PHYSICAL REVIEW D **85,** 112007 (2012)

Measurement of the $t\bar{t}$ production cross section in pp collisions at $\sqrt{s} = 7$ TeV in dilepton final states containing a τ

S. Chatrchyan *et al.**
(CMS Collaboration)

(Received 30 March 2012; published 19 June 2012)

The top quark pair production cross section is measured in dilepton events with one electron or muon, and one hadronically decaying τ lepton from the decay $t\bar{t} \rightarrow (\ell\nu_\ell)(\tau_h\nu_\tau)b\bar{b}$, ($\ell = e, \mu$). The data sample corresponds to an integrated luminosity of 2.0 fb^{-1} for the electron channel and 2.2 fb^{-1} for the muon channel, collected by the CMS detector at the LHC. This is the first measurement of the $t\bar{t}$ cross section explicitly including τ leptons in proton-proton collisions at $\sqrt{s} = 7$ TeV. The measured value $\sigma_{t\bar{t}} = 143 \pm 14(\text{stat}) \pm 22(\text{syst}) \pm 3(\text{lumi})$ pb is consistent with the standard model predictions.

DOI: 10.1103/PhysRevD.85.112007 PACS numbers: 14.65.Ha

I. INTRODUCTION

Top quarks at the Large Hadron Collider (LHC) are mostly produced in pairs with the subsequent decay . The decay modes of the two W bosons determine the observed event signature. The dilepton decay channel denotes the case where both W bosons from the decaying top quark pair decay leptonically. In this Letter, top quark decays in the "tau dilepton" channel are studied, where one W boson decays into $e\nu$ or $\mu\nu$ and the other into the hadronically decaying τ lepton and ν, in the final state $t\bar{t} \rightarrow (\ell\nu_\ell)(\tau_h\nu_\tau)b\bar{b}$, where $\ell = e, \mu$. The expected fraction of events in the dilepton channel with at least one τ lepton in the final state is approximately 6% (5/81) of all $t\bar{t}$ decays, i.e. higher than the fraction of the light dilepton channels (ee, $\mu\mu$, $e\mu$) which is equal to 4/81 of all $t\bar{t}$ decays. The tau dilepton channel is of particular interest because the existence of a charged Higgs boson [1,2] with a mass smaller than the top quark mass could give rise to anomalous τ lepton production, which could be directly observable in this decay channel. Furthermore, in the final state studied, the $t \rightarrow (\tau\nu_\tau)b$ decay exclusively involves third generation leptons and quarks. Understanding the τ yield in top quark decays is important to increase the acceptance for $t\bar{t}$ events and to search for new physics processes.

This is the first measurement of the $t\bar{t}$ production cross section at the LHC that explicitly includes τ leptons, improving over the results obtained at the Tevatron which are limited by the small number of candidate events found [3–5]. Experimentally, the τ lepton is identified by its decay products, either hadrons (τ_h) or leptons (τ_ℓ), with the corresponding branching fractions $Br(\tau_h \rightarrow \text{hadrons} + \nu_\tau) \simeq 65\%$ and $Br(\tau_\ell \rightarrow \ell\nu_\ell\nu_\tau, \ell = \text{e}, \mu) \simeq 35\%$. In the first case, a narrow jet with a distinct signature is produced; in the case of leptonic decays, the distinction from prompt electron or muon production is experimentally difficult, consequently only hadronic τ decays are studied here. The cross section is measured by counting the number of $e\tau_h + X$ and $\mu\tau_h + X$ events consistent with originating from $t\bar{t}$, subtracting the contributions from other processes, and correcting for the efficiency of the event selection. The measurement is based on data collected by the Compact Muon Solenoid (CMS) experiment in 2011. The integrated luminosity of the data samples are 1.99 fb^{-1} and 2.22 fb^{-1} for the $e\tau_h$ and $\mu\tau_h$ final states, respectively.

The CMS detector is briefly summarized in Sec. II, details of the simulated samples are given in Sec. III, a brief description of the event reconstruction and event selection is provided in Sec. IV, followed by the description of the background determination and systematic uncertainties in Secs. V and VI, respectively. The measurement of the cross section is discussed in Sec. VII, and the results are summarized in Sec. VIII.

II. THE CMS DETECTOR

The central feature of the CMS apparatus is a superconducting solenoid, 13 m in length and 6 m in diameter, which provides an axial magnetic field of 3.8 T. Inside the solenoid, various particle detection systems are employed. Charged particle trajectories are measured by the silicon pixel and strip tracker, covering $0 < \varphi < 2\pi$ in azimuth and $|\eta| < 2.5$, where the pseudorapidity η is defined as $\eta = -\ln[\tan(\theta/2)]$, with θ being the polar angle of the trajectory of the particle with respect to the counterclockwise beam direction. A crystal electromagnetic calorimeter and a brass/scintillator hadron calorimeter surround the tracking volume; in this analysis the calorimetry provides high-resolution energy and direction measurements of electrons and hadronic jets. Muon detection systems are located outside of the solenoid and embedded in the steel return yoke. The detector is nearly hermetic, allowing for energy balance measurements in the plane transverse to the

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

beam directions. A two-level trigger system selects the most interesting proton-proton collision events for use in physics analysis. A more detailed description of the CMS detector can be found elsewhere [6].

III. EVENT SIMULATION

The analysis makes use of simulated samples of $t\bar{t}$ events as well as other processes that result in τs in the final state. These samples are used to design the event selection, to calculate the acceptance to $t\bar{t}$ events, and to estimate some of the backgrounds in the analysis.

Signal $t\bar{t}$ events are simulated with the MADGRAPH event generator (v. 5.1.1.0) [7] with matrix elements corresponding to up to three additional partons, for a top quark mass of 172.5 GeV$/c^2$. The number of expected $t\bar{t}$ events is estimated with the approximate next-to-next-to-leading order (NNLO) expected standard model (SM) cross section value of 165^{+4}_{-9}(scale)$^{+7}_{-7}$(PDF) pb [8,9], where the first uncertainty is due to renormalization and factorization scales, and the second is due to the parton distribution function (PDF) uncertainty. This cross section is used for illustrative purposes to normalize the $t\bar{t}$ $e\tau_h$ and $\mu\tau_h$ expectations discussed in Section IV. The generated events are subsequently processed with PYTHIA (v. 6.422) [10] to provide the showering of the partons, and to perform the matching of the soft radiation with the contributions from direct emissions accounted for in the matrix-element calculations. The Z2 tune [11] is used with the CTEQ6L PDFs [12]. The τ decays are simulated with TAUOLA (v. 27.121.5) [13] which correctly accounts for the τ lepton polarization in describing the decay kinematics. The CMS detector response is simulated with GEANT4 (v. 9.3 Rev01) [14].

The background samples used in the measurement of the cross section are simulated with MADGRAPH and PYTHIA. The W + jet samples include only the leptonic decays of the boson, and are normalized to the inclusive next-to-next-leading-order (NNLO) cross section of 31.3 ± 1.6 nb, calculated with the FEWZ (Fully Exclusive W and Z boson) production program [15]. Drell–Yan (DY) pair production of charged leptons in the final state is generated with MADGRAPH for dilepton invariant masses above 50 GeV$/c^2$, and is normalized to a cross section of 3.04 ± 0.13 nb, computed with FEWZ. The DY events with masses between 10 and 50 GeV$/c^2$ are generated with MADGRAPH with a cross section (with a k-factor of 1.33 to correct for NLO) of 12.4 nb.

The electroweak production of single top quarks is considered as a background process, and is simulated with POWHEG [16]. The t-channel single top quark NLO cross section is $\sigma_{t\text{-ch}} = 64.6^{+3.4}_{-3.2}$ pb from MCFM [17–20]. The single top quark associated production (tW) cross section amounts to $\sigma_{tW} = 15.7 \pm 1.2$ pb [21]. The s-channel single top quark next-to-next-leading-log (NNLL) cross section is determined as $\sigma_{s\text{-ch}} = 4.6 \pm 0.06$ pb [22]. Finally, the production of WW, WZ, and ZZ pairs, with inclusive cross sections of 43.0 ± 1.5 pb, 18.8 ± 0.7 pb, and 7.4 ± 0.2 pb, respectively (all calculated at the NLO with MCFM), are simulated with PYTHIA.

