Phys. Lett. B 857 (2024) 138964

Contents lists available at ScienceDirect

Physics Letters B

journal homepage: www.elsevier.com/locate/physletb

Letter

Measurement of the production cross section of a Higgs boson with large transverse momentum in its decays to a pair of τ leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV

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ARTICLE INFO

Editor: M. Doser

Dataset link: CMS data preservation, re-use and open access policy

Keywords:
CMS
Higgs boson
Tau lepton

ABSTRACT

A measurement of the production cross section of a Higgs boson with transverse momentum greater than 250 GeV is presented where the Higgs boson decays to a pair of τ leptons. It is based on proton-proton collision data collected by the CMS experiment at the CERN LHC at a center-of-mass energy of 13 TeV. The data sample corresponds to an integrated luminosity of 138 fb^{-1}. Because of the large transverse momentum of the Higgs boson the τ leptons from its decays are boosted and produced spatially close, with their decay products overlapping. Therefore, a dedicated algorithm was developed to reconstruct and identify them. The observed (expected) significance of the measured signal with respect to the standard model background-only hypothesis is 3.5 (2.2) standard deviations. The product of the production cross section and branching fraction is measured to be $1.64^{+0.68}_{-0.54}$ times the standard model expectation. The fiducial differential production cross section is also measured as functions of the Higgs boson and leading jet transverse momenta. This measurement extends the probed large-transverse-momentum region in the $\tau\tau$ final state beyond 600 GeV.

1. Introduction

Since the discovery of a particle compatible with the standard model (SM) Higgs boson (H) [1–3], many of its properties have been scrutinized, without evidence of deviations from the SM expectations [4,5]. Measuring the production of the Higgs boson with large transverse momentum (p_T) tests the existence of physics beyond the SM (BSM) in the scalar sector, to which inclusive measurements could be insensitive [6]. Such measurements can shed light on the structure of the interactions of the Higgs boson with massive particles. In particular, the cross section of the gluon-gluon production mode of the Higgs boson (ggH) is sensitive at large p_T to the structure of the effective ggH coupling [7,8].

The ATLAS and CMS Collaborations have reported measurements of the differential production cross section of the Higgs boson as a function of its transverse momentum p_T^H [9–21]. While the measurement precision at low p_T^H is driven by the $H \to \gamma\gamma$, $H \to ZZ \to 4\ell$, and $H \to WW \to 2\ell 2\nu$ decay modes ($\ell =$ e or μ), the sensitivity at larger p_T^H is improved by including the $H \to \tau\tau$ and $H \to bb$ decay modes because of their larger branching fractions. In this Letter, a dedicated measurement of the production cross section of a Higgs boson with large p_T decaying to a pair of τ leptons is presented. This measurement extends the probed large-p_T region beyond 600 GeV [19]. Because of the large-p_T of the Higgs boson, the τ leptons from its decays are boosted and produced spatially close with their decay products overlapping. A Higgs boson with $p_T^H \gtrsim 250$ GeV leads to a separation $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.8$ between the τ leptons. To handle overlapping τ decay products, a dedicated algorithm to identify the close-by τ leptons is employed. All four main Higgs boson production modes have been included in this measurement and four final states including hadronic and leptonic τ decays are considered: $\mu\tau_h$, $e\tau_h$, $\tau_h\tau_h$, and $e\mu$, where τ_h denotes the visible decay products of a τ lepton decaying into hadrons. The results are extracted using a multiclass neural network (NN) categorizing the events into signal- and background-enriched regions. The analysis is based on proton-proton (pp) collision data collected by the CMS experiment at the CERN LHC at a center-of-mass energy of 13 TeV. The data sample corresponds to an integrated luminosity of 138 fb^{-1} [22–24].

2. The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintil-

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https://doi.org/10.1016/j.physletb.2024.138964
Received 29 March 2024; Received in revised form 18 July 2024; Accepted 13 August 2024

Available online 22 August 2024

lator hadron calorimeter, each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity (η) 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 of interest are selected using a two-tiered trigger system. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed latency of 4 μs [25]. The second level, known as the high-level trigger, consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage [26]. 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. [27].

3. Event simulation

The POWHEG 2.0 [28–31] generator is used to generate Higgs boson signal samples at next-to-leading order (NLO) in the four leading production modes. The distributions of p_T^H and jet multiplicity in the gluon fusion production simulation are corrected to match the predictions of the NNLOPS event generator based upon the POWHEG+MiNLO approach [32,33]. The W+jets and Z/γ^*+jets processes are modeled with MADGRAPH5_aMC@NLO 2.2.2 (2.4.2) generator [34] with the MLM jet matching and merging scheme [35]. A combination of the POWHEG 2.0 [36,37] and MADGRAPH5_aMC@NLO generators is used to model the diboson (WW, WZ, and ZZ) processes at NLO. Single top quark and $t\bar{t}$ productions are modeled with the POWHEG [38,39] generator at NLO. The NNPDF 3.1 [40] parton distribution functions (PDF) are used, and all simulated samples are interfaced with PYTHIA 8.212 [41] to describe parton showering and hadronization. The CUETP8M1 [42] and CP5 [43] tunes are used for the 2016 and 2017–2018 samples, respectively. Additional inelastic pp interactions (pileup) generated by PYTHIA are overlaid on all simulated events, according to the luminosity profile of the analyzed data. The average pileup ranges from 23 interactions in 2016 to 32 in 2018. All the generated signal and background samples are processed with the simulation of the CMS detector based on GEANT4 [44]. Differences between data and simulation in trigger, particle identification, isolation efficiencies, and in the resolution of the jet p_T and missing transverse momentum ($\vec{p}_T^{\,miss}$) are corrected by applying scale factors to simulated events.

