

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France

Georgian Technical University, Tbilisi, Georgia
T. Toriashvili

Tbilisi State University, Tbilisi, Georgia
Z. Tsamalaidze

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
G. Bencze, C. Hajdu, D. Horvath\textsuperscript{23}, Ā. Hunyadi, F. Sikler, T.Á. Vámi, V. Veszpremi, G. Vesztergombi\textsuperscript{1}

\textbf{Institute of Nuclear Research ATOMKI, Debrecen, Hungary}
N. Beni, S. Czellar, J. Karancsi\textsuperscript{24}, A. Makovec, J. Molnar, Z. Szillasi

\textbf{Institute of Physics, University of Debrecen, Debrecen, Hungary}
P. Raics, Z.L. Trocsanyi, B. Ujvari

\textbf{Indian Institute of Science (IISc), Bangalore, India}
S. Choudhury, J.R. Komaragiri, P.C. Tiwari

\textbf{National Institute of Science Education and Research, HBNI, Bhubaneswar, India}
S. Bahinipati\textsuperscript{25}, C. Kar, P. Mal, K. Mandal, A. Nayak\textsuperscript{26}, D.K. Sahoo\textsuperscript{25}, S.K. Swain

\textbf{Panjab University, Chandigarh, India}

\textbf{University of Delhi, Delhi, India}
A. Bhardwaj, B.C. Choudhary, R.B. Garg, M. Gola, S. Keshri, Ashok Kumar, S. Malhotra, M. Naimuddin, P. Priyanka, K. Ranjan, Aashaq Shah, R. Sharma

\textbf{Saha Institute of Nuclear Physics, HBNI, Kolkata, India}
R. Bhardwaj\textsuperscript{27}, M. Bharti\textsuperscript{27}, R. Bhattacharya, S. Bhattacharya, U. Bhowandeep\textsuperscript{27}, D. Bhowmik, S. Dey, S. Dutt\textsuperscript{27}, S. Dutta, S. Ghosh, K. Mondal, S. Nandan, A. Purohit, P.K. Rout, A. Roy, S. Roy Chowdhury, G. Saha, S. Sarkar, M. Sharan, B. Singh\textsuperscript{27}, S. Thakur\textsuperscript{27}

\textbf{Indian Institute of Technology Madras, Madras, India}
P.K. Behera

\textbf{Bhabha Atomic Research Centre, Mumbai, India}
R. Chudasama, D. Dutta, V. Jha, V. Kumar, P.K. Netrakanti, L.M. Pant, P. Shukla

\textbf{Tata Institute of Fundamental Research-A, Mumbai, India}
T. Aziz, M.A. Bhat, S. Dugad, G.B. Mohanty, N. Sur, B. Sutar, RavindraKumar Verma

\textbf{Tata Institute of Fundamental Research-B, Mumbai, India}
S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, S. Jain, S. Karmakar, S. Kumar, M. Maity\textsuperscript{28}, G. Majumder, K. Mazumdar, N. Sahoo, T. Sarkar\textsuperscript{28}

\textbf{Indian Institute of Science Education and Research (IISER), Pune, India}
S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kothekar, S. Pandey, A. Rane, S. Sharma

\textbf{Institute for Research in Fundamental Sciences (IPM), Tehran, Iran}
S. Chenarani\textsuperscript{29}, E. Eskandari Tadavani, S.M. Etesami\textsuperscript{29}, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, F. Rezaei Hosseinabadi, B. Safarzadeh\textsuperscript{30}, M. Zeinali