IV. EVENT SELECTION

The signal topology is defined by the presence of two b jets from the top quark decays, one W boson decaying leptonically into $e\nu$ or $\mu\nu$, and a second boson decaying into $\tau\nu$. In the event, all objects are reconstructed with a particle-flow (PF) algorithm [23]. The PF algorithm combines the information from all subdetectors to identify and reconstruct all types of particles produced in the collision, namely, charged hadrons, photons, neutral hadrons, muons, and electrons. The resulting list of particles is used to construct a variety of higher-level objects and observables such as jets, missing transverse energy (E_T^{miss}), leptons (including τs), photons, b-tagging discriminators, and isolation variables. The missing transverse energy E_T^{miss} is computed as the absolute value of the vectorial sum of the transverse momenta of all reconstructed particles in the event.

Electron or muon candidates are required to be isolated relative to other activity in the event. The relative isolation is based on PF objects and defined as $I_{\text{rel}} = (E_{\text{ch}} + E_{\text{nh}} + E_{\text{ph}})/p_T \cdot c$, where E_{ch} is the transverse energy deposited by charged hadrons in a cone of radius $\Delta R = 0.3$ around the electron or muon track, E_{nh} and E_{ph} are the respective transverse energies of the neutral hadrons and photons, and p_T is the electron or muon transverse momentum. The electron (muon) candidate is considered to be non-isolated and is rejected if $I_{\text{rel}} > 0.1 (>0.2)$. Jets are reconstructed with the anti-k_T [24,25] jet algorithm with a distance parameter $R = 0.5$.

Hadronic τ decays are reconstructed with the Hadron Plus Strips (HPS) algorithm [26]. The identification process starts with the clustering of all PF particles into jets with the anti-k_T algorithm with a distance parameter $R = 0.5$. For each jet, a charged hadron is combined with other nearby charged hadrons or photons to identify the decay modes. The identification of π^0 mesons is enhanced by clustering electrons and photons in "strips" along the bending plane to take into account possible broadening of calorimeter signatures by early showering photons. Then, strips and charged hadrons are combined to reconstruct the following combinations: single hadron, hadron plus a strip, hadron plus two strips and three hadrons. To reduce the contamination from quark and gluon jets, the τ_h candidate isolation is calculated in a cone of $\Delta R = 0.5$ around the reconstructed τ-momentum direction. It is required that there be no charged hadrons with $p_T > 1.0$ GeV$/c$ and no photons with $E_T > 1.5$ GeV in the isolation cone, other than the τ decay particles. Additional requirements are applied to discriminate genuine τ leptons from prompt electrons and muons. The τ

charge is taken as the sum of the charges of the charged hadrons (prongs) in the signal cone; its uncertainty is less than 1% and it is estimated from same sign $Z \to \tau\tau \to \mu\tau_h$ events [27]. The τ reconstruction efficiency of this algorithm is estimated to be approximately 37% (i.e. "medium" working point in Ref. [26]) for $p_T^{\tau h} > 20$ GeV$/c$, and it is measured in a sample enriched in $Z \to \tau\tau \to \mu\tau_h$ events with a "tag-and-probe" technique [28]. The medium working point corresponds to a probability of approximately 0.5% for generic hadronic jets to be misidentified as τ_h.

For the $e\tau_h$ final state, events are triggered by the combined electron plus two jets plus H_T^{miss} trigger (e + dijet + H_T^{miss}), where H_T^{miss} is the absolute value of the vectorial sum of all jet momenta in the plane transverse to the beams. The thresholds for the electron and for H_T^{miss} are respectively $p_T > 17$–27 GeV$/c$ and $H_T^{miss} >$ 15–20 GeV depending on the data-taking period, and the p_T thresholds for the two jets are 30 GeV$/c$ and 25 GeV$/c$. The trigger efficiency is estimated from a suite of triggers with lower thresholds assuming the factorization $\epsilon_{trig} = \epsilon_e \times \epsilon_{jets} \times \epsilon_{MHT}$, where ϵ_e is the electron efficiency, ϵ_{jets} is the efficiency for selecting two jets, and ϵ_{MHT} is the efficiency for H_T^{miss}. The data-to-simulation scale factor for the electron trigger efficiency is 0.99 ± 0.01. The efficiencies $\epsilon_{MHT} = 1.00^{+0.00}_{-0.01}$ and ϵ_{jets}, which is parameterized as a function of jet p_T, are estimated from data. In the $\mu\tau_h$ final state, data are collected with a trigger requiring at least one isolated muon with threshold of $p_T > 17(24)$ GeV$/c$, for the earlier (later) part of the data sample; the data-to-simulation scale factor for the trigger efficiency is 0.99 ± 0.01.

Events are selected by requiring one isolated electron (muon) with transverse momentum $p_T >$ 35(30) GeV$/c$ and $|\eta| < 2.5(2.1)$, at least two jets with $p_T > 35(30)$ GeV$/c$ and $|\eta| < 2.4$, missing transverse energy $E_T^{miss} > 45(40)$ GeV and one hadronically decaying τ lepton (τ jet) with $p_T > 20$ GeV$/c$ and $|\eta| < 2.4$. Electrons or muons are required to be separated from any jet in the (η, φ) plane by a distance $\Delta R > 0.3$. Events with any additional loosely isolated ($I_{rel} < 0.2$) electron (muon) of $p_T > 15(10)$ GeV$/c$ are rejected.

The τ jet and the lepton are required to have electric charges of opposite sign (OS). At least one of the jets is required to be identified as originating from b quark hadronization (b tagged). The b-tagging algorithm used ("TCHEL" in Ref. [29]) is based on sorting tracks according to their impact parameter significance (S_{IP}); the S_{IP} value of the second track is used as the discriminator. The b-tagging efficiency of this algorithm is 76 ± 1%, measured in a sample of events enriched with jets from semileptonic b-hadron decays. The misidentification rate of light-flavor jets is obtained from inclusive jet studies and is measured to be 13 ± 3% for jets in the p_T range relevant to this analysis. After the final event selection, a fraction of approximately 12% of the generated $t\bar{t}$ tau dilepton events within the geometric and kinematic fiducial region are selected.

The b-tagged jet multiplicity for the $e\tau_h$ and $\mu\tau_h$ final states is shown in Fig. 1 for the events in the preselected sample, i.e. one isolated electron (muon), missing transverse energy above 45 (40) GeV, and at least three jets, two jets with $p_T > 35(30)$ GeV$/c$ and one jet with $p_T >$ 20 GeV$/c$. The observed numbers of events are consistent with the expected numbers of signal and background events obtained from the simulation. The distributions of the E_T^{miss} and of the transverse momentum of the τ lepton

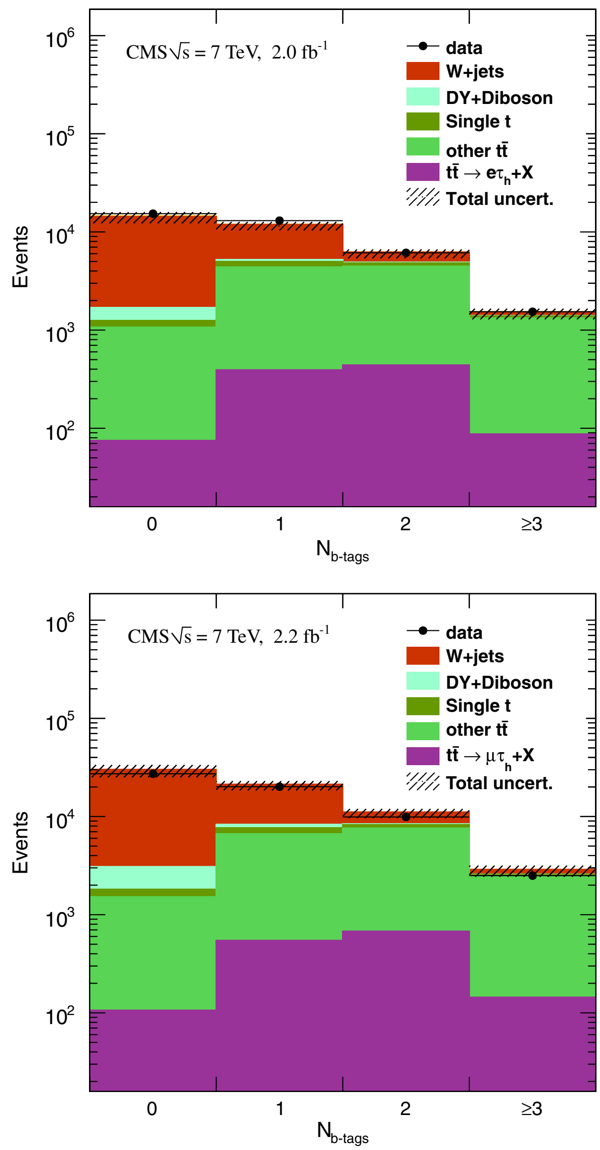

FIG. 1 (color online). The b-tagged jet multiplicity for preselected events with one electron (top) or muon (bottom). Distributions obtained from data (points) are compared with simulation. The simulated contributions are normalized to the SM predicted values. The hatched area shows the total systematic uncertainty.