4. Event reconstruction and selection

The physics objects are reconstructed by the particle-flow (PF) algorithm [45], which combines information from all subdetectors to identify individual particles (PF candidates). The primary vertex is taken to be the vertex corresponding to the hardest scattering in the event, evaluated using tracking information alone, as described in Section 9.4.1 of Ref. [46]. Standard muon and electron reconstruction, identification, and isolation methods are used, and are similar to those described in Ref. [19]. Starting from PF candidates, AK4 and AK8 jets are reconstructed using the anti-k_T FASTJET algorithm with a distance parameter of 0.4 and 0.8, respectively [47,48]. Jet energy corrections are applied to both simulation and data so that the average measured energy of jets becomes identical to that of simulated particle-level jets, to account for residual differences between the jet energy in data and in simulation [49,50], and to reduce pileup effects.

The PF candidates in AK4 jets are used to reconstruct τ_h objects, using the hadrons-plus-strips (HPS) algorithm [51,52], which combines one or three charged particles with neutral pion candidates within a narrow signal cone, to identify the τ_h decay modes. PF candidates inside a cone of size $\Delta R = 0.5$, defined as an isolation cone, around the τ_h candidate are used to determine its isolation. To distinguish genuine τ_h decays from jets originating from the hadronization of quarks or gluons, a multivariate analysis (MVA) discriminant is used [53], called "MVA isolation" in the following. It combines information about the energy carried by PF candidates within the isolation cone with lifetime information. The lifetime information includes the impact parameter of the leading track of the tau candidate and its significance. In the case of 3-prong tau leptons, the secondary vertex is fitted using the tau tracks and a flight path length, i.e. a signed distance between the primary vertex and secondary vertex, and its significance are used in addition to the impact parameter. Electrons and muons reconstructed as τ_h candidates are rejected with dedicated discriminants [53].

If a τ lepton pair originates from a particle with high p_T, the decay products of the τ leptons are emitted close to each other, forming a single jet. The separation of the τ leptons is approximately equal to $\frac{2m_H}{p_T^H}$. The presence of two close-by τ leptons spoils the isolation requirement, leading to a drop in efficiency. To recover this loss, a modified version of the HPS algorithm, relying on jet substructure techniques, has been developed [53]. Particles are first clustered in a large-radius jet with the Cambridge–Aachen algorithm [54] with a distance parameter of 0.8, and the jet is required to have $p_T > 170$ GeV. The final step of the jet clustering is reversed to find two subjets consistent with τ leptons. The subjets are then processed with the HPS algorithm to identify the τ_h decay modes. A crucial step in the boosted τ_h reconstruction algorithm is the requirement that the overlapping τ leptons do not share any common PF candidate. This is, by construction, satisfied by the two subjets seeding the τ lepton reconstruction algorithm. Thus, the isolation of a given τ is computed after removal of the PF candidates that belong to the other τ lepton. Since electrons and muons give rise to subjets, the method also excludes these leptons from the list of neighboring tau lepton isolation candidates in the $e\tau_h$ and $\mu\tau_h$ final states. The final step is to compute discriminants to reject jets, electrons, and muons mis-reconstructed as τ_h candidates.

Fig. 1 compares the $\tau_h\tau_h$ and τ_h isolation efficiencies for the standard and boosted HPS algorithms as a function of p_T^H, in the $\tau_h\tau_h$ (left) and $\ell\tau_h$ (right) final states. As p_T^H increases and the τ leptons get spatially closer, the HPS τ lepton isolation efficiency decreases while the boosted τ lepton efficiency reaches a plateau and remains constant. This effect is more pronounced in the $\tau_h\tau_h$ final state because of the presence of a pair of τ_h candidates. A drop in the isolation efficiency of HPS τ_h candidate around 450 GeV occurs when the distance between the τ_h candidate becomes equal to the size of the τ_h isolation cone of 0.5.