\textbf{University College Dublin, Dublin, Ireland}
M. Felcini, M. Grunewald

\textbf{INFN Sezione di Bari }\textsuperscript{a}, Università di Bari }\textsuperscript{b}, Politecnico di Bari }\textsuperscript{c}, Bari, Italy
M. Abbrescia\textsuperscript{a,b}, C. Calabria\textsuperscript{a,b}, A. Colaleo\textsuperscript{a}, D. Creanza\textsuperscript{a,c}, L. Cristella\textsuperscript{a,b}, N. De Filippis\textsuperscript{a,c}, M. De Palma\textsuperscript{a,b}, A. Di Florio\textsuperscript{a,b}, F. Errico\textsuperscript{a,b}, L. Fiore\textsuperscript{a}, A. Gelmi\textsuperscript{a,b}, G. Iselli\textsuperscript{a,c}, M. Ince\textsuperscript{a,b}, S. Lezki\textsuperscript{a,b}, G. Maggi\textsuperscript{a,c}, M. Maggi\textsuperscript{a}, G. Miniello\textsuperscript{a,b}, S. My\textsuperscript{a,b}, S. Nuzzo\textsuperscript{a,b}, A. Pompili\textsuperscript{a,b},
G. Pugliese\textsuperscript{a,c}, R. Radogna\textsuperscript{a}, A. Ranieri\textsuperscript{a}, G. Selvaggi\textsuperscript{a,b}, A. Sharma\textsuperscript{a}, L. Silvestris\textsuperscript{a}, R. Venditti\textsuperscript{a}, P. Verwilligen\textsuperscript{d}, G. Zito\textsuperscript{d}

\textbf{INFN Sezione di Bologna} \textsuperscript{a}, \textbf{Università di Bologna} \textsuperscript{b}, Bologna, Italy

G. Abbiendi\textsuperscript{c}, G. Battilana\textsuperscript{a,b}, D. Bonacorsi\textsuperscript{a,b}, L. Borgonovi\textsuperscript{a,b}, S. Braibant-Giacomelli\textsuperscript{a,b}, R. Campanini\textsuperscript{a,b}, P. Capiluppi\textsuperscript{a,b}, A. Castro\textsuperscript{a,b}, F.R. Cavallo\textsuperscript{a}, S.S. Chhibra\textsuperscript{a,b}, C. Ciocca\textsuperscript{a}, G. Codispoti\textsuperscript{a,b}, M. Cuffiani\textsuperscript{a,b}, G.M. Dallavalle\textsuperscript{a}, F. Fabbri\textsuperscript{a}, A. Fanfani\textsuperscript{a,b}, E. Fontanesi, P. Giacomelli\textsuperscript{a}, C. Grandi\textsuperscript{a}, L. Guiducci\textsuperscript{a,b}, S. Lo Meo\textsuperscript{a}, S. Marcellini\textsuperscript{a}, G. Masetti\textsuperscript{a}, A. Montanari\textsuperscript{a}, F.L. Navarria\textsuperscript{a,b}, A. Perrotta\textsuperscript{a}, F. Primavera\textsuperscript{a,b,18}, A.M. Rossi\textsuperscript{a,b}, T. Rovelli\textsuperscript{a,b}, G.P. Siroli\textsuperscript{a,b}, N. Tosi\textsuperscript{d}

\textbf{INFN Sezione di Catania} \textsuperscript{a}, \textbf{Università di Catania} \textsuperscript{b}, Catania, Italy

S. Albergo\textsuperscript{a,b}, A. Di Mattia\textsuperscript{a}, R. Potenza\textsuperscript{a,b}, A. Tricomi\textsuperscript{a,b}, C. Tuve\textsuperscript{a,b}

\textbf{INFN Sezione di Firenze} \textsuperscript{a}, \textbf{Università di Firenze} \textsuperscript{b}, Firenze, Italy

G. Barbaglia\textsuperscript{a}, K. Chatterjee\textsuperscript{a,b}, V. Ciulli\textsuperscript{a,b}, C. Civinini\textsuperscript{a}, R. D’Alessandro\textsuperscript{a,b}, E. Focardi\textsuperscript{a,b}, G. Latino, P. Lenzi\textsuperscript{a,b}, M. Meschini\textsuperscript{a}, S. Paoletti\textsuperscript{a}, L. Russo\textsuperscript{a,31}, G. Sguazzoni\textsuperscript{a}, D. Strom\textsuperscript{a}, L. Viliani\textsuperscript{a}

