Measurement of the Inclusive and Differential Higgs Boson Production Cross Sections in the Decay Mode to a Pair of τ Leptons in pp Collisions at $\sqrt{s} = 13$ TeV

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Measurements of the inclusive and differential fiducial cross sections of the Higgs boson are presented, using the τ lepton decay channel. The differential cross sections are measured as functions of the Higgs boson transverse momentum, jet multiplicity, and transverse momentum of the leading jet in the event, if any. The analysis is performed using proton-proton collision data collected with the CMS detector at the LHC at a center-of-mass energy of 13 TeV and corresponding to an integrated luminosity of 138 fb^{-1}. These are the first differential measurements of the Higgs boson cross section in the final state of two τ leptons. In final states with a large jet multiplicity or with a Lorentz-boosted Higgs boson, these measurements constitute a significant improvement over measurements performed in other final states.

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Measuring differential production cross sections of the Higgs boson could eventually highlight the contribution of beyond-the-standard-model physics to the Higgs boson couplings [1,2], e.g., by the observation of deviations from the standard model (SM) in the Higgs boson transverse momentum p_T distribution predicted with high accuracy at next-to-next-to-leading-order (NNLO) precision [3]. Such measurements are also powerful probes of the SM predictions, in particular, of the higher-order corrections in perturbation theory, and could help improve event modeling.

Differential cross sections of Higgs boson production have been measured in the $\gamma\gamma$, ZZ, W^+W^-, and $b\bar{b}$ decay channels for various sets of observables by the ATLAS and CMS Collaborations at the CERN LHC at center-of-mass energies of 7, 8, and 13 TeV [4–10]. The $H \to \tau^+\tau^-$ decay channel [11,12] can also contribute to differential measurements of the Higgs boson production, providing complementary information with other decay modes. It is competitive in parts of the phase space where small production cross sections are compensated by a relatively large branching fraction $\mathcal{B}(H \to \tau^+\tau^-) = 6.2\%$ [13]; this is particularly the case for high jet multiplicities (N_{jets}) and large Lorentz boosts of the Higgs boson. This Letter presents the first differential fiducial measurements of the Higgs boson production cross section using its decays to a pair of τ leptons. The Higgs boson cross section is measured as functions of its transverse momentum (p_T^H), N_{jets}, and the leading jet p_T ($p_T^{j_1}$), using data collected by the CMS experiment in proton-proton (pp) collisions at a center-of-mass energy of 13 TeV between 2016 and 2018, corresponding to an integrated luminosity of 138 fb^{-1}. A measurement of the inclusive fiducial Higgs boson cross section is also presented in a phase space complementary to those studied with other final states.

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 scintillator hadron calorimeter, each composed of a barrel and two end cap sections. Forward calorimeters extend the pseudorapidity coverage provided by the barrel and end cap detectors. Muons are detected in gaseous detectors embedded in the steel flux-return yoke outside the solenoid. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [14].

Simulated events with Higgs bosons are generated for the different production modes (gluon fusion, vector boson fusion, and productions in association with a vector boson, W or Z, or with top quarks) at next-to-leading-order (NLO) precision in perturbative quantum chromodynamics (QCD), including finite quark mass effects, with the POWHEG 2.0 [15–19] generator. The distributions of p_T^H and N_{jets} in the gluon fusion production simulation are corrected to match the predictions of the NNLOPS generator [20,21]. The Higgs boson mass is assumed to be 125.38 GeV [22].