The τ_h candidates must have $p_T > 30$ GeV, $|\eta| < 2.3$, and pass an MVA isolation requirement that corresponds to a typical identification efficiency of 60% in $Z/\gamma^* \to \tau\tau$ events for a 3% misidentification rate of jets. The loose working point of the discriminator against muons (electrons) is used, suppressing muons (electrons) by more than 90% and maintaining the τ_h identification efficiency above 95%. The $\vec{p}_T^{\,miss}$ is computed as the negative vector sum of the transverse momenta of all the PF candidates in an event, and its magnitude is denoted as p_T^{miss} [55]. The $\vec{p}_T^{\,miss}$ is modified to account for corrections to the energy scale of the reconstructed jets in the event. Another correction accounts for the effect of additional pileup interactions [50]. Two variables to quantify the hadronic activity in the event are used. The first one is the total visible hadronic activity H_T, which is defined as the scalar sum of transverse momenta of jets with $p_T > 30$ GeV and $|\eta| < 3$. The second variable is the momentum imbalance $\vec{H}_T^{miss}$ and is defined as the negative vector sum of the transverse momenta of jets with $p_T > 30$ GeV and $|\eta| < 5$. Its magnitude is denoted as H_T^{miss}.

Collision events were collected using single-lepton (muon or electron) triggers in the $\mu\tau_h$, $e\tau_h$, and $e\mu$ channels, while a combination of triggers relying on p_T^{miss}, jet p_T, H_T, and H_T^{miss} was used in the $\tau_h\tau_h$ channel. In the $\mu\tau_h$ ($e\tau_h$) channel, events passing single-lepton triggers with p_T threshold of 50 (115) GeV and no isolation requirement must have an offline lepton with $p_T > 52$ (120) GeV, while events passing single isolated lepton triggers must have an offline lepton with p_T between 28 (38) and 52 (120) GeV and passing isolation criteria, as well as $p_T^{miss} > 30$ GeV. Events in the $e\mu$ channel must pass any of the

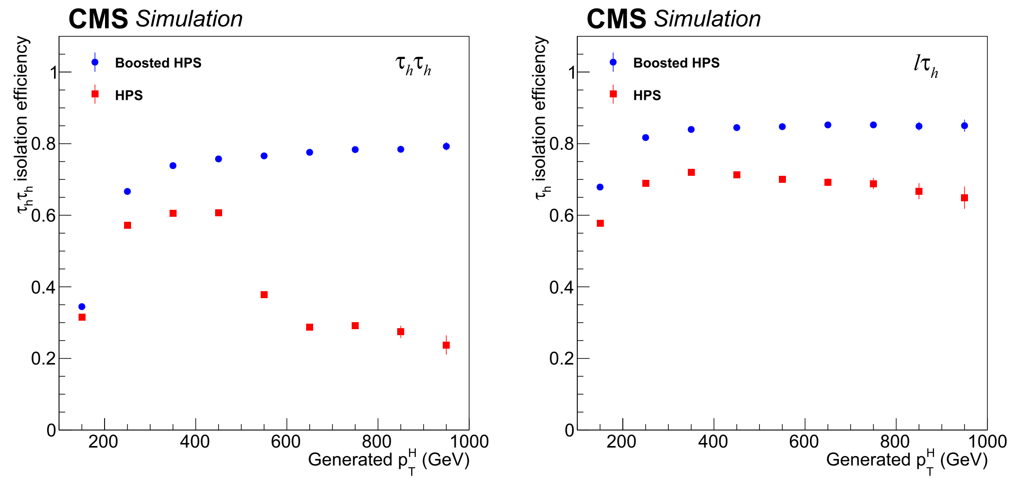

Fig. 1. Comparison of the isolation efficiencies for the standard and boosted HPS algorithms in the $\tau_h\tau_h$ (left) and $\ell\tau_h$ (right) final states.

Table 1
Selection requirements for the four $\tau\tau$ final states. The relative isolation variable, $I_{rel}^{\mu,e}$, for muons and electrons is evaluated as the scalar sum of the p_T of the reconstructed particles in a cone around the lepton track relative to the p_T of the lepton. In the $\tau_h\tau_h$ channel, the trigger requirement is defined by a combination of trigger candidates above a given threshold, indicated inside parentheses in GeV. The thresholds for the offline selection are driven by the trigger requirements. Except for the $I_{rel}^{\mu,e}$, the quantities are in units of GeV.

Final state	Trigger	Selection criteria
$\mu\tau_h$	$\mu(50)$	$p_T^{\mu} > 52$, $p_T^{\tau_h} > 30$
$\mu\tau_h$	Iso $\mu(27)$	$p_T^{\mu} > 28$, $p_T^{\tau_h} > 30$, $I_{rel}^{\mu} < 0.3$, $p_T^{miss} > 30$
$e\tau_h$	$e(115)$	$p_T^{e} > 120$, $p_T^{\tau_h} > 30$
$e\tau_h$	Iso $e(35)$	$p_T^{e} > 38$, $p_T^{\tau_h} > 30$, $I_{rel}^{e} < 0.3$, $p_T^{miss} > 30$
μe	$\mu(50)$	$p_T^{\mu} > 52$, $p_T^{e} > 10$
μe	Iso $\mu(27)$	$p_T^{\mu} > 28$, $p_T^{e} > 10$, $I_{rel}^{\mu,e} < 0.3$, $p_T^{miss} > 30$
$e\mu$	$e(115)$	$p_T^{e} > 120$, $p_T^{\mu} > 10$
$e\mu$	Iso $e(35)$	$p_T^{e} > 38$, $p_T^{\mu} > 10$, $I_{rel}^{\mu,e} < 0.3$, $p_T^{miss} > 30$
$\tau_h\tau_h$ (2016)	p_T^{AK8} (360) & m^{AK8} (30)	$p_T^{AK8} > 450, m^{AK8} > 30$
$\tau_h\tau_h$ (2016)	H_T (300) & p_T^{miss} (110)	$H_T > 400, p_T^{miss} > 180$
$\tau_h\tau_h$ (2017–2018)	p_T^{AK8} (400) & m^{AK8} (30)	$p_T^{AK8} > 450, m^{AK8} > 30$
$\tau_h\tau_h$ (2017–2018)	H_T (500) & p_T^{miss} (100) & H_T^{miss} (100)	$H_T > 700, (p_T^{miss} + H_T^{miss}) > 280$