\textbf{INFN Laboratori Nazionali di Frascati} , Frascati, Italy

L. Benussi, S. Bianco, F. Fabbri, D. Piccolo

\textbf{INFN Sezione di Genova} \textsuperscript{a}, \textbf{Università di Genova} \textsuperscript{b}, Genova, Italy

F. Ferro\textsuperscript{a}, F. Ravera\textsuperscript{a,b}, E. Robutti\textsuperscript{a}, S. Tosi\textsuperscript{a,b}

\textbf{INFN Sezione di Milano-Bicocca} \textsuperscript{a}, \textbf{Università di Milano-Bicocca} \textsuperscript{b}, Milano, Italy

A. Benaglia\textsuperscript{a}, A. Beschi\textsuperscript{a}, F. Brivio\textsuperscript{a,b}, V. Ciriolo\textsuperscript{a,b,18}, S. Di Guida\textsuperscript{a,d,18}, M.E. Dinardo\textsuperscript{a,b}, S. Fiorendi\textsuperscript{a,b}, S. Gennai\textsuperscript{a}, A. Ghezzi\textsuperscript{a,b}, P. Govoni\textsuperscript{a,b}, M. Malberti\textsuperscript{a,b}, S. Malvezzi\textsuperscript{a}, A. Massironi\textsuperscript{a,b}, D. Menasce\textsuperscript{a}, F. Monti, L. Moroni\textsuperscript{a}, M. Paganoni\textsuperscript{a,b}, D. Pedrini\textsuperscript{a}, S. Ragazzi\textsuperscript{a}, T. Tabarelli de Fatis\textsuperscript{a,b}, D. Zuo\textsuperscript{a,b}

\textbf{INFN Sezione di Napoli} \textsuperscript{a}, \textbf{Università di Napoli ‘Federico II’} \textsuperscript{b}, Napoli, Italy, \textbf{Università della Basilicata} \textsuperscript{c}, Potenza, Italy, \textbf{Università G. Marconi} \textsuperscript{d}, Roma, Italy

S. Buontempo\textsuperscript{a}, N. Cavallo\textsuperscript{a,c}, A. De Iorio\textsuperscript{a,b}, A. Di Crescenzo\textsuperscript{a,b}, F. Fabozzi\textsuperscript{a,c}, F. Fienga\textsuperscript{a}, G. Galati\textsuperscript{a}, A.O.M. Iorio\textsuperscript{a,b}, W.A. Khan\textsuperscript{a}, L. Lista\textsuperscript{a}, S. Meola\textsuperscript{a,d,18}, P. Paolucci\textsuperscript{a,b,18}, C. Sciacca\textsuperscript{a,b}, E. Voevodina\textsuperscript{a,b}

\textbf{INFN Sezione di Padova} \textsuperscript{a}, \textbf{Università di Padova} \textsuperscript{b}, Padova, Italy, \textbf{Università di Trento} \textsuperscript{c}, Trento, Italy

P. Azzi\textsuperscript{a}, N. Bacchetta\textsuperscript{a}, A. Boletti\textsuperscript{a,b}, A. Bragagnolo, R. Carlin\textsuperscript{a,b}, P. Checchia\textsuperscript{a}, M. Dall’Osso\textsuperscript{a,b}, P. De Castro Manzano\textsuperscript{a}, T. Dorigo\textsuperscript{a}, U. Dosselli\textsuperscript{a}, F. Gasparini\textsuperscript{a,b}, U. Garafini\textsuperscript{a,b}, A. Gozzelino\textsuperscript{a}, S.Y. Hoh, S. Lacaprara\textsuperscript{a}, P. Lujan, M. Margoni\textsuperscript{a,b}, A.T. Meneguzzo\textsuperscript{a,b}, J. Pazzini\textsuperscript{a,b}, N. Pozzobon\textsuperscript{a,b}, P. Ronchese\textsuperscript{a,b}, R. Rossini\textsuperscript{a,b}, F. Simonetto\textsuperscript{a,b}, A. Tiko, E. Torassa\textsuperscript{a}, M. Zanetti\textsuperscript{a,b}, P. Zotto\textsuperscript{a,b}, G. Zumerle\textsuperscript{a,b}