after the final event selection are shown in Fig. 2 and in Fig. 3, respectively, for both the $e\tau_h$ and $\mu\tau_h$ final states. The distributions show good agreement between the observed numbers of events and the expected numbers of signal and background events obtained from the simulation. The E_T^{miss} distribution for the $e\tau_h$ final state has a deficit of events in the first bin due to the higher E_T^{miss} threshold, when compared to the $e\tau_h$ final state.

The top quark mass is reconstructed with the KINb [30] algorithm (Fig. 4), treating the additional neutrino in the τ decay as a contribution to the E_T^{miss}. Numerical solutions for the kinematic reconstruction of $t\bar{t}$ decays with two charged leptons in the final state are found for each event. The jet transverse momentum, the E_T^{miss} direction, and the longitudinal momentum of the $t\bar{t}$ system are varied independently within their measured resolutions to scan the kinematic phase space compatible with the $t\bar{t}$ system. Solutions with the lowest invariant mass of the $t\bar{t}$ system are accepted if the difference between the two top quark masses is less than 3 GeV$/c^2$. The reconstructed top quark mass in Fig. 4 shows that the kinematic properties of the

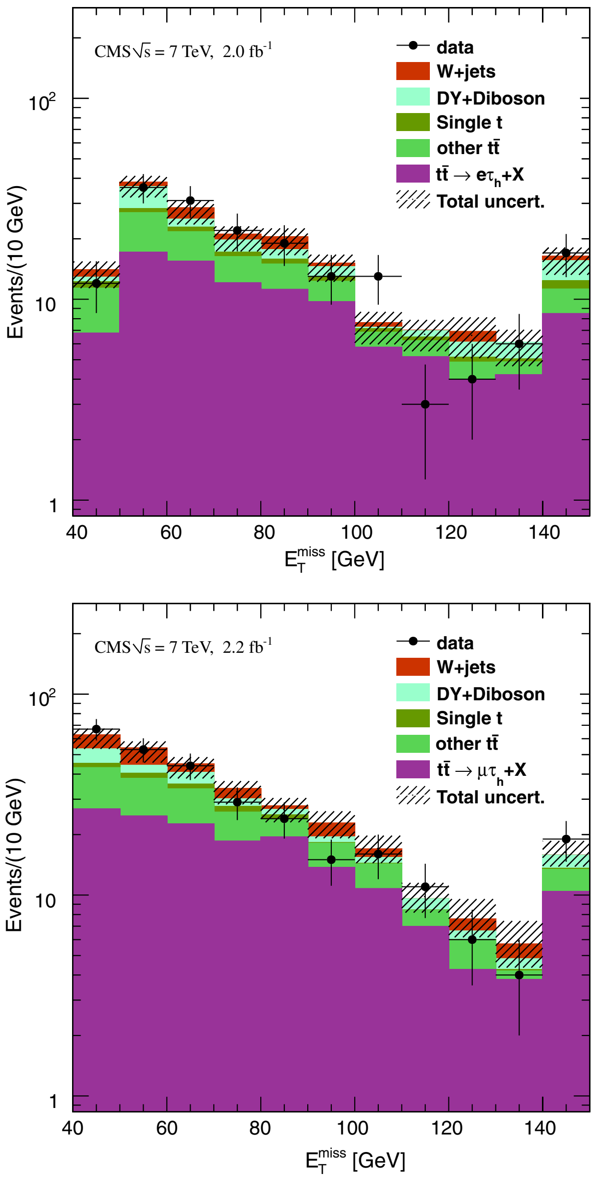

FIG. 2 (color online). E_T^{miss} distribution after the full event selection for the $e\tau_h$ (top) and $\mu\tau_h$ (bottom) final states. Distributions obtained from data (points) are compared with simulation. The last bin includes the overflow. The simulated contributions are normalized to the SM predicted values. The hatched area shows the total systematic uncertainty.

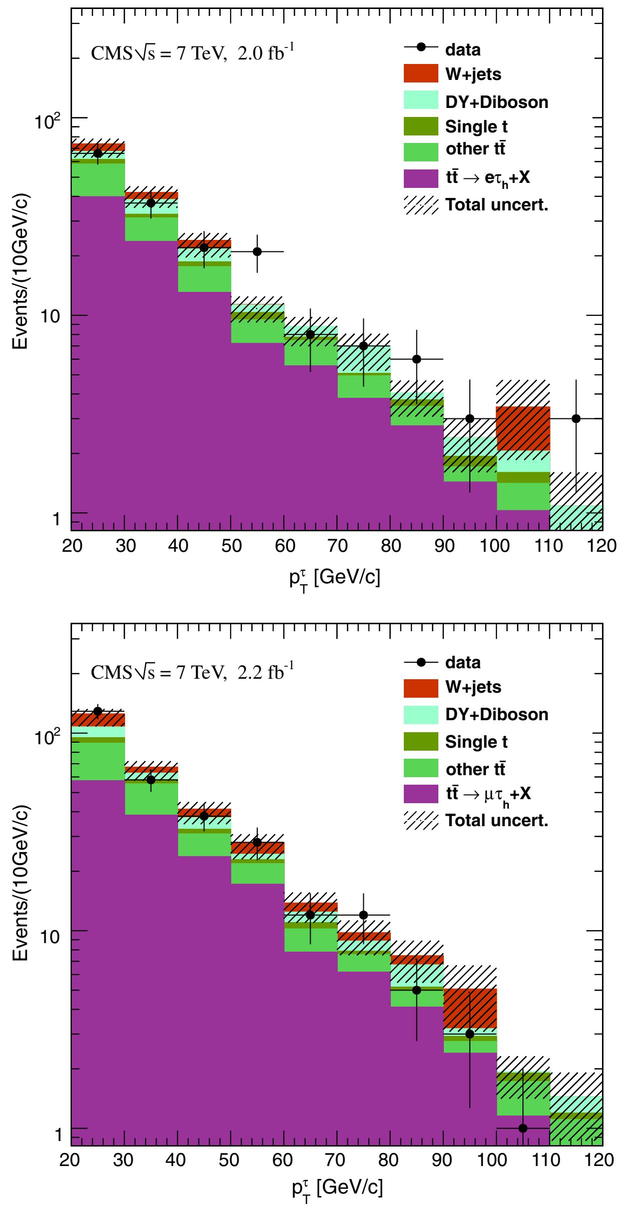

FIG. 3 (color online). The τ p_T distribution after the full event selection for the $e\tau_h$ (top) and $\mu\tau_h$ (bottom) final states. Distributions obtained from data (points) are compared with simulation. The simulated contributions are normalized to the SM predicted values. The hatched area shows the total systematic uncertainty.

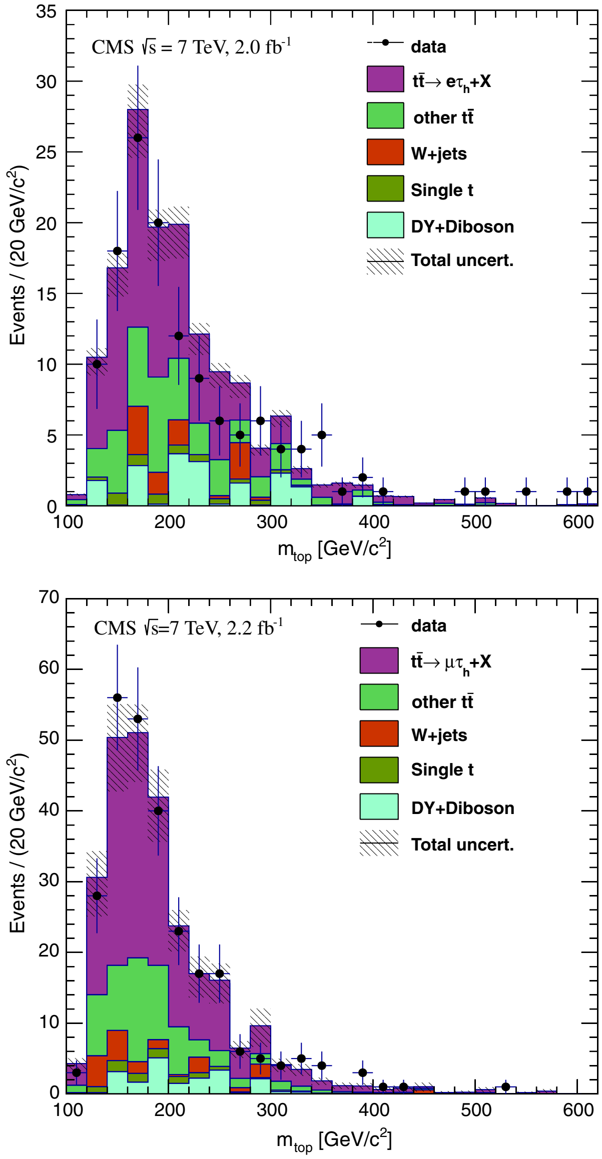

FIG. 4 (color online). Reconstructed top quark mass m_{top} distribution for the τ dilepton candidate events after the full event selection, in the $e\tau_{\mathrm{h}}$ (top) and $\mu\tau_{\mathrm{h}}$ (bottom) final states. Distributions obtained from data (points) are compared with simulation. The hatched area shows the total systematic uncertainty.

selected events are statistically compatible with predictions based on a top quark mass of 172.5 GeV/c^2, indicating the consistency of the selected sample in data with the sum of top quark pair production plus the background.

V. BACKGROUND ESTIMATE

The background comes from two categories of events, the "misreconstructed τ" background (N^{misid}) which is estimated from data, and the "other" background (N^{other}) which is estimated from simulation.

The main background (misreconstructed τ) comes from events with one lepton (electron or muon), $E_{\mathrm{T}}^{\mathrm{miss}}$ requirement and three or more jets, where one jet is misidentified as a τ jet. The dominant contribution to this background is from events where one W boson is produced in association with jets, and from $t\bar{t} \rightarrow W^+ bW^- \bar{b} \rightarrow \ell \nu b\, q\bar{q}'\bar{b}$ events. In order to estimate this background from data, the probability $w(\mathrm{jet} \rightarrow \tau_{\mathrm{h}})$ that a jet is misidentified as a τ jet as a function of the jet p_{T}, η, and jet width (R_{jet}) is determined, then applied to every jet in the preselected sample with one b-tagged jet. The quantity R_{jet} is defined as $\sqrt{\sigma_{\eta\eta}^2 + \sigma_{\phi\phi}^2}$, where $\sigma_{\eta\eta}$ ($\sigma_{\phi\phi}$) expresses the extent in η (ϕ) of the jet cluster. Thus the expected number of background is obtained as:

$$N^{\mathrm{misid}} = \sum_i^N \sum_j^n w_i^j(\mathrm{jet} \rightarrow \tau) - N^{\mathrm{other}}, \tag{1}$$

where j is the jet index of the event i. The quantity N^{other} is the small ($\simeq 18\%$) contamination of other contributions to the misidentified τ background, which is estimated from simulation. This is mostly due to the presence of genuine τ jets in the $W+ \geq 3$ jet sample. In order to estimate this contribution, the same procedure described above is applied to simulated events of $\mathrm{Z}/\gamma^* \rightarrow \tau\tau$, single top quark production, diboson production, and the part of the SM $t\bar{t}$ background not included in the misidentified τ background estimate.

In order to estimate the misidentification probability, the hadronic multijet events are selected from a sample triggered by at least one jet with $p_{\mathrm{T}} > 30$ GeV$/c$, by requiring events to have at least two jets with $p_{\mathrm{T}} > 20$ GeV$/c$ and $|\eta| < 2.4$. The triggering jet is removed from the misidentification rate calculation in order to avoid a trigger bias. The $W+ \geq 1$ jet events are selected by requiring only one isolated muon with $p_{\mathrm{T}} > 20$ GeV$/c$ and $|\eta| < 2.1$, and at least one jet with $p_{\mathrm{T}} > 20$ GeV$/c$ and $|\eta| < 2.4$. The probability $w(\mathrm{jet} \rightarrow \tau_{\mathrm{h}})$ is evaluated from all jets in a sample enriched in QCD multijet events (w_{QCD}), and all jets in another sample enriched in $W+ \geq 1$ jet events ($w_{W+\mathrm{jets}}$). The probability that a jet is misidentified as a τ jet as a function of jet p_{T}, η and R_{jet} is compared between simulated events (Z2 tune [11]) and data, and a good agreement is found [26].

Jets in QCD multijet events are mainly gluon jets ($\simeq 75\%$ obtained from simulation), while the jets in $W+ \geq 1$ jet events are predominantly quark jets ($\simeq 64\%$ obtained from simulation), where $w_{\mathrm{QCD}} < w_{W+\mathrm{jets}}$. Since the quark and gluon jet composition in $\ell + E_{\mathrm{T}}^{\mathrm{miss}} + \geq 3$ jet events lies between two categories of events, QCD multijet and $W+ \geq 1$ jet events, the N^{misid} value is under- (over-) estimated by applying the w_{QCD} ($w_{W+\mathrm{jets}}$) probability. Thus, the N^{misid} and its systematic uncertainty are estimated as in the following:

$$N^{\mathrm{misid}} = \frac{\sum_i^N \sum_j^n w_{W+\mathrm{jets},i}^j + \sum_i^N \sum_j^n w_{\mathrm{QCD},i}^j}{2}, \tag{2}$$

$$\Delta N^{\mathrm{misid}} = \frac{\sum_i^N \sum_j^n w^j_{W+\mathrm{jets},i} - \sum_i^N \sum_j^n w^j_{\mathrm{QCD},i}}{2}. \quad (3)$$

The contribution of N_{other} described earlier is subtracted from Eq. (2). Finally, the efficiency $\varepsilon_{\mathrm{OS}}$ of the OS requirement obtained from simulated events is applied to obtain the misidentified τ background $N^{\mathrm{misid}}_{\mathrm{OS}} = \varepsilon_{\mathrm{OS}} \times N^{\mathrm{misid}}$. The estimated efficiencies for the $e\tau_{\mathrm{h}}$ and $\mu\tau_{\mathrm{h}}$ final states are $\varepsilon_{\mathrm{OS}} = 0.72 \pm 0.09(\mathrm{stat}) \pm 0.02(\mathrm{syst})$ and $\varepsilon_{\mathrm{OS}} = 0.69 \pm 0.07(\mathrm{stat}) \pm 0.03(\mathrm{syst})$, respectively, where the statistical uncertainty comes from the limited number of simulated events, and the systematic uncertainty is taken as half of the difference of the efficiency estimated from W + jets and lepton + jet $t\bar{t}$ simulated events.

Other backgrounds in this analysis are $Z/\gamma^* \to \tau\tau$, single top quark production, diboson production, and the part of the SM $t\bar{t}$ background not included in the misidentified τ background, and are estimated from simulation. Events from $Z \to ee$, $\mu\mu$ are also taken into account because they contain misidentified τ jets, where the misidentified τ lepton can originate from an electron or muon misidentified as a τ jet. The statistical uncertainties are due to the limited number of simulated events.

VI. SYSTEMATIC UNCERTAINTIES

Different sources of systematic uncertainties on the measurement of the cross section due to signal selection efficiencies and backgrounds are considered, as shown in Table I. The main sources of systematic uncertainties are due to τ identification, b-tagging and mistagging efficiencies, jet energy scale (JES), jet energy resolution (JER), $E_{\mathrm{T}}^{\mathrm{miss}}$ scale, and to the estimate of the misreconstructed τ background (from data). The systematic uncertainties for the determination of the misidentified τ background are discussed in detail in Sec. V.

The uncertainty on the τ jet identification includes contributions from τ identification efficiency and $\ell \to \tau_{\mathrm{h}}$ ($\ell = e, \mu$) misidentification. The uncertainty on τ identification efficiency is estimated to be 6% (from an updated measurement with respect to [26]), and it includes the uncertainty on charge determination which is estimated to be smaller than 1%. The uncertainty on the $\ell \to \tau_{\mathrm{h}}$ misidentification rate is estimated as the difference of τ misidentification rate measured in data and in simulated events, and is taken to be 15% [26]. These uncertainties are applied to the simulated $Z \to ee$, $\mu\mu$, and $t\bar{t}$ dilepton background events.

The uncertainties related to b-tagging and mistagging efficiencies are estimated from a variety of control samples enriched in b quarks, and the data-to-simulation scale factors amount to 0.95 ± 0.06 and 1.11 ± 0.11, respectively [29].

The uncertainties on JES, JER, and $E_{\mathrm{T}}^{\mathrm{miss}}$ scale are estimated according to the prescription described in Ref. [32]. These uncertainties also take into account the uncertainty due to the JES dependence on the parton flavor. The uncertainty on JES is evaluated as a function of jet p_{T} and jet η. The JES and JER uncertainties are propagated in order to estimate the uncertainty of the $E_{\mathrm{T}}^{\mathrm{miss}}$ scale. An additional 10% uncertainty on the contribution to $E_{\mathrm{T}}^{\mathrm{miss}}$ coming from the energy of particles that are not clustered into jets is also taken into account.

The theoretical uncertainty on the signal acceptance is estimated to be 4% [30]. It accounts for variations in the renormalization and factorization scales (2%), τ lepton and hadron decay modelling (2%), top quark mass (1.6%), leptonic branching fractions of the W boson (1.7%), and

TABLE I. List of systematic uncertainties (in %) on the cross section measurement. The Best Linear Unbiased Estimation method [31] is used to combine the cross section measurements in the $e\tau_{\mathrm{h}}$ and $\mu\tau_{\mathrm{h}}$ channels, with the corresponding weights. Systematic uncertainties common to the two channels are assumed to be 100% correlated.

Source	Uncertainty [%] $e\tau_{\mathrm{h}}$	Uncertainty [%] $\mu\tau_{\mathrm{h}}$	Combination [%]
τ misidentification background	12.6	9.8	10.8
τ jet identification	6.4	6.3	6.3
b-jet tagging, misidentification	5.3	5.3	5.3
jet energy scale, jet energy resolution, $E_{\mathrm{T}}^{\mathrm{miss}}$	5.1	6.2	5.8
theoretical uncertainty on signal efficiency	4.0	4.0	4.0
pile-up modelling	2.3	2.3	2.3
electron selection	3.1	0	1.1
muon selection	0	2.0	1.3
cross section of MC backgrounds	1.6	1.4	1.5
luminosity	2.2	2.2	2.2
weight	0.38	0.62	$\chi^2/N_{\mathrm{dof}} = 2.381/1$ (p-value = 0.198)

jet and $E_{\mathrm{T}}^{\mathrm{miss}}$ modelling (1%). Uncertainties on the PDFs are found to be negligible.

The uncertainty on the integrated luminosity is estimated to be 2.2% [33]. The number of interactions per bunch crossing in the data (pile-up) is estimated from the measured luminosity in each bunch crossing times an average total inelastic cross section (with an uncertainty of 6.5%). The estimated number of interactions has a total uncertainty of approximately 8%, which corresponds to an overall uncertainty of the pile-up distribution. The mean of pile-up in the data sample is about 5–6 interactions, with the uncertainty estimated conservatively by shifting the overall mean up or down by 0.6 interactions.

The lepton trigger, identification, and isolation efficiencies are measured with the "tag-and-probe" method in events containing a lepton pair of invariant mass between 76 and 106 GeV/c^2. Within the precision of the present measurement, the scale factors between efficiencies measured in data and in simulation are estimated to be equal to one. The combined uncertainty on the electron (muon) trigger, identification and isolation efficiencies is 3% (2%).

Theoretical uncertainties on the cross sections of single top quark, diboson, and DY processes are estimated as in Ref. [34]. The uncertainties include the scale and PDF uncertainties on theoretical cross sections.

VII. CROSS SECTION MEASUREMENT

The number of events expected from the backgrounds, the number of signal events from $t\bar{t}$, and the number of observed events after all selection cuts are summarized in Table II. The statistical and systematic uncertainties are also shown.

The $t\bar{t}$ production cross section measured from tau dilepton events is:

$$\sigma_{t\bar{t}} = \frac{N - B}{L \cdot A_{\mathrm{tot}}}, \tag{4}$$

TABLE II. Number of expected events for signal and backgrounds. The background from "misidentified τ" is estimated from data, while the other backgrounds are estimated from simulation. Statistical and systematic uncertainties are shown.

Source	N_{events}($\pm$stat $\pm$ syst) $e\tau_{\mathrm{h}}$	$\mu\tau_{\mathrm{h}}$
$t\bar{t} \to WbWb \to \ell\nu b\tau\nu b$	99.9 ± 3.0 ± 10.1	162.0 ± 4.0 ± 16.7
misidentified τ	54.3 ± 6.4 ± 8.1	88.5 ± 8.9 ± 10.8
$Z/\gamma^* \to \tau\tau$	16.6 ± 3.3 ± 2.9	25.8 ± 4.3 ± 6.1
$t\bar{t} \to WbWb \to \ell\nu b\ell\nu b$	9.0 ± 0.9 ± 1.7	13.3 ± 1.2 ± 2.5
$Z/\gamma^* \to ee, \mu\mu$	4.8 ± 1.8 ± 1.3	0.7 ± 0.7 ± 0.7
Single top	7.9 ± 0.4 ± 1.1	13.5 ± 0.5 ± 1.9
VV	1.3 ± 0.1 ± 0.2	2.0 ± 0.2 ± 0.3
Total expected	193.9 ± 4.9 ± 18.0	306.1 ± 6.1 ± 27.9
Data	176	288

where N is the number of observed candidate events, B is the estimate of the background, L is the integrated luminosity. The total acceptance A_{tot} is the product of all branching fractions, geometrical and kinematical acceptance, efficiencies for trigger, lepton identification and the overall reconstruction efficiency, and it is evaluated with respect to the inclusive $t\bar{t}$ sample. After the OS requirement:

$$A_{\mathrm{tot}}(e\tau_{\mathrm{h}}) = [0.0304 \pm 0.0009(\mathrm{stat}) \pm 0.0031(\mathrm{syst})]\%; \tag{5}$$

$$A_{\mathrm{tot}}(\mu\tau_{\mathrm{h}}) = [0.0443 \pm 0.0011(\mathrm{stat}) \pm 0.0047(\mathrm{syst})]\%. \tag{6}$$

The statistical uncertainties are due to the limited number of simulated events and the systematic uncertainties are estimated by varying all sources of systematics in Table I affecting the signal (i.e., all uncertainties except for the luminosity and for the background). All systematic and statistical uncertainties in Table II are propagated from Eq. (4) to the final cross section measurement. The measured $t\bar{t}$ cross section is:

$$\sigma_{t\bar{t}}(e\tau_{\mathrm{h}}) = 136 \pm 23(\mathrm{stat}) \pm 23(\mathrm{syst}) \pm 3(\mathrm{lumi})\ \mathrm{pb}; \tag{7}$$

$$\sigma_{t\bar{t}}(\mu\tau_{\mathrm{h}}) = 147 \pm 18(\mathrm{stat}) \pm 22(\mathrm{syst}) \pm 3(\mathrm{lumi})\ \mathrm{pb}. \tag{8}$$

The Best Linear Unbiased Estimation method [31] is used to combine the cross section measurements in the $e\tau_{\mathrm{h}}$ and $\mu\tau_{\mathrm{h}}$ channels with the associated uncertainties and correlation factors. Systematic uncertainties common to the two channels are assumed to be 100% correlated. The combined result is

$$\sigma_{t\bar{t}} = 143 \pm 14(\mathrm{stat}) \pm 22(\mathrm{syst}) \pm 3(\mathrm{lumi})\ \mathrm{pb}, \tag{9}$$

in agreement with the measured values in the dilepton [30] and lepton + jet [34,35] final states, and with the SM expectations in the approximate NNLO calculation of 163^{+7}_{-5}(scale) ± 9(PDF) pb [36].

VIII. SUMMARY

We present the first measurement of the $t\bar{t}$ production cross section in the tau dilepton channel $t\bar{t} \to (\ell\nu_\ell)(\tau_{\mathrm{h}}\nu_\tau)b\bar{b}$, ($\ell = e, \mu$) with data samples corresponding to an integrated luminosity of 2.0–2.2 fb^{-1} collected in proton-proton collisions at $\sqrt{s} = 7$ TeV. Events are selected by requiring the presence of one electron or muon, two or more jets (at least one jet is b tagged), missing transverse energy, and one hadronically decaying τ lepton. The largest background contributions come from events where one W boson is produced in association with jets, and from $t\bar{t} \to W^+bW^-\bar{b} \to \ell\nu b\ (q\bar{q}'\bar{b})$ events, where one jet is misidentified as the τ, and from $Z \to \tau\tau$ events. The measured cross section is $\sigma_{t\bar{t}} = 143 \pm 14(\mathrm{stat}) \pm 22(\mathrm{syst}) \pm 3(\mathrm{lumi})$ pb, in agreement with SM expectations.

ACKNOWLEDGMENTS

We wish to congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC machine. We thank the technical and administrative staff at CERN and other CMS institutes, and acknowledge support from: FMSR (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES (Croatia); RPF (Cyprus); MoER, SF0690030s09 and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NKTH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); NRF and WCU (Korea); LAS (Lithuania); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); MSI (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Armenia, Belarus, Georgia, Ukraine, Uzbekistan); MON, RosAtom, RAS and RFBR (Russia); MSTD (Serbia); MICINN and CPAN (Spain); Swiss Funding Agencies (Switzerland); NSC (Taipei); TUBITAK and TAEK (Turkey); STFC (United Kingdom); DOE and NSF (USA). Individuals have received support from the Marie-Curie programme and the European Research Council (European Union); the Leventis Foundation; the A. P. Sloan Foundation; the Alexander von Humboldt Foundation; 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 Council of Science and Industrial Research, India; and the HOMING PLUS programme of Foundation for Polish Science, cofinanced from European Union, Regional Development Fund.

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Liu,[120] O. R. Long,[120] A. Luthra,[120] H. Nguyen,[120] S. Paramesvaran,[120] J. Sturdy,[120] S. Sumowidagdo,[120] R. Wilken,[120] S. Wimpenny,[120] W. Andrews,[121] J. G. Branson,[121] G. B. Cerati,[121] S. Cittolin,[121] D. Evans,[121] F. Golf,[121] A. Holzner,[121] R. Kelley,[121] M. Lebourgeois,[121] J. Letts,[121] I. Macneill,[121] B. Mangano,[121] J. Muelmenstaedt,[121] S. Padhi,[121] C. Palmer,[121] G. Petrucciani,[121] M. Pieri,[121] R. Ranieri,[121] M. Sani,[121] V. Sharma,[121] S. Simon,[121] E. Sudano,[121] M. Tadel,[121] Y. Tu,[121] A. Vartak,[121] S. Wasserbaech,[121,uu] F. Würthwein,[121] A. Yagil,[121] J. Yoo,[121] D. Barge,[122] R. Bellan,[122] C. Campagnari,[122] M. D'Alfonso,[122] T. Danielson,[122] K. Flowers,[122] P. Geffert,[122] J. Incandela,[122] C. Justus,[122] P. Kalavase,[122] S. A. Koay,[122] D. Kovalskyi,[122,b] V. Krutelyov,[122] S. Lowette,[122] N. Mccoll,[122] V. Pavlunin,[122] F. Rebassoo,[122] J. Ribnik,[122] J. Richman,[122] R. Rossin,[122] D. Stuart,[122] W. To,[122] C. West,[122] A. Apresyan,[123] A. Bornheim,[123] Y. Chen,[123] E. Di Marco,[123] J. Duarte,[123] M. Gataullin,[123] Y. Ma,[123] A. Mott,[123] H. B. Newman,[123] C. Rogan,[123] V. Timciuc,[123] P. Traczyk,[123] J. Veverka,[123] R. Wilkinson,[123] Y. Yang,[123] R. Y. Zhu,[123] B. Akgun,[124] R. Carroll,[124] T. Ferguson,[124] Y. Iiyama,[124] D. W. Jang,[124] Y. F. Liu,[124] M. Paulini,[124] H. Vogel,[124] I. Vorobiev,[124] J. P. Cumalat,[125] B. R. Drell,[125] C. J. Edelmaier,[125] W. T. Ford,[125] A. Gaz,[125] B. Heyburn,[125] E. Luiggi Lopez,[125] J. G. Smith,[125] K. Stenson,[125] K. A. Ulmer,[125] S. R. Wagner,[125] L. Agostino,[126] J. Alexander,[126] A. Chatterjee,[126] N. Eggert,[126] L. K. Gibbons,[126] B. Heltsley,[126] W. Hopkins,[126] A. Khukhunaishvili,[126] B. Kreis,[126] N. Mirman,[126] G. Nicolas Kaufman,[126] J. R. Patterson,[126] A. Ryd,[126] E. Salvati,[126] W. Sun,[126] W. D. Teo,[126] J. Thom,[126] J. Thompson,[126] J. Vaughan,[126] Y. Weng,[126] L. Winstrom,[126] P. Wittich,[126] D. Winn,[127] S. Abdullin,[128] M. Albrow,[128] J. Anderson,[128] L. A. T. Bauerdick,[128] A. Beretvas,[128] J. Berryhill,[128] P. C. Bhat,[128] I. Bloch,[128] K. Burkett,[128] J. N. Butler,[128] V. Chetluru,[128] H. W. K. Cheung,[128] F. Chlebana,[128] V. D. Elvira,[128] I. Fisk,[128] J. Freeman,[128] Y. Gao,[128] D. Green,[128] O. Gutsche,[128] A. Hahn,[128] J. Hanlon,[128] R. M. Harris,[128] J. Hirschauer,[128] B. Hooberman,[128] S. Jindariani,[128] M. Johnson,[128] U. Joshi,[128] B. Kilminster,[128] B. Klima,[128] S. Kunori,[128] S. Kwan,[128] D. Lincoln,[128] R. Lipton,[128] L. Lueking,[128] J. Lykken,[128] K. Maeshima,[128] J. M. Marraffino,[128] S. Maruyama,[128] D. Mason,[128] P. McBride,[128] K. Mishra,[128] S. Mrenna,[128] Y. Musienko,[128,vv] C. Newman-Holmes,[128] V. O'Dell,[128] O. Prokofyev,[128] E. Sexton-Kennedy,[128] S. Sharma,[128] W. J. Spalding,[128] L. Spiegel,[128] P. Tan,[128] L. Taylor,[128] S. Tkaczyk,[128] N. V. Tran,[128] L. Uplegger,[128] E. W. Vaandering,[128] R. Vidal,[128] J. Whitmore,[128] W. Wu,[128] F. Yang,[128] F. Yumiceva,[128] J. C. Yun,[128] D. Acosta,[129] P. Avery,[129] D. Bourilkov,[129] M. Chen,[129] S. Das,[129] M. De Gruttola,[129] G. P. Di Giovanni,[129] D. Dobur,[129] A. Drozdetskiy,[129] R. D. Field,[129] M. Fisher,[129] Y. Fu,[129] I. K. Furic,[129] J. Gartner,[129] J. Hugon,[129] B. Kim,[129] J. Konigsberg,[129] A. Korytov,[129] A. Kropivnitskaya,[129] T. Kypreos,[129] J. F. Low,[129] K. Matchev,[129] P. Milenovic,[129,ww] G. Mitselmakher,[129] L. Muniz,[129] R. Remington,[129] A. Rinkevicius,[129] P. Sellers,[129] N. Skhirtladze,[129] M. Snowball,[129] J. Yelton,[129] M. Zakaria,[129] V. Gaultney,[130] L. M. Lebolo,[130] S. Linn,[130] P. Markowitz,[130] G. Martinez,[130] J. L. Rodriguez,[130] T. Adams,[131] A. Askew,[131] J. Bochenek,[131] J. Chen,[131] B. Diamond,[131] S. V. Gleyzer,[131] J. Haas,[131] S. Hagopian,[131] V. Hagopian,[131] M. Jenkins,[131] K. F. 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Ofierzynski,[146] B. Pollack,[146] A. Pozdnyakov,[146] M. Schmitt,[146] S. Stoynev,[146] M. Velasco,[146] S. Won,[146] L. Antonelli,[147] D. Berry,[147] A. Brinkerhoff,[147] M. Hildreth,[147] C. Jessop,[147] D. J. Karmgard,[147] J. Kolb,[147] K. Lannon,[147] W. Luo,[147] S. Lynch,[147] N. Marinelli,[147] D. M. Morse,[147] T. Pearson,[147] R. Ruchti,[147] J. Slaunwhite,[147] N. Valls,[147] J. Warchol,[147] M. Wayne,[147] M. Wolf,[147] J. Ziegler,[147] B. Bylsma,[148] L. S. Durkin,[148] C. Hill,[148] R. Hughes,[148] P. Killewald,[148] K. Kotov,[148] T. Y. Ling,[148] D. Puigh,[148] M. Rodenburg,[148] C. Vuosalo,[148] G. Williams,[148] B. L. Winer,[148] N. Adam,[149] E. Berry,[149] P. Elmer,[149] D. Gerbaudo,[149] V. Halyo,[149] P. Hebda,[149] J. Hegeman,[149] A. Hunt,[149] E. Laird,[149] D. Lopes Pegna,[149] P. Lujan,[149] D. Marlow,[149] T. Medvedeva,[149] M. Mooney,[149] J. Olsen,[149] P. Piroué,[149] X. Quan,[149] A. Raval,[149] H. Saka,[149] D. Stickland,[149] C. Tully,[149] J. S. 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Harel,[154] S. Korjenevski,[154] D. C. Miner,[154] D. Vishnevskiy,[154] M. Zielinski,[154] A. Bhatti,[155] R. Ciesielski,[155] L. Demortier,[155] K. Goulianos,[155] G. Lungu,[155] S. Malik,[155] C. Mesropian,[155] S. Arora,[156] A. Barker,[156] J. P. Chou,[156] C. Contreras-Campana,[156] E. Contreras-Campana,[156] D. Duggan,[156] D. Ferencek,[156] Y. Gershtein,[156] R. Gray,[156] E. Halkiadakis,[156] D. Hidas,[156] D. Hits,[156] A. Lath,[156] S. Panwalkar,[156] M. Park,[156] R. Patel,[156] A. Richards,[156] J. Robles,[156] K. Rose,[156] S. Salur,[156] S. Schnetzer,[156] C. Seitz,[156] S. Somalwar,[156] R. Stone,[156] S. Thomas,[156] G. Cerizza,[157] M. Hollingsworth,[157] S. Spanier,[157] Z. C. Yang,[157] A. York,[157] R. Eusebi,[158] W. Flanagan,[158] J. Gilmore,[158] T. Kamon,[158,zz] V. Khotilovich,[158] R. Montalvo,[158] I. Osipenkov,[158] Y. Pakhotin,[158] A. Perloff,[158] J. Roe,[158] A. Safonov,[158] T. Sakuma,[158] S. Sengupta,[158] I. Suarez,[158] A. Tatarinov,[158] D. 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Loveless,[163] A. Mohapatra,[163] I. Ojalvo,[163] G. A. Pierro,[163] I. Ross,[163] A. Savin,[163] W. H. Smith,[163] and J. Swanson[163]

(CMS Collaboration)

[1]*Yerevan Physics Institute, Yerevan, Armenia*
[2]*Institut für Hochenergiephysik der OeAW, Wien, Austria*
[3]*National Centre for Particle and High Energy Physics, Minsk, Belarus*
[4]*Universiteit Antwerpen, Antwerpen, Belgium*
[5]*Vrije Universiteit Brussel, Brussel, Belgium*
[6]*Université Libre de Bruxelles, Bruxelles, Belgium*
[7]*Ghent University, Ghent, Belgium*
[8]*Université Catholique de Louvain, Louvain-la-Neuve, Belgium*
[9]*Université de Mons, Mons, Belgium*
[10]*Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil*
[11]*Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil*
[12]*Instituto de Fisica Teorica, Universidade Estadual Paulista, Sao Paulo, Brazil*
[13]*Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria*
[14]*University of Sofia, Sofia, Bulgaria*
[15]*Institute of High Energy Physics, Beijing, China*
[16]*State Key Lab. of Nucl. Phys. and Tech., Peking University, Beijing, China*
[17]*Universidad de Los Andes, Bogota, Colombia*
[18]*Technical University of Split, Split, Croatia*
[19]*University of Split, Split, Croatia*
[20]*Institute Rudjer Boskovic, Zagreb, Croatia*
[21]*University of Cyprus, Nicosia, Cyprus*
[22]*Charles University, Prague, Czech Republic*
[23]*Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt*
[24]*National Institute of Chemical Physics and Biophysics, Tallinn, Estonia*
[25]*Department of Physics, University of Helsinki, Helsinki, Finland*
[26]*Helsinki Institute of Physics, Helsinki, Finland*
[27]*Lappeenranta University of Technology, Lappeenranta, Finland*
[28]*Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France*
[29]*DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France*
[30]*Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France*
[31]*Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France*
[32]*Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules (IN2P3), Villeurbanne, France*
[33]*Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France*
[34]*Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia*
[35]*RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany*
[36]*RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany*
[37]*RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany*
[38]*Deutsches Elektronen-Synchrotron, Hamburg, Germany*
[39]*University of Hamburg, Hamburg, Germany*
[40]*Institut für Experimentelle Kernphysik, Karlsruhe, Germany*
[41]*Institute of Nuclear Physics "Demokritos", Aghia Paraskevi, Greece*
[42]*University of Athens, Athens, Greece*
[43]*University of Ioánnina, Ioánnina, Greece*
[44]*KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary*
[45]*Institute of Nuclear Research ATOMKI, Debrecen, Hungary*
[46]*University of Debrecen, Debrecen, Hungary*
[47]*Panjab University, Chandigarh, India*
[48]*University of Delhi, Delhi, India*
[49]*Saha Institute of Nuclear Physics, Kolkata, India*
[50]*Bhabha Atomic Research Centre, Mumbai, India*
[51]*Tata Institute of Fundamental Research-EHEP, Mumbai, India*
[52]*Tata Institute of Fundamental Research - HECR, Mumbai, India*
[53]*Institute for Research in Fundamental Sciences (IPM), Tehran, Iran*
[54a]*INFN Sezione di Bari, Politecnico di Bari, Bari, Italy*
[54b]*Università di Bari, Politecnico di Bari, Bari, Italy*

[54c]Politecnico di Bari, Politecnico di Bari, Bari, Italy
[55a]INFN Sezione di Bologna, Bologna, Italy
[55b]Università di Bologna, Bologna, Italy
[56a]INFN Sezione di Catania, Catania, Italy
[56b]Università di Catania, Catania, Italy
[57a]INFN Sezione di Firenze, Firenze, Italy
[57b]Università di Firenze, Firenze, Italy
[58]INFN Laboratori Nazionali di Frascati, Frascati, Italy
[59]INFN Sezione di Genova, Genova, Italy
[60a]INFN Sezione di Milano-Bicocca, Milano, Italy
[60b]Università di Milano-Bicocca, Milano, Italy
[61a]INFN Sezione di Napoli, Napoli, Italy
[61b]Università di Napoli "Federico II", Napoli, Italy
[62a]INFN Sezione di Padova, Padova, Italy
[62b]Università di Padova, Padova, Italy
[62c]Università di Trento (Trento), Padova, Italy
[63a]INFN Sezione di Pavia, Pavia, Italy
[63b]Università di Pavia, Pavia, Italy
[64a]INFN Sezione di Perugia, Perugia, Italy
[64b]Università di Perugia, Perugia, Italy
[65a]INFN Sezione di Pisa, Pisa, Italy
[65b]Università di Pisa, Pisa, Italy
[65c]Scuola Normale Superiore di Pisa, Pisa, Italy
[66a]INFN Sezione di Roma, Roma, Italy
[66b]Università di Roma "La Sapienza", Roma, Italy
[67a]INFN Sezione di Torino, Torino, Italy
[67b]Università di Torino, Torino, Italy
[67c]Università del Piemonte Orientale (Novara), Torino, Italy
[68a]INFN Sezione di Trieste, Trieste, Italy
[68b]Università di Trieste, Trieste, Italy
[69]Kangwon National University, Chunchon, Korea
[70]Kyungpook National University, Daegu, Korea
[71]Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
[72]Konkuk University, Seoul, Korea
[73]Korea University, Seoul, Korea
[74]University of Seoul, Seoul, Korea
[75]Sungkyunkwan University, Suwon, Korea
[76]Vilnius University, Vilnius, Lithuania
[77]Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
[78]Universidad Iberoamericana, Mexico City, Mexico
[79]Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
[80]Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
[81]University of Auckland, Auckland, New Zealand
[82]University of Canterbury, Christchurch, New Zealand
[83]National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
[84]Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
[85]Soltan Institute for Nuclear Studies, Warsaw, Poland
[86]Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
[87]Joint Institute for Nuclear Research, Dubna, Russia
[88]Petersburg Nuclear Physics Institute, Gatchina (St Petersburg), Russia
[89]Institute for Nuclear Research, Moscow, Russia
[90]Institute for Theoretical and Experimental Physics, Moscow, Russia
[91]Moscow State University, Moscow, Russia
[92]P.N. Lebedev Physical Institute, Moscow, Russia
[93]State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia
[94]University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
[95]Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
[96]Universidad Autónoma de Madrid, Madrid, Spain
[97]Universidad de Oviedo, Oviedo, Spain
[98]Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
[99]CERN, European Organization for Nuclear Research, Geneva, Switzerland

[100]*Paul Scherrer Institut, Villigen, Switzerland*
[101]*Institute for Particle Physics, ETH Zurich, Zurich, Switzerland*
[102]*Universität Zürich, Zurich, Switzerland*
[103]*National Central University, Chung-Li, Taiwan*
[104]*National Taiwan University (NTU), Taipei, Taiwan*
[105]*Cukurova University, Adana, Turkey*
[106]*Middle East Technical University, Physics Department, Ankara, Turkey*
[107]*Bogazici University, Istanbul, Turkey*
[108]*Istanbul Technical University, Istanbul, Turkey*
[109]*National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine*
[110]*University of Bristol, Bristol, United Kingdom*
[111]*Rutherford Appleton Laboratory, Didcot, United Kingdom*
[112]*Imperial College, London, United Kingdom*
[113]*Brunel University, Uxbridge, United Kingdom*
[114]*Baylor University, Waco, USA*
[115]*The University of Alabama, Tuscaloosa, USA*
[116]*Boston University, Boston, USA*
[117]*Brown University, Providence, USA*
[118]*University of California, Davis, Davis, USA*
[119]*University of California, Los Angeles, Los Angeles, USA*
[120]*University of California, Riverside, Riverside, USA*
[121]*University of California, San Diego, La Jolla, USA*
[122]*University of California, Santa Barbara, Santa Barbara, USA*
[123]*California Institute of Technology, Pasadena, USA*
[124]*Carnegie Mellon University, Pittsburgh, USA*
[125]*University of Colorado at Boulder, Boulder, USA*
[126]*Cornell University, Ithaca, USA*
[127]*Fairfield University, Fairfield, USA*
[128]*Fermi National Accelerator Laboratory, Batavia, USA*
[129]*University of Florida, Gainesville, USA*
[130]*Florida International University, Miami, USA*
[131]*Florida State University, Tallahassee, USA*
[132]*Florida Institute of Technology, Melbourne, USA*
[133]*University of Illinois at Chicago (UIC), Chicago, USA*
[134]*The University of Iowa, Iowa City, USA*
[135]*Johns Hopkins University, Baltimore, USA*
[136]*The University of Kansas, Lawrence, USA*
[137]*Kansas State University, Manhattan, USA*
[138]*Lawrence Livermore National Laboratory, Livermore, USA*
[139]*University of Maryland, College Park, USA*
[140]*Massachusetts Institute of Technology, Cambridge, USA*
[141]*University of Minnesota, Minneapolis, USA*
[142]*University of Mississippi, University, USA*
[143]*University of Nebraska-Lincoln, Lincoln, USA*
[144]*State University of New York at Buffalo, Buffalo, USA*
[145]*Northeastern University, Boston, USA*
[146]*Northwestern University, Evanston, USA*
[147]*University of Notre Dame, Notre Dame, USA*
[148]*The Ohio State University, Columbus, USA*
[149]*Princeton University, Princeton, USA*
[150]*University of Puerto Rico, Mayaguez, USA*
[151]*Purdue University, West Lafayette, USA*
[152]*Purdue University Calumet, Hammond, USA*
[153]*Rice University, Houston, USA*
[154]*University of Rochester, Rochester, USA*
[155]*The Rockefeller University, New York, USA*
[156]*Rutgers, the State University of New Jersey, Piscataway, USA*
[157]*University of Tennessee, Knoxville, USA*
[158]*Texas A&M University, College Station, USA*
[159]*Texas Tech University, Lubbock, USA*
[160]*Vanderbilt University, Nashville, USA*

[161]University of Virginia, Charlottesville, USA
[162]Wayne State University, Detroit, USA
[163]University of Wisconsin, Madison, USA

[a]Deceased.
[b]Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
[c]Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia.
[d]Also at Universidade Federal do ABC, Santo Andre, Brazil.
[e]Also at California Institute of Technology, Pasadena, USA.
[f]Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France.
[g]Also at Suez Canal University, Suez, Egypt.
[h]Also at Cairo University, Cairo, Egypt.
[i]Also at British University, Cairo, Egypt.
[j]Also at Fayoum University, El-Fayoum, Egypt.
[k]Also at Soltan Institute for Nuclear Studies, Warsaw, Poland.
[l]Also at Université de Haute-Alsace, Mulhouse, France.
[m]Also at Moscow State University, Moscow, Russia.
[n]Also at Brandenburg University of Technology, Cottbus, Germany.
[o]Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
[p]Also at Eötvös Loránd University, Budapest, Hungary.
[q]Also at Tata Institute of Fundamental Research - HECR, Mumbai, India.
[r]Also at University of Visva-Bharati, Santiniketan, India.
[s]Also at Sharif University of Technology, Tehran, Iran.
[t]Also at Isfahan University of Technology, Isfahan, Iran.
[u]Also at Shiraz University, Shiraz, Iran.
[v]Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Teheran, Iran.
[w]Also at Facoltà Ingegneria Università di Roma, Roma, Italy.
[x]Also at Università della Basilicata, Potenza, Italy.
[y]Also at Università degli Studi Guglielmo Marconi, Roma, Italy.
[z]Also at Università degli studi di Siena, Siena, Italy.
[aa]Also at Faculty of Physics of University of Belgrade, Belgrade, Serbia.
[bb]Also at University of Florida, Gainesville, USA.
[cc]Also at University of California, Los Angeles, Los Angeles, USA.
[dd]Also at Scuola Normale e Sezione dell' INFN, Pisa, Italy.
[ee]Also at INFN Sezione di Roma, Università di Roma ''La Sapienza'', Roma, Italy.
[ff]Also at University of Athens, Athens, Greece.
[gg]Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
[hh]Also at The University of Kansas, Lawrence, USA.
[ii]Also at Paul Scherrer Institut, Villigen, Switzerland.
[jj]Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
[kk]Also at Gaziosmanpasa University, Tokat, Turkey.
[ll]Also at Adiyaman University, Adiyaman, Turkey.
[mm]Also at The University of Iowa, Iowa City, USA.
[nn]Also at Mersin University, Mersin, Turkey.
[oo]Also at Kafkas University, Kars, Turkey.
[pp]Also at Suleyman Demirel University, Isparta, Turkey.
[qq]Also at Ege University, Izmir, Turkey.
[rr]Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
[ss]Also at INFN Sezione di Perugia, Università di Perugia, Perugia, Italy.
[tt]Also at University of Sydney, Sydney, Australia.
[uu]Also at Utah Valley University, Orem, USA.
[vv]Also at Institute for Nuclear Research, Moscow, Russia.
[ww]Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
[xx]Also at Argonne National Laboratory, Argonne, USA.
[yy]Also at Erzincan University, Erzincan, Turkey.
[zz]Also at Kyungpook National University, Daegu, Korea.