single-lepton triggers, with or without isolation, depending on the offline leading lepton p_T. The lepton not associated with the trigger must have p_T larger than 10 GeV and pass loose identification and isolation criteria.

In the $\tau_h\tau_h$ channel, events triggered in 2016 (2017-2018) on the basis of an AK8 jet with $p_T > 360$ (400) GeV and mass, using the soft drop algorithm [56], greater than 30 GeV are required to have an AK8 jet reconstructed offline with $p_T > 450$ GeV and mass above 30 GeV. Events that do not pass the AK8 jet trigger are then checked against a combination of p_T^{miss}-based trigger criteria. Events that pass an online selection based on $H_T > 300$ (500) GeV, $p_T^{miss} > 110$ (100) GeV, and $H_T^{miss} > 0$ (100) GeV, are required to have offline $H_T > 400$ (700) GeV and $p_T^{miss} > 180$ GeV ($p_T^{miss} + H_T^{miss} > 280$ GeV). The trigger selection efficiency for events passing the offline requirements described here for the $\tau_h\tau_h$ channel is about 90% across all three years. The trigger requirements and kinematic selection criteria are summarized in Table 1.

To reconstruct the Higgs boson candidates, the two identified objects (e, μ, or τ_h candidates) are required to have opposite charges. None of the jets in the event must be identified as originating from a bottom quark, using the medium (tight) working point of the DeepCSVv2 algorithm [57] in the $\mu\tau_h$ and $e\tau_h$ ($e\mu$) final states. The quantity H_T must be greater than 200 GeV and the di-τ invariant mass, estimated from the visible momenta of the τ lepton decay products and $\vec{p}_T^{miss}$, using a maximum likelihood technique [58], must exceed 50 GeV. The reconstructed p_T^H is defined as the magnitude of the vectorial sum of the p_T of the τ leptons visible decay products and $\vec{p}_T^{miss}$, and must be larger than 250 GeV. Finally, to reduce the background with leptonically decaying W bosons, the transverse mass of the lepton and $\vec{p}_T^{miss}$ in the $\mu\tau_h$ and $e\tau_h$ channels, and of the dilepton and $\vec{p}_T^{miss}$ in the $e\mu$ channel, must be less than 80 GeV. To ensure there is no overlap across different final states, events are vetoed in the presence of additional loosely identified and isolated lepton.

The dominant background in all four final states is the Drell–Yan process, which constitutes an irreducible background. This is followed by events with at least one jet being mis-identified as a τ_h, muon, electron, and quantum chromodynamics (QCD) multijet events with nonprompt leptons. The tt and diboson processes constitute the remaining background.

5. Background estimation

The Drell–Yan process is modeled using simulated samples. To correct the effect of missing higher order corrections in simulation, a scale factor that depends on the Z/γ^* boson mass and p_T is measured in a control region (CR) containing a pair of muons, and applied to the simulation in the signal region (SR). The tt background is estimated from simulation. Simulated tt events are weighted to reproduce the observed distribution of the top quark p_T and to account for any possible missing higher order corrections [59,60]. The background arising from the misidentification of leptons or τ_h candidates, called "mis-ID background", is estimated from data. It is mostly comprised of W + jets and QCD multijet events, where at least one jet is misidentified as an electron, muon, or τ_h candidate. In events with at least one τ_h candidate, a misidentification rate method is used to estimate the contribution of these two processes, collectively, in the SR. The probability for a jet that has passed a very loose isolation to pass the nominal isolation requirement of a τ_h candidate, called the misidentification rate, is estimated in a region dominated by the mis-ID background, obtained by requiring one identified and isolated muon, and one jet separated from the muon by $\Delta R > 0.8$. This sample has a negligible signal component, while the small contribution from the other backgrounds is estimated from simulation and subtracted from data. The misidentification rate, f, is parameterized as a function of the p_T of the τ_h candidate. To estimate the mis-ID background in the SR, an adjusted misidentification rate, $\frac{f}{1-f}$, is applied as a weight to events in the application region in data. The application region definition is identical to that of SR with the exception that the τ_h candidate fails the nominal MVA isolation. The denominator accounts for the fraction $(1-f)$ of mis-ID background events failing the isolation. The small contribution from the signal and other backgrounds is estimated from simulation and subtracted from data before the reweighting is applied.