\textbf{INFN Sezione di Pavia} \textsuperscript{a}, \textbf{Università di Pavia} \textsuperscript{b}, Pavia, Italy

A. Braghieri\textsuperscript{a}, A. Magnani\textsuperscript{a}, P. Montagna\textsuperscript{a,b}, S.P. Ratti\textsuperscript{a,b}, V. Re\textsuperscript{a}, M. Ressegotti\textsuperscript{a,b}, C. Riccardi\textsuperscript{a,b}, P. Salvini\textsuperscript{a}, I. Vai\textsuperscript{a,b}, P. Vittolo\textsuperscript{a,b}

\textbf{INFN Sezione di Perugia} \textsuperscript{a}, \textbf{Università di Perugia} \textsuperscript{b}, Perugia, Italy

M. Biasini\textsuperscript{a,b}, G.M. Bilei\textsuperscript{a}, C. Cecchi\textsuperscript{a,b}, D. Ciangottini\textsuperscript{a,b}, L. Fano\textsuperscript{a,b}, P. Lariccia\textsuperscript{a,b}, R. Leonardi\textsuperscript{a,b}, E. Manoni\textsuperscript{a}, G. Mantovani\textsuperscript{a,b}, V. Mariani\textsuperscript{a,b}, M. Menichelli\textsuperscript{a}, A. Rossi\textsuperscript{a,b}, A. Santocchia\textsuperscript{a,b}, D. Spiga\textsuperscript{a}
INFN Sezione di Pisa, Università di Pisa, Scuola Normale Superiore di Pisa, Pisa, Italy
K. Androsov\textsuperscript{a}, P. Azzurri\textsuperscript{a}, G. Bagliesi\textsuperscript{a}, L. Bianchini\textsuperscript{a}, T. Boccali\textsuperscript{a}, L. Borrello, R. Castaldi\textsuperscript{a}, M.A. Ciocci\textsuperscript{a,b}, R. Dell’Orso\textsuperscript{a}, G. Fedi\textsuperscript{a}, F. Fiori\textsuperscript{a,c}, L. Giannini\textsuperscript{a,c}, A. Giassi\textsuperscript{a}, M.T. Grippo\textsuperscript{a}, F. Ligabue\textsuperscript{a,c}, E. Manca\textsuperscript{a,c}, G. Mandorli\textsuperscript{a,c}, A. Messineo\textsuperscript{a,b}, F. Palla\textsuperscript{a}, A. Rizzi\textsuperscript{a,b}, P. Spagnolo\textsuperscript{a}, R. Tenchini\textsuperscript{a}, G. Tonelli\textsuperscript{a,b}, A. Venturi\textsuperscript{a}, P.G. Verdini\textsuperscript{a}

INFN Sezione di Roma, Sapienza Università di Roma, Rome, Italy
L. Barone\textsuperscript{a,b}, F. Cavallari\textsuperscript{a}, M. Cipriani\textsuperscript{a,b}, D. Del Re\textsuperscript{a,b}, E. Di Marco\textsuperscript{a,b}, M. Diemoz\textsuperscript{a}, S. Gelli\textsuperscript{a,b}, E. Longo\textsuperscript{a,b}, B. Marzocchi\textsuperscript{a,b}, P. Meridiani\textsuperscript{a}, G. Organtini\textsuperscript{a,b}, F. Pandolfi\textsuperscript{a}, R. Paramatti\textsuperscript{a,b}, F. Preiato\textsuperscript{a,b}, S. Rahatlou\textsuperscript{a,b}, C. Rovelli\textsuperscript{a}, F. Santanastasio\textsuperscript{a,b}