The MADGRAPH5_AMC@NLO2.2.2 (2.4.2) event generator [23] is used to simulate the Drell-Yan process at

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leading order with the MLM jet matching and merging scheme [24] for the simulation of data taken in 2016 (2017 and 2018). It is also used to model the diboson production at NLO in (α_S), whereas POWHEG 2.0 and 1.0 are used for $t\bar{t}$ and single top quark production, respectively. Single top quark production in the t-channel and diboson events are normalized to their cross sections at NLO precision or higher [25,26]. Drell-Yan events, as well as $t\bar{t}$ events and single top quark production in the tW channel, are normalized to their cross sections at NNLO precision [27,28]. The generators are interfaced with PYTHIA8.212 [29] to model the parton showering and fragmentation, as well as the decay of the τ leptons. The PYTHIA tunes CUETP8M1 and CUETP8M4 [30] are used in simulation corresponding to the 2016 data-taking conditions, and the CP5 tune [31] is used for 2017 and 2018 simulations. The parton density function (PDF) set is NNPDF3.0 for 2016 simulations, and NNPDF 3.1 for 2017 and 2018 simulations [32–34]. Additional proton-proton interactions per bunch crossing, called pileup, are added to the simulations with the profile observed in data. Simulated events are processed through a GEANT4 [35] simulation of the CMS detector.

The particle-flow (PF) algorithm [36] is used to reconstruct the events on the basis of information from the different CMS subdetectors. Muons are reconstructed from tracks and hits in the tracker and muon systems [37,38]. Electrons are reconstructed from tracks in the tracking system and calorimeter deposits, and identified with a multivariate discriminant described in Ref. [39]. The relative isolation of electrons (muons) is calculated on the basis of the p_T of tracks in a cone of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.3$ (0.4) centered on the lepton track, corrected for charged and neutral pileup contributions; it is required to be less than 0.15. Jets are clustered from PF candidates using the anti-(k_T) FASTJET algorithm with distance parameter R of 0.4 [40,41], requiring $p_T >$ 30 GeV and $|\eta| < 4.7$. Jet energy corrections are applied on an event-by-event basis [36,42,43]. In events collected in 2017, jets with $p_T < 50$ GeV and $2.65 < |\eta| < 3.14$ are discarded to eliminate spurious jets caused by detector noise. Hadronic jets originating from b quarks are tagged with the medium working point of the DEEPCSV algorithm [44]. The hadrons-plus-strips algorithm [45], which combines one or three tracks with energy deposits in the calorimeters, is used to reconstruct τ leptons decaying hadronically, denoted as τ_h. Deep neural network discriminants are used to reduce the fraction of quark and gluon jets, electrons, and muons misidentified as τ_h candidates [46]. All particles reconstructed in the event are used to determine the missing transverse momentum $\vec{p}_T^{\text{miss}}$, which is defined as the negative vectorial sum of the transverse momenta of all PF candidates originating from the primary pp interaction vertex, which is the vertex with the largest value of summed physics object p_T^2 [47]. It is adjusted for the effect of jet energy corrections. Corrections to the $\vec{p}_T^{\text{miss}}$ are applied to reduce the mismodeling of the simulated $Z+$jets and Higgs boson samples [11].

Events are selected in four final states: $e\mu$, $e\tau_h$, $\mu\tau_h$, and $\tau_h\tau_h$. In the $e\mu$ final state, a combination of triggers requiring an electron and a muon is used, and in the $\tau_h\tau_h$ final state, the triggers require the presence of two isolated τ_h candidates. In the $e\tau_h$ ($\mu\tau_h$) final state, the events are selected with a trigger that relies on the presence of a single electron (muon) with p_T above 25–32 (22–24) GeV, or a trigger that requires both an electron with $p_T > 24$ GeV and a τ_h candidate with $p_T >$ 20–27 GeV (a muon with $p_T >$ 19–20 GeV and a τ_h candidate with $p_T >$ 27–30 GeV) if the lepton p_T is too low to satisfy the single-lepton trigger thresholds. In the $\tau_h\tau_h$ final state, the triggers select two τ_h candidates with $p_T >$ 35–40 GeV. The thresholds depend on the data-taking year. The off-line event selection criteria are given in Table I, where the symbol m_T denotes the invariant mass between two objects in the transverse plane. In the $e\mu$, $e\tau_h$, and $\mu\tau_h$ final states, the small fraction of events without a reconstructed jet with $p_T > 30$ GeV and with ΔR between the visible decay products of the two τ leptons below 2 is vetoed because of the difficulty in accurately estimating the backgrounds in this particular topology. In the $\tau_h\tau_h$ final state, all events are required to contain at least one jet. This requirement significantly reduces the QCD multijet background, while it does not affect the signal acceptance significantly since the Higgs bosons need to be boosted for their decay products to pass the high-p_T trigger thresholds. All events with a jet tagged as originating from a bottom quark are discarded in the $e\mu$, $e\tau_h$, and $\mu\tau_h$ final states, where the $t\bar{t}$ background would otherwise be consequential.