To estimate the QCD multijet contribution in the $e\mu$ channel, a sample is built from events that pass the signal selection criteria except that the requirement on the charge of two leptons is inverted. The small remaining contribution of the signal and other backgrounds is subtracted from data on the basis of simulation. The contribution of the QCD multijet background in the SR is derived by applying an opposite-sign to same-sign scale factor, measured in a region where the lepton isolation requirements are inverted.

6. Analysis strategy

A multiclass NN is used to construct a discriminant that separates the signal from the two dominant background processes, i.e. Drell–Yan and mis-ID backgrounds, following closely the method described in Ref. [61]. The NN is constructed with a feed-forward architecture containing two hidden layers and three output nodes. The number of nodes per layer is kept to a minimum to reduce the complexity of the neural network without compromising its performance. The value of each output node represents the probability for an event to belong to a given class. Ten variables are used as input to the NN: the p_T of the two leptons and leading jet, p_T^{miss}, the mass and p_T of the Higgs boson reconstructed from the τ candidates and $\vec{p}_T^{miss}$, S_T (defined as the scalar sum of the p_T of all leptons and jets with $p_T > 30$ GeV and $|\eta| < 3$ in the event), the transverse mass reconstructed from the lepton p_T and $\vec{p}_T^{miss}$, the value of the MVA isolation of the closest boosted τ_h candidate to the muon (electron) in the $\mu\tau_h$ and $e\mu$ ($e\tau_h$ and $e\mu$) channels, and the di-τ mass. The NN is trained for the combination of the three data-taking years and separately for each final state.

Based on the maximum of the three output values, by construction larger than 1/3, events are sorted into one signal-enriched region and two background-dominated regions. The signal-enriched region is split into four bins depending on p_T^H, with lower bin boundaries of 250, 350, 450, and 600 GeV. To establish the presence of a signal a simultaneous binned maximum likelihood fit is performed to all three NN output distributions. The combined NN distributions in the signal-enriched region for all four p_T^H bins and three data-taking years are shown in Fig. 2.

7. Systematic uncertainties

Two types of systematic uncertainties are considered: normalization uncertainties in the event yields and uncertainties that affect both the shape and yield of the distributions. The uncertainties in the muon and electron trigger efficiencies, identification, and isolation, estimated with a tag-and-probe method [52], range from 1 to 5%, depending on the p_T and η of the lepton.

The uncertainty in the H_T and $\vec{p}_T^{miss}$ trigger efficiencies in the $\tau_h\tau_h$ channel is 10%, mostly arising from the difference in trigger efficiency in data and simulation. The uncertainty in the efficiency of selecting boosted τ_h candidates is parametrized as a function of p_T^H. To evaluate this uncertainty, a maximum likelihood fit is performed using the Z boson p_T distributions reconstructed using the dilepton four momenta and p_T^{miss}. The fit is performed in the Drell–Yan-dominated region, which is by definition orthogonal to the signal-enriched region. A large prefit uncertainty (U_{prefit}) is assigned to the τ_h identification efficiency, uncorrelated between final states, data-taking years, and bins of p_T^Z. This is equivalent to letting this uncertainty freely float in the fit. After the fit, the magnitude of the postfit τ_h identification efficiency uncertainty ($U_{postfit}$) is compared to $|U_{prefit} - U_{postfit}|$. The largest value in each final state, data-taking years and p_T^Z range is taken as the uncertainty in the τ_h identification efficiency. It typically ranges between 10 and 20% except for the very last p_T^Z bin in the $\tau_h\tau_h$ final state where it reaches 50%.

The uncertainty in the integrated luminosity amounts to 1.2–2.5%, depending on the year [22–24]. A 2% normalization uncertainty is considered for the muon/electron energy scale, while a 3% uncertainty in the τ_h energy scale is treated as a shape uncertainty that modifies final observable templates and propagated to the di-τ mass and $\vec{p}_T^{miss}$. Uncertainties associated with the jet energy scale and p_T^{miss} are also considered [62].

Uncertainties of 2.0, 4.2, 5.0, and 5.0% are used for the predicted cross sections of the Drell–Yan, $t\bar{t}$, single top quark, and diboson productions, respectively [63–66]. The PDF, renormalization and factorization scales, initial and final state radiation uncertainties are considered for the Drell–Yan and $t\bar{t}$ processes. They vary from a few percent to about 20% depending on the final state, process, and data-taking year as they are evaluated with different Pythia tunes.

A 20% uncertainty is assigned to the QCD multijet background to cover for differences between the observed and predicted background rates in dedicated CRs. An additional uncertainty related to the probability for a jet to be misidentified as a τ_h candidate, as well as an uncertainty in the normalization of the non-QCD background subtracted from data in the application region, are included and vary between 10 and 20%, depending on the final state. Uncertainties related to the top quark p_T reweighting in simulated $t\bar{t}$ events are evaluated by varying the reweighting parameters between zero and twice their nominal values [59,60].

