

# Measurement of the inclusive Z cross section via decays to tau pairs in pp collisions at $\sqrt{s}=7$ TeV

## Journal Article

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# Measurement of the inclusive $Z$ cross section via decays to tau pairs in $pp$ collisions at $\sqrt{s} = 7$ TeV

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**The CMS collaboration**

**ABSTRACT:** The first measurement of inclusive  $Z \rightarrow \tau^+\tau^-$  production in  $pp$  collisions at the LHC is presented, in the final states  $\mu$ +hadrons,  $e$ +hadrons,  $e+\mu$ , and  $\mu+\mu$ . The data sample corresponds to an integrated luminosity of  $36 \text{ pb}^{-1}$  collected with the CMS detector. The measured cross section is  $\sigma(pp \rightarrow ZX) \times \mathcal{B}(Z \rightarrow \tau^+\tau^-) = 1.00 \pm 0.05 \text{ (stat.)} \pm 0.08 \text{ (syst.)} \pm 0.04 \text{ (lumi.) nb}$ , which is in good agreement with the next-to-next-to-leading order QCD prediction and improves on previous measurements in the  $Z \rightarrow e^+e^-$  and  $\mu^+\mu^-$  channels. The reconstruction efficiency for hadronic  $\tau$  decays is determined with a precision of 7%.

**KEYWORDS:** Hadron-Hadron Scattering

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**1 Introduction**

The measurement of the inclusive  $Z$  production cross section with  $Z \rightarrow \tau^+\tau^-$  constitutes an important physics benchmark at the Large Hadron Collider (LHC). The  $\tau$  lepton can decay either into purely leptonic final states ( $\tau \rightarrow e\bar{\nu}_e\nu_\tau$  denoted as “ $\tau_e$ ” or  $\tau \rightarrow \mu\bar{\nu}_\mu\nu_\tau$  denoted as “ $\tau_\mu$ ”) or into hadronic final states denoted by “ $\tau_{\text{had}}$ ” consisting of a hadronic system and a  $\nu_\tau$ . Constrained by the  $\tau$  mass, the hadronic system is characterized by a low particle multiplicity and a highly collimated jet which allows a  $\tau_{\text{had}}$  signal to be separated from the large QCD jet backgrounds. The validation of the  $\tau_{\text{had}}$  signal is essential in searches for new physics based on  $\tau$  leptons, such as Higgs boson decays to  $\tau^+\tau^-$  [1]. The Compact Muon Solenoid (CMS) Collaboration recently reported a search for the Higgs boson in this channel [2]. Tau leptons can also be important signatures for searches of supersymmetry, extra dimensions, and extra gauge bosons [3].

The  $Z \rightarrow \tau^+\tau^-$  production cross section has been previously measured in proton-antiproton collisions by the CDF and D0 Collaborations [4, 5]. In this study,  $Z \rightarrow \tau^+\tau^-$  events in the  $\tau_\mu\tau_{\text{had}}$ ,  $\tau_e\tau_{\text{had}}$ ,  $\tau_e\tau_\mu$ , and  $\tau_\mu\tau_\mu$  final states are selected from a sample of  $\sqrt{s} = 7$  TeV proton-proton collision data recorded by the CMS experiment at the LHC. The data sample corresponds to an integrated luminosity of  $36 \pm 1$  pb $^{-1}$ . Previous measurements of the  $Z$  production cross section have been made with lower statistics and higher luminosity uncertainty in the  $e^+e^-$  and  $\mu^+\mu^-$  final states [6, 7]. The results presented in this paper constitute the first measurement of the  $Z$  production cross section with the

full integrated luminosity collected in 2010 and the first step of a comprehensive set of measurements of the  $Z$  cross section, with all three lepton species. The measurement of the  $Z \rightarrow \tau^+\tau^-$  production cross section provides also a validation of  $\tau_{\text{had}}$  reconstruction and identification [8–10] and a direct measurement of the tau selection efficiency.

## 2 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 field volume are the silicon pixel and strip tracker, the crystal electromagnetic calorimeter (ECAL) and the brass/scintillator hadron calorimeter (HCAL). Muons are measured in gas-ionization detectors embedded in the steel return yoke.

CMS uses a right-handed coordinate system, with the origin at the nominal interaction point, the  $x$  axis pointing to the centre of the LHC, the  $y$  axis pointing up perpendicular to the LHC plane, and the  $z$  axis along the counterclockwise-beam direction. The polar angle  $\theta$  is measured from the positive  $z$  axis and the azimuthal angle  $\phi$  is measured in the  $xy$  plane. Variables used in this article are the pseudorapidity,  $\eta \equiv -\ln[\tan(\theta/2)]$ , and the transverse momentum,  $p_{\text{T}} = \sqrt{p_x^2 + p_y^2}$ .

The ECAL is designed to have both excellent energy resolution and high granularity, which are crucial for reconstructing electrons and photons produced in  $\tau$  decays. The ECAL is constructed with projective lead tungstate crystals in two pseudorapidity regions: the