The fiducial region is defined to be as close as possible to the reconstructed event selection. All variables used in the definition of the fiducial region are calculated at the generator level after parton showering and hadronization, and the electrons and muons are "dressed" in that the lepton momentum includes the momenta of photons radiated within

TABLE I. Event selection criteria. The p_T ranges are related to different triggers used during different data-taking periods. In events collected in 2016 in the $\mu\tau_h$ channel, τ_h candidates with $0.2 < |\eta| < 0.3$ are discarded because of a significantly larger misidentification rate of muons as τ_h objects.

	$e\mu$	$e\tau_h$	$\mu\tau_h$	$\tau_h\tau_h$
p_T^e (GeV)	$> 15/24$	$>$ 25–26	⋯	⋯
$\lvert\eta^e\rvert$	< 2.4	< 2.1	⋯	⋯
p_T^μ (GeV)	$> 24/15$	⋯	$>$ 20–21	⋯
$\lvert\eta^\mu\rvert$	< 2.4	⋯	< 2.1	⋯
$p_T^{\tau_h}$ (GeV)	⋯	> 30	> 30	> 40
$\lvert\eta^{\tau_h}\rvert$	⋯	< 2.3	< 2.3	< 2.1
$m_T(e/\mu, \vec{p}_T^{\text{miss}})$ (GeV)	⋯	< 50	< 50	⋯
$m_T(e+\mu, \vec{p}_T^{\text{miss}})$ (GeV)	< 60	⋯	⋯	⋯
N_{jets}	⋯	⋯	⋯	> 0

a cone of $\Delta R < 0.1$ centered on the lepton. In the $e\tau_h$ ($\mu\tau_h$) final state, the electron (muon) is required to have p_T above 25 (20) GeV and $|\eta| < 2.1$, while the τ_h candidate must have a visible p_T greater than 30 GeV and visible $|\eta| < 2.3$. Here, the term visible refers to the kinematic variables constructed from the momenta of the visible decay products of the τ leptons, excluding the invisible neutrinos. In addition, the transverse mass $m_T(e/\mu, \vec{p}_T^{\text{miss}})$ must be less than 50 GeV. In the $\tau_h\tau_h$ final state, the visible p_T of both τ_h must exceed 40 GeV, while their visible $|\eta|$ must be within 2.1, and there must be at least one jet with $p_T > 30$ GeV. In the $e\mu$ final state, the leading (subleading) lepton must have $p_T > 24$ (15) GeV, both leptons must have $|\eta| < 2.4$, and the m_T of the dilepton system and $\vec{p}_T^{\text{miss}}$ must be below 60 GeV to remove the overlap with the $H \to WW$ measurement [8]. Decays of the Higgs boson other than $H \to \tau\tau$ are considered to be outside the fiducial region. About 95% of $H \to \tau\tau$ events passing the reconstructed event selection belong to the fiducial region as estimated from simulation. The SM prediction for the Higgs boson cross section in this fiducial region is 408 ± 27 fb, using the inclusive cross sections and branching fractions in Refs. [48–50] and the fiducial acceptance from the NLO predictions of the POWHEG 2.0 generator with corrections from the NNLOPS generator for the gluon fusion production mechanism. In particular, the gluon fusion simulation is normalized to the cross section computed at next-to-NNLO QCD accuracy and NLO electroweak precision. Events outside the fiducial region are treated as backgrounds in the measurement and are normalized to their SM expectations. This treatment is chosen because most nonfiducial events correspond to Higgs boson decays to a pair of W bosons, especially in the $e\mu$ final state, for which the differential distributions have been measured to be compatible with the SM expectation [8].