Theoretical uncertainties for the signal in the gluon fusion production mode are derived from the LHC Higgs Cross Section WG1 scheme [67]. Statistical uncertainties associated with the limited number of simulated events in the signal-enriched region or observed event yields in the control regions are accounted for as described in Ref. [68].

8. Results

A binned maximum likelihood fit is performed to all three NN output distributions to compute the probability of the compatibility of observed data with the background-only hypothesis [69,70]. The inclusion of the two background-dominated control regions helps to constrain the normalization and systematic uncertainties of the Drell–Yan and mis-ID backgrounds. The systematic uncertainties are taken as nuisance parameters. An observed significance of 3.5 standard deviations is obtained for a $H \to \tau\tau$ signal with $p_T^H \geq 250$ GeV by combining all channels and data-taking years, to be compared with an expected significance of 2.2 standard deviations. The best fit signal strength modifier, defined as the ratio of the inclusive Higgs boson production cross section to the SM expectation, is also extracted from a maximum likelihood fit to the same distributions and is found to be $1.64^{+0.68}_{-0.54}$, in agreement with the SM prediction. The sensitivity of this analysis is driven by the $\mu\tau_h$ and $e\tau_h$ channels in the low-p_T region, and by the $\tau_h\tau_h$ channel in the high-p_T region. The sensitivity of the $\tau_h\tau_h$ channel increases with the Higgs boson p_T because of the increase in efficiency of the H_T/p_T^{miss} triggers.

The differential production cross section is measured in a fiducial phase space that is defined per final state. Requirements on generator-

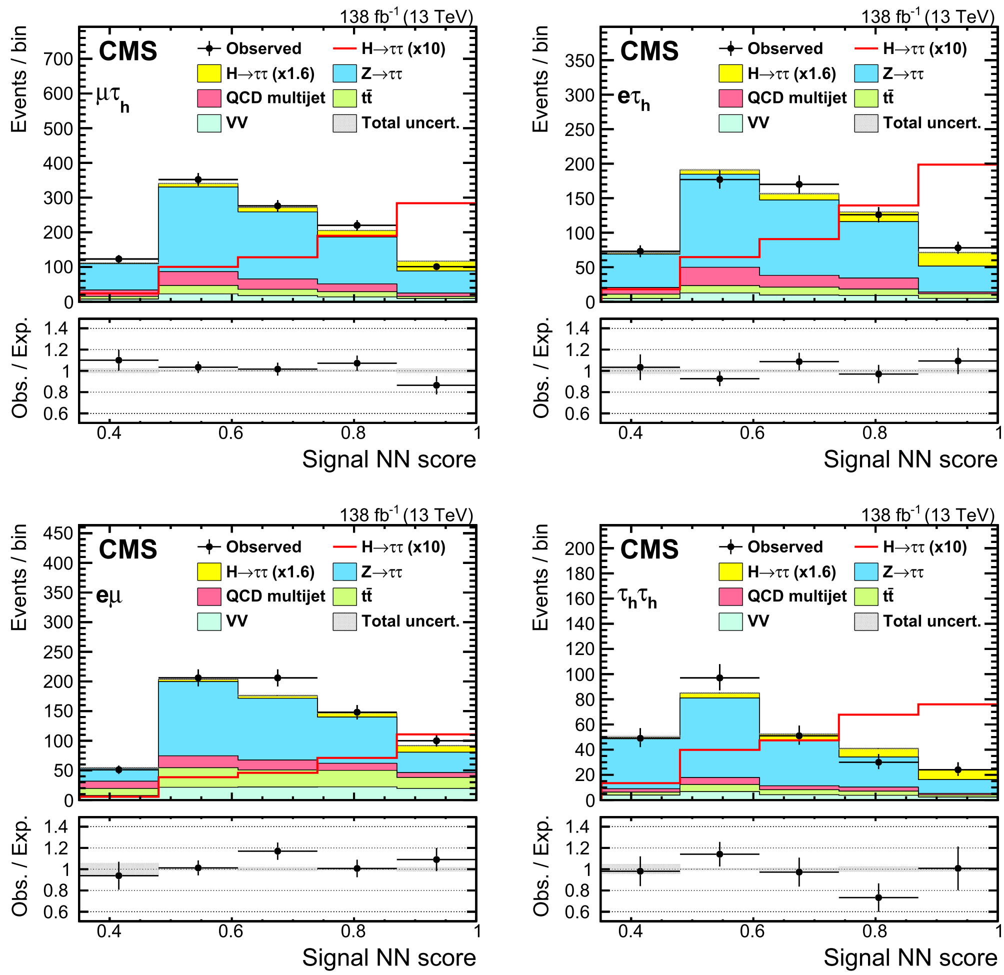

Fig. 2. Observed and expected NN distributions in the signal-enriched region, after combining all four p_T^H bins, in the $\mu\tau_h$ (upper left), $e\tau_h$ (upper right), $e\mu$ (lower left), and $\tau_h\tau_h$ (lower right) channels. The signal and background distributions are the result of a simultaneous binned maximum likelihood fit to all three output NN distributions, including all individual p_T bins and data-taking years. The bottom panel shows the ratio of the number of events observed in data to that of the expected background.