INFN Sezione di Torino, Università di Torino, Torino, Italy
N. Amapane\textsuperscript{a,b}, R. Arcidiacono\textsuperscript{a,c}, S. Argiro\textsuperscript{a,b}, M. Arneodo\textsuperscript{a,c}, N. Bartosik\textsuperscript{a}, R. Bellan\textsuperscript{a,b}, C. Biino\textsuperscript{a}, N. Cartiglia\textsuperscript{a}, F. Cenna\textsuperscript{a,b}, S. Cometti\textsuperscript{a}, M. Costa\textsuperscript{a,b}, R. Covarelli\textsuperscript{a,b}, N. Demaria\textsuperscript{a}, B. Kiani\textsuperscript{a,b}, C. Mariotti\textsuperscript{a}, S. Maselli\textsuperscript{a}, E. Migliore\textsuperscript{a,b}, V. Monaco\textsuperscript{a,b}, E. Montei\textsuperscript{a,b}, M. Monteno\textsuperscript{a}, M.M. Obertino\textsuperscript{a,b}, L. Pacher\textsuperscript{a,b}, N. Pastrone\textsuperscript{a}, M. Pelliccioni\textsuperscript{a}, G.L. Pinna Angioni\textsuperscript{a,b}, A. Romero\textsuperscript{a,b}, M. Ruspa\textsuperscript{a,c}, R. Sacchi\textsuperscript{a,b}, K. Shchelina\textsuperscript{a,b}, V. Sola\textsuperscript{a}, A. Solano\textsuperscript{a,b}, D. Soldi\textsuperscript{a,b}, A. Staiano\textsuperscript{a}

INFN Sezione di Trieste, Università di Trieste, Trieste, Italy
S. Belforte\textsuperscript{a}, V. Candelise\textsuperscript{a,b}, M. Casarsa\textsuperscript{a}, F. Cossutti\textsuperscript{a}, A. Da Rold\textsuperscript{a,b}, G. Della Ricca\textsuperscript{a,b}, F. Vazzoler\textsuperscript{a,b}, A. Zanetti\textsuperscript{a}

Kyunpook National University, Daegu, Korea

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
H. Kim, D.H. Moon, G. Oh

Hanyang University, Seoul, Korea
J. Goh\textsuperscript{32}, T.J. Kim

Korea University, Seoul, Korea

Sejong University, Seoul, Korea
H.S. Kim

Seoul National University, Seoul, Korea

University of Seoul, Seoul, Korea

Sungkyunkwan University, Suwon, Korea
Y. Choi, C. Hwang, J. Lee, I. Yu

Vilnius University, Vilnius, Lithuania
V. Dudenas, A. Juodagalvis, J. Vaitkus
National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia

Universidad de Sonora (UNISON), Hermosillo, Mexico
J.F. Benitez, A. Castaneda Hernandez, J.A. Murillo Quijada

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico

Universidad Iberoamericana, Mexico City, Mexico
S. Carrillo Moreno, C. Oropeza Barrera, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
J. Eysermans, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
A. Morelos Pineda

University of Auckland, Auckland, New Zealand
D. Krofcheck

University of Canterbury, Christchurch, New Zealand
S. Bheesette, P.H. Butler

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
A. Ahmad, M. Ahmad, M.I. Asghar, Q. Hassan, H.R. Hoorani, A. Saddique, M.A. Shah, M. Shoaib, M. Waqas

National Centre for Nuclear Research, Swierk, Poland

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal

Joint Institute for Nuclear Research, Dubna, Russia

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
V. Golovtsov, Y. Ivanov, V. Kim, E. Kuznetsova, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sokov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia
Institute for Theoretical and Experimental Physics, Moscow, Russia
V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, A. Stepennov, V. Stolin, M. Toms, E. Vlasov, A. Zhokin

Moscow Institute of Physics and Technology, Moscow, Russia
T. Aushev

National Research Nuclear University ‘Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia
M. Chadeeva, P. Parygin, D. Philippov, S. Polikarpov, E. Popova, V. Rusanov

P.N. Lebedev Physical Institute, Moscow, Russia
V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, S.V. Rusakov, A. Terkulov

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

Novosibirsk State University (NSU), Novosibirsk, Russia
A. Barnyakov, V. Blinov, T. Dimova, L. Kardapoltsev, Y. Skovpen

Institute for High Energy Physics of National Research Centre ‘Kurchatov Institute’, Protvino, Russia

National Research Tomsk Polytechnic University, Tomsk, Russia
A. Babaev, S. Baidali, V. Okhotnikov

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
P. Adzic, P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain

Universidad Autónoma de Madrid, Madrid, Spain
C. Albajar, J.F. de Trocóniz

Universidad de Oviedo, Oviedo, Spain

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
Middle East Technical University, Physics Department, Ankara, Turkey
B. Isildak, G. Karapinar, M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey
I.O. Atakisi, E. Gülmez, M. Kaya, O. Kaya, S. Ozkorucuklu, S. Tekten, E.A. Yetkin

Istanbul Technical University, Istanbul, Turkey
M.N. Agaras, A. Cakir, K. Cankocak, Y. Komurcu, S. Sen

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine
B. Grynyov

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine
L. Levchuk

University of Bristol, Bristol, United Kingdom

Rutherford Appleton Laboratory, Didcot, United Kingdom

Imperial College, London, United Kingdom

Brunel University, Uxbridge, United Kingdom
J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, C.K. Mackay, A. Morton, I.D. Reid, L. Teodorescu, S. Zahid

Baylor University, Waco, USA
K. Call, J. Dittmann, K. Hatakeyama, H. Liu, C. Madrid, B. Mcmaster, N. Pastika, C. Smith

Catholic University of America, Washington DC, USA
R. Bartek, A. Dominguez

The University of Alabama, Tuscaloosa, USA
A. Buccilli, S.I. Cooper, C. Henderson, P. Rumerio, C. West

Boston University, Boston, USA

Brown University, Providence, USA

University of California, Davis, Davis, USA
R. Band, C. Brainerd, R. Breedon, D. Burns, M. Calderon De La Barca Sanchez, M. Chertok,
University of California, Los Angeles, USA

University of California, Riverside, Riverside, USA

University of California, San Diego, La Jolla, USA

University of California, Santa Barbara - Department of Physics, Santa Barbara, USA

California Institute of Technology, Pasadena, USA

Carnegie Mellon University, Pittsburgh, USA

University of Colorado Boulder, Boulder, USA

Cornell University, Ithaca, USA

Fermi National Accelerator Laboratory, Batavia, USA
University of Florida, Gainesville, USA

Florida International University, Miami, USA
Y.R. Joshi, S. Linn

Florida State University, Tallahassee, USA

Florida Institute of Technology, Melbourne, USA

University of Illinois at Chicago (UIC), Chicago, USA

The University of Iowa, Iowa City, USA

Johns Hopkins University, Baltimore, USA

The University of Kansas, Lawrence, USA

Kansas State University, Manhattan, USA

Lawrence Livermore National Laboratory, Livermore, USA
F. Rebassoo, D. Wright

University of Maryland, College Park, USA

Massachusetts Institute of Technology, Cambridge, USA
University of Minnesota, Minneapolis, USA

University of Mississippi, Oxford, USA
J.G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, USA

State University of New York at Buffalo, Buffalo, USA

Northeastern University, Boston, USA

Northwestern University, Evanston, USA

University of Notre Dame, Notre Dame, USA

The Ohio State University, Columbus, USA

Princeton University, Princeton, USA

University of Puerto Rico, Mayaguez, USA
S. Malik, S. Norberg

Purdue University, West Lafayette, USA

Purdue University Northwest, Hammond, USA
T. Cheng, J. Dolen, N. Parashar

Rice University, Houston, USA

University of Rochester, Rochester, USA
A. Bodek, P. de Barbaro, R. Demina, Y.t. Duh, J.L. Dulemba, C. Fallon, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, O. Hindrichs, A. Khukhunaishvili, P. Tan, R. Taus
Rutgers, The State University of New Jersey, Piscataway, USA

University of Tennessee, Knoxville, USA
A.G. Delannoy, J. Heideman, G. Riley, S. Spanier

Texas A&M University, College Station, USA

Texas Tech University, Lubbock, USA

Vanderbilt University, Nashville, USA

University of Virginia, Charlottesville, USA
M.W. Arenton, P. Barria, B. Cox, R. Hirosky, M. Joyce, A. Ledovskoy, H. Li, C. Neu, T. Sinthuprasith, Y. Wang, E. Wolfe, F. Xia

Wayne State University, Detroit, USA

University of Wisconsin - Madison, Madison, WI, USA

†: Deceased
1: Also at Vienna University of Technology, Vienna, Austria
2: Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
3: Also at Universidade Estadual de Campinas, Campinas, Brazil
4: Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
5: Also at Université Libre de Bruxelles, Bruxelles, Belgium
6: Also at University of Chinese Academy of Sciences, Beijing, China
7: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
8: Also at Joint Institute for Nuclear Research, Dubna, Russia
9: Also at Cairo University, Cairo, Egypt
10: Also at Helwan University, Cairo, Egypt
11: Now at Zewail City of Science and Technology, Zewail, Egypt
12: Also at British University in Egypt, Cairo, Egypt
13: Now at Ain Shams University, Cairo, Egypt
14: Also at Department of Physics, King Abdulaziz University, Jeddah, Saudi Arabia
15: Also at Université de Haute Alsace, Mulhouse, France
16: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
17: Also at Tbilisi State University, Tbilisi, Georgia
18: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
19: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
20: Also at University of Hamburg, Hamburg, Germany
21: Also at Brandenburg University of Technology, Cottbus, Germany
22: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
23: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
24: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
25: Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India
26: Also at Institute of Physics, Bhubaneswar, India
27: Also at Shoolini University, Solan, India
28: Also at University of Visva-Bharati, Santiniketan, India
29: Also at Isfahan University of Technology, Isfahan, Iran
30: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
31: Also at Università degli Studi di Siena, Siena, Italy
32: Also at Kyunghee University, Seoul, Korea
33: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
34: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
35: Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico
36: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
37: Also at Institute for Nuclear Research, Moscow, Russia
38: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
39: Also at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
40: Also at University of Florida, Gainesville, USA
41: Also at P.N. Lebedev Physical Institute, Moscow, Russia
42: Also at California Institute of Technology, Pasadena, USA
43: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
44: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
45: Also at INFN Sezione di Pavia a, Università di Pavia b, Pavia, Italy
46: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
47: Also at Scuola Normale e Sezione dell’INFN, Pisa, Italy
48: Also at National and Kapodistrian University of Athens, Athens, Greece
49: Also at Riga Technical University, Riga, Latvia
50: Also at Universität Zürich, Zurich, Switzerland
51: Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria
52: Also at Adiyaman University, Adiyaman, Turkey
53: Also at Istanbul Aydin University, Istanbul, Turkey
54: Also at Mersin University, Mersin, Turkey
55: Also at Piri Reis University, Istanbul, Turkey
56: Also at Gaziosmanpasa University, Tokat, Turkey
57: Also at Ozyegin University, Istanbul, Turkey
58: Also at Gaziosmanpasa University, Tokat, Turkey
59: Also at Marmara University, Istanbul, Turkey
60: Also at Kafkas University, Kars, Turkey
61: Also at Istanbul University, Faculty of Science, Istanbul, Turkey
62: Also at Istanbul Bilgi University, Istanbul, Turkey
63: Also at Hacettepe University, Ankara, Turkey
64: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
65: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
66: Also at Monash University, Faculty of Science, Clayton, Australia
67: Also at Bethel University, St. Paul, USA
68: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
69: Also at Utah Valley University, Orem, USA
70: Also at Purdue University, West Lafayette, USA
71: Also at Beykent University, Istanbul, Turkey
72: Also at Bingol University, Bingol, Turkey
73: Also at Sinop University, Sinop, Turkey
74: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
75: Also at Texas A&M University at Qatar, Doha, Qatar
76: Also at Kyungpook National University, Daegu, Korea