The di-τ background, mainly composed of $Z \to \tau\tau$, leptonically decaying $t\bar{t}$, and diboson processes, is modeled with an "embedded sample" [51], where muons from dimuon events in data are replaced with simulated τ leptons. The background with jets misidentified as τ_h candidates is estimated from data with a so-called "misidentification rate method" [52]. The probability for loosely isolated jets to be misidentified as τ_h is measured in control regions enriched in QCD multijet, $W +$ jets, or $t\bar{t}$ events, as a function of $p_T^{\tau_h}$, for different N_{jets}, and separately in the barrel and end caps of the detector. Differences between processes, N_{jets}, and the detector region are typically of the order of 15%, 10%, and 10%, respectively. The misidentification probabilities are corrected on an event-by-event basis depending on the p_T of the other τ lepton in the event p_T^H and $p_T^{j_1}$, with multiplicative corrections ranging 0.5–1.2 for each variable. The reconstructed variable p_T^H is evaluated as the vectorial p_T sum of the visible decay products of the τ leptons and $\vec{p}_T^{\text{miss}}$, multiplied with a correction factor that is measured in signal simulation and depends on this same vectorial sum to make it an unbiased estimator of the generated p_T^H. The correction factor reaches a plateau between 1.05 and 1.10 at high-p_T^H values, and is significantly below 1.0 at low-p_T^H values. For events with $p_T^H >$ 350 GeV at the generator level, the reconstructed p_T^H resolution is better than 10%, whereas it is worse than 30% for $p_T^H < 45$ GeV.

The misidentification probabilities as a function of the p_T of the other τ, p_T^H, and $p_T^{j_1}$ were measured after the initial tau p_T misidentification measurement due to the large number of variables impacting the misidentification probabilities. These corrections are determined by a comparison of data-to-prediction distributions in the aforementioned control regions. Additionally, corrections for the selection criteria that differ between the signal and control regions, such as the same-sign charge requirement for the τ leptons in the QCD-enriched region and the high m_T requirement in the W-enriched region, are introduced and depend on the reconstructed di-τ mass, $m_{\tau\tau}$. They are typically close to 1.0 but can reach up to 1.2 in parts of the phase space. In the $e\tau_h$ and $\mu\tau_h$ final states, the overall misidentification rate is a weighted average of the corrected misidentification rates measured for the different types of processes. The weights are proportional to the expected fraction of each process with respect to the total background determined event by event as a function of N_{jets} and $m_{\tau\tau}$ using simulations for the $W +$ jets and $t\bar{t}$ backgrounds. In the $\tau_h\tau_h$ final state, the misidentification probabilities are measured only in the dominant QCD multijet background. They are used to reweight events where the leading τ_h candidate fails the τ_h identification criteria. The very small contribution of events where only the subleading τ_h is a jet but the leading τ_h is genuine is estimated from simulation.

The background with jets misidentified as electrons or muons in the $e\mu$ final state, essentially events from QCD multijet, $W +$ jets, and semileptonically decaying $t\bar{t}$ production, is estimated from data events where the electron and the muon have the same sign, reweighted with an extrapolation factor that depends on N_{jets} and $\Delta R(e, \mu)$. Other backgrounds are estimated from simulation and scaled to their theoretical cross sections.