level variables are chosen to be close to the trigger and offline selections. In the $\mu\tau_h$ ($e\tau_h$) channel, the lepton is required to have generated $p_T > 28$ (30) GeV and $|\eta| < 2.4$ (2.5). If the generated p_T of the muon (electron) is less than 52 (115) GeV, a minimum threshold of 30 GeV is applied to the generated p_T^{miss} as well. The generated visible p_T of τ_h leptons must exceed 30 GeV and their $|\eta|$ must be less than 2.3 in the $\mu\tau_h$, $e\tau_h$, and $\tau_h\tau_h$ channels. In the $\tau_h\tau_h$ channel, the generated p_T of the AK8 jet must be greater than 450 GeV or the generated H_T must be greater than 400 (700) GeV with a generated p_T^{miss} greater than 180 (140) GeV for 2016 (2017–2018) samples. In the $e\mu$ channel, two sets of events are selected. The first set includes events with generated muon $p_T > 52$ GeV, or between 28 and 52 GeV and p_T^{miss} above 30 GeV. The second set includes events with generated electron $p_T > 115$ GeV, or between 38 and 115 GeV and p_T^{miss} above 30 GeV. In both sets, the other lepton must have generated p_T above 10 GeV. In all channels, the ΔR between two leptons must be between 0.1 and 0.8, the generated p_T^H must be above 250 GeV, and there must be at least one jet with p_T larger than 30 GeV.

To derive the differential production cross section, the signal is split into four bins with lower bin boundaries of 250, 350, 450, and 600 GeV on the value of the generated (gen) p_T^H or with lower bin boundaries of 0, 350, 450, and 600 GeV on the value of the gen leading jet p_T ($p_T^{j_1}$). The definitions of the signal- and background-dominated regions are identical to those used in the inclusive analysis. The same binning is used at reconstructed- (reco-) level to categorize events. The gen- and reco-level observable values are not perfectly aligned because of the limited resolution, and events from one gen-level bin can migrate to a different reco-level bin. The contributions from the four gen-level bins are left floating independently from each other. By performing one simultaneous fit over all reco-level bin histograms of the NN distributions, the signal strength modifiers of the gen-level observable bins are determined utilizing the full statistical power of the data set. This is equivalent to extracting the signal in the reco-level bins and performing an unfolding to gen-level bins. The procedure follows the strategy adopted in Ref. [19]. Fiducial differential production cross sections measured as functions of p_T^H and $p_T^{j_1}$ are shown in Fig. 3. Tabulated results are available in the HepData database [71]. The results are dominated by statistical uncertainties, especially in the highest-p_T bins. The next dominant components, especially in the lowest-p_T bins, are the tau energy scale uncertainty, which affects both the normalization and shape of the signal and background processes. Other important systematic uncertainties include theoretical uncertainties in the signal prediction arising from the infinite top mass assumption and initial and final states radiation. The ggH production mode contribution in the total signal yield reduces from 63% in the lowest p_T^H bin to 53% in the highest p_T^H bin, indicating the importance of other production modes at large p_T values. This measurement extends the probed large-p_T region beyond 600 GeV. No significant deviation with respect to the SM predictions is observed and the measurements are compatible with both the POWHEG and NNLOPS expectations. The fit has a p-value with respect to the SM expectation

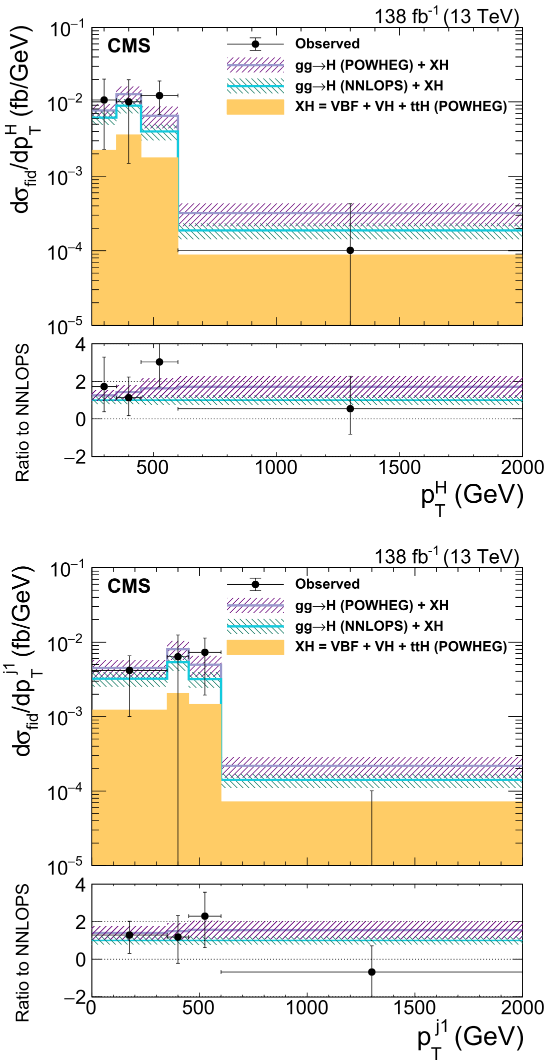

Fig. 3. Observed and expected differential fiducial cross sections in bins of p_T^H (upper) and $p_T^{j_1}$ (lower). The last bins include the overflow. The uncertainty bands in the theoretical predictions include uncertainties from the following sources: PDF, renormalization and factorization scales, underlying event and parton showering, and the branching fraction $\mathcal{B}(H \to \tau\tau)$.

from the NNLOPS prediction of 56 and 74% for the measurements with respect to p_T^H and $p_T^{j_1}$, respectively.