To increase the signal sensitivity without introducing a strong model dependence, events are classified in different categories depending on $p_T^{\tau_h}$. In the $e\tau_h$ and $\mu\tau_h$ final states, the categories are defined with the following requirements: $30 < p_T^{\tau_h} < 50$, $50 < p_T^{\tau_h} < 70$, and $p_T^{\tau_h} > 70$ GeV. In the $\tau_h\tau_h$ channel, the requirements are based on the subleading τ_h candidate because the misidentification probability decreases with $p_T^{\tau_h}$: $40 < p_T^{\tau_h} < 50$, $50 < p_T^{\tau_h} < 70$, and $p_T^{\tau_h} > 70$ GeV. No categorization is introduced in the $e\mu$ channel because the signal-to-background ratio does not significantly increase with the lepton p_T.

Systematic uncertainties are associated with the triggering and reconstruction of the different objects selected in the analysis and they amount to typically 2%–3% in the efficiency and 0.5%–3.0% in the energy scale, per object.

Uncertainties in the small misidentification rates of electrons and muons as τ_h candidates range between 5% and 40% depending on the decay mode and η, while the uncertainty in the momentum scale for these objects is up to 6%. Similar uncertainties, partially correlated, are considered for the objects in the embedded samples [51]. Uncertainties in the jet momentum scales and $\vec{p}_T^{\text{miss}}$ measurement are evaluated event by event. The uncertainty in the b tagging reaches up to 10% for processes with heavy-flavor jets.

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 [25–28]. The $Z \to \tau\tau$ process yield, which is estimated with embedded samples, has an uncertainty of 4% to account for the dimuon trigger used to select the initial events in data before the muons are replaced with τ leptons. Additionally, an uncertainty of 10% is assigned to the normalization of embedded events without any jet in the $e\tau_h$ and $\mu\tau_h$ final states to cover for a potential mismodeling introduced by the $m_T(e/\mu, \vec{p}_T^{\text{miss}})$ selection criterion.

Several sources of uncertainty are taken into account for the estimate of the background with jets misidentified as τ_h candidates: statistical uncertainties in the misidentification rate measurement as a function of $p_T^{\tau_h}$; systematic uncertainties in the description of other variables ($p_T^{j_1}$, $p_T^{e/\mu}$, and p_T^H), as determined from closure tests; systematic uncertainties in the extrapolation between the regions where the misidentification rates are measured and the signal region; systematic uncertainties to cover for a finer granularity of some variables in the signal region, e.g., signal regions with two, three, or four jets while the misidentification rates are measured inclusively for $N_{\text{jets}} \geq 2$. In particular, the last source of uncertainty includes a 5% uncertainty in the yield of the reducible background in each bin of N_{jets}. Events with misidentified jets in the highest-$p_T^{\tau_h}$ categories also have a yield uncertainty in the range of 5%–10%, depending on the final state. This avoids propagating constraints from the low-$p_T^{\tau_h}$ categories under the assumption that the p_T dependence of the misidentification probabilities is linear.

Statistical uncertainties in the number of simulated events in the signal region or observed event yields in the control regions are considered in all bins of the distributions. The uncertainty in the integrated luminosity for the combined 2016–2018 period is 1.6%, while individual years have uncertainties in the range 1.2%–2.5%, with partial correlations between data-taking years [53–55]

For the signal, uncertainties from missing higher-order corrections in the perturbative QCD expansion are estimated by varying the renormalization and factorization scales by factors of 2. In the case of the gluon fusion production, the uncertainty scheme proposed in Ref. [48] is used. For the signal in the fiducial region, the uncertainties are implemented in such a way that they do not modify the fiducial cross sections in any of the generator-level bins before the selection considering the shape effect only. The uncertainties can, however, modify the normalization of the Higgs boson events outside of the fiducial region since the cross section for these events is normalized to the SM expectation. The fraction of the Higgs boson events in this region is less than 3% and 8% in the $\tau_h\tau_h$ and $\mu\tau_h$ final states, respectively.

In each category, two-dimensional distributions of $m_{\tau\tau}$ reconstructed with a simplified matrix element algorithm [56] with a resolution around 20%, and of the variable considered for the differential measurement (p_T^H, N_{jets}, or $p_T^{j_1}$) are built. In practice, this is equivalent to making $m_{\tau\tau}$ distributions in different bins of the other observable. At the generator level, p_T^H, N_{jets}, and $p_T^{j_1}$ are evaluated with a RIVET implementation [57] of the simplified template cross sections scheme [48], where jets with $p_T > 30$ GeV are formed from clusters of final-state particles from the primary vertex, excluding the decay products of the Higgs boson. Signal events from one generator-level bin contribute to multiple reconstruction-level bins. By performing one simultaneous fit over all reconstruction-level bins, the signal strength modifiers of the different generator-level observable bins modeled as freely floating parameters of interest, can be determined using all the selected events. This simultaneous fit is equivalent to a signal extraction in the reconstruction-level bins and its unfolding into generator-level bins performed in a single step. The signal strengths per observable range are assumed fully correlated among final states since similar phase spaces are selected with the fiducial region definitions. This unfolding procedure can be sensitive to statistical fluctuations in the observed distributions and to small variations in the response matrix, and a Tikhonov regularization of the unfolded distribution is performed by adding to the likelihood function a multiplicative penalty term [58,59]. Regularization reduces statistical fluctuations and unphysical solutions, but it can lead to undercoverage of the uncertainty intervals and introduce systematic biases, which, in this Letter, are negligible with respect to the systematic and statistical uncertainties. These effects are controlled by optimizing the strength of the regularization term with the minimum global correlation coefficient [60]. The optimum regularization factor is 1.85 (1.35 and 2.35) for the p_T^H (N_{jets} and $p_T^{j_1}$, respectively) measurement.

The predicted and measured differential fiducial cross sections are shown in Fig. 1 for the regularized fits. Tabulated results are available in the HepData database [61] for the regularized and unregularized cases. The fit has a p value with respect to the SM expectation from the NNLOPS prediction of 17%, 71%, and 45% for the measurements of p_T^H, N_{jets}, and $p_T^{j_1}$, respectively. No significant deviation with respect to the SM predictions is observed, and the measurements are compatible with both the POWHEG and NNLOPS expectations. The low measured cross sections for $0 < p_T^H < 45$ GeV and $45 < p_T^H < 80$ GeV do not coincide with the much more precise measurements performed in this

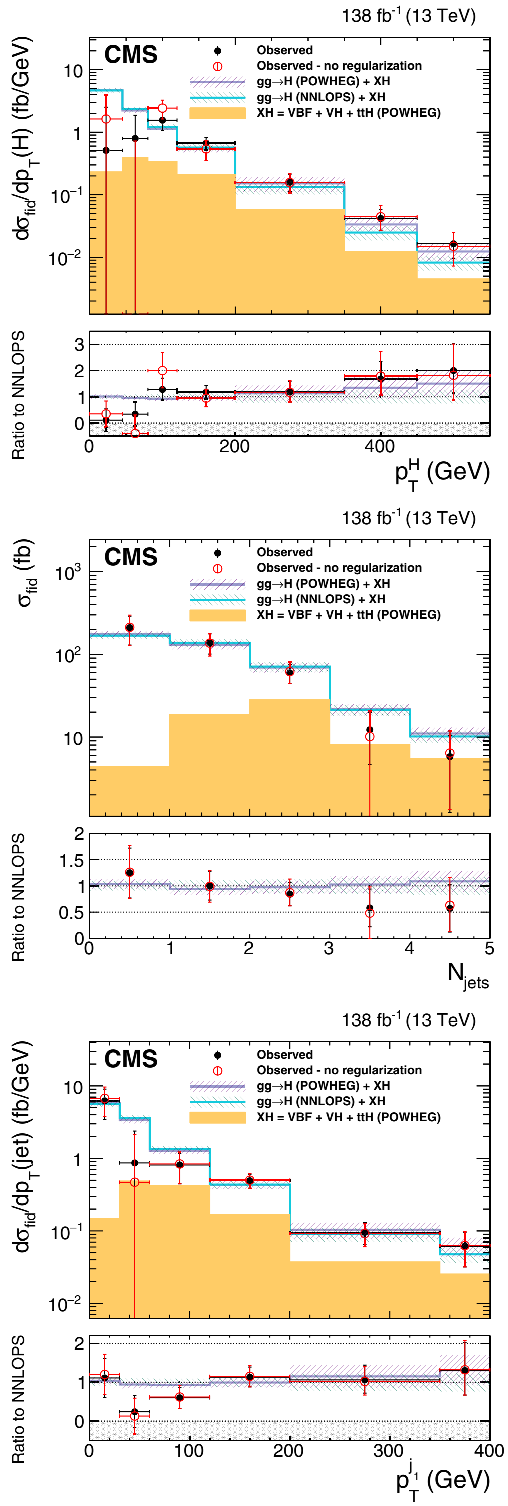

FIG. 1. Observed and expected differential fiducial cross section in bins of p_T^H (upper), N_{jets} (middle), and $p_T^{j_1}$ (lower). Both regularized (full markers) and unregularized (hollow markers) are shown. The most-left bin in the $p_T^{j_1}$ distribution includes all events without a jet with $p_T > 30$ GeV. The uncertainty bands in the theoretical predictions include uncertainties from the following sources: PDF, renormalization and factorization scale, underlying event and parton showering, and branching fraction of the Higgs boson to τ leptons. The last bins include the overflow.

phase space in other final states [6,9], and are attributed to statistical fluctuations.

The results are dominated by statistical and theoretical uncertainties. After the maximum likelihood fit described later in this Letter, the uncertainty in the background with jets misidentified as τ_h candidates is at the percent level in the phase space region with large background contributions, and up to 10%–15% at high p_T^H. The impacts on the template normalization from the uncertainties for embedded events without any reconstructed jet are 7% and 4% in the case of no jets and one jet, respectively, and become negligible at high jet multiplicity. Acceptance uncertainties for the ggH signal give the largest contribution to the overall impacts on the fit results from the theoretical part. The impacts on the fits from the uncertainties due to migration between different jet multiplicity bins are less than 8% overall, while the combined effect of the other theoretical uncertainties is less than 3%.

The measurement is precise with respect to the measurements in other final states for $120 < p_T^H < 600$ GeV, $N_{\text{jets}} \geq 2$, and $p_T^{j_1} > 120$ GeV. More specifically, this measurement for $120 < p_T^H < 200$ GeV is comparable in precision with the measurements by the CMS [10] and ATLAS [9] Collaborations in the $H \to ZZ \to 4\ell$ decay channel with 137–139 fb^{-1}, and 50% more sensitive than the CMS measurement in the $H \to WW$ channel with 137 fb^{-1} [8] and the combination performed by the CMS Collaboration with 36 fb^{-1} in the bb, $\gamma\gamma$, and ZZ decay channels [6]. For $200 < p_T^H < 600$ GeV, the current measurement has a significantly higher precision and granularity than the measurements in Refs. [4–10].

The inclusive fiducial cross section is measured from the distributions used in the differential measurements of N_{jets} by reformulating the parameters of interest such that one modifies the total inclusive fiducial cross section. Its measured value is 426 ± 102 fb, compatible with the SM expectation of 408 ± 27 fb.

In summary, measurements of the differential fiducial cross sections of the Higgs boson have been performed for the first time at the LHC in the decay channel of two τ leptons. The differential cross sections as functions of the Higgs boson transverse momentum, the jet multiplicity, and transverse momentum of the leading jet are in agreement with the expectations of the standard model, with a competitive precision with respect to measurements in other final states in the phase spaces with a large jet multiplicity, or with a Higgs boson transverse momentum above 120 GeV. In addition, the fiducial inclusive cross section has been measured to be 426 ± 102 fb, in agreement with the standard model expectation of 408 ± 27 fb.

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[uuuu]Also at Texas A&M University at Qatar, Doha, Qatar.
[vvvv]Also at Kyungpook National University, Daegu, Korea.