The inclusive fiducial production cross section is measured from the p_T^H distributions used in the differential analysis, by reformulating the parameters of interest such that one modifies the total inclusive fiducial production cross section. Its best fit value is $3.88^{+1.69}_{-1.35}$ fb, which is consistent with the SM prediction of 2.36 ± 0.51 fb obtained with the NNLOPS generator.

9. Summary

The measurement of the production cross section of a Higgs boson with large p_T decaying to a pair of τ leptons has been performed using proton-proton collision data collected by the CMS experiment at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 138 fb^{-1}. A dedicated reconstruction algorithm has been used to resolve the overlapping decay products of the two close-by τ leptons. The $H \to \tau\tau$ signal with $p_T^H > 250$ GeV is established with a significance of 3.5 standard deviations (2.2 expected). The best fit of the product of the observed $H \to \tau\tau$ signal production cross section and branching fraction is $1.64^{+0.68}_{-0.54}$ times the SM expectation. The fiducial inclusive production cross section has been measured to be $3.88^{+1.69}_{-1.35}$ fb, which is consistent with the SM prediction of 2.36 ± 0.51 fb. The fiducial differential production cross section is also measured as functions of the Higgs boson and leading jet transverse momenta. This measurement extends the probed large-transverse-momentum region beyond 600 GeV. No significant deviation with respect to the SM predictions is observed in the transverse momentum distribution of the Higgs boson with large p_T^H.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Release and preservation of data used by the CMS Collaboration as the basis for publications is guided by the CMS data preservation, re-use and open access policy.

Acknowledgements

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 acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid and other centers for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC, the CMS detector, and the supporting computing infrastructure provided by the following funding agencies: SC (Armenia), BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES and BNSF (Bulgaria); CERN; CAS, MOST, and NSFC (China); Minciencias (Colombia); MSES and CSF (Croatia); RIF (Cyprus); SENESCYT (Ecuador); ERC PRG, RVTT3 and MoER TK202 (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); SRNSF (Georgia); BMBF, DFG, and HGF (Germany); GSRI (Greece); NKFIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LMTLT (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, Conahcyt, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MES and NSC (Poland); FCT (Portugal); MESTD (Serbia); MCIN/AEI and PCTI (Spain); MoSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); MHESI and NSTDA (Thailand); TUBITAK and TENMAK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, contract Nos. 675440, 724704, 752730, 758316, 765710, 824093, 101115353, 101002207, and COST Action CA16108 (European Union); the Leventis Foundation; The Alfred P. Sloan Foundation; the Alexander von Humboldt Foundation; the Science Committee, project no. 22rl-037 (Armenia); the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the F.R.S.-FNRS and FWO (Belgium) under the “Excellence of Science – EOS” – be.h project n. 30820817; the Beijing Municipal Science & Technology Commission, No. Z191100007219010 and Fundamental Research Funds for the Central Universities (China); The Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Shota Rustaveli National Science Foundation, grant FR-22-985 (Georgia); the Deutsche Forschungsgemeinschaft (DFG), under Germany's Excellence Strategy – EXC 2121 “Quantum Universe” – 390833306, and under project number 400140256 - GRK2497; the

Hellenic Foundation for Research and Innovation (HFRI), Project Number 2288 (Greece); the Hungarian Academy of Sciences, the New National Excellence Program - ÚNKP, the NKFIH research grants K 131991, K 133046, K 138136, K 143460, K 143477, K 146913, K 146914, K 147048, 2020-2.2.1-ED-2021-00181, and TKP2021-NKTA-64 (Hungary); the Council of Science and Industrial Research, India; ICSC – National Research Center for High Performance Computing, Big Data and Quantum Computing, funded by the EU NexGeneration program (Italy); the Latvian Council of Science; the Ministry of Education and Science, project no. 2022/WK/14, and the National Science Center, contracts Opus 2021/41/B/ST2/01369 and 2021/43/B/ST2/01552 (Poland); the Fundação para a Ciência e a Tecnologia, grant CEECIND/01334/2018 (Portugal); the National Priorities Research Program by Qatar National Research Fund; MCIN/AEI/10.13039/501100011033, ERDF "a way of making Europe", and the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant MDM-2017-0765 and Programa Severo Ochoa del Principado de Asturias (Spain); the Chulalongkorn Academic into Its 2nd Century Project Advancement Project, and the National Science, Research and Innovation Fund via the Program Management Unit for Human Resources & Institutional Development, Research and Innovation, grant B37G660013 (Thailand); the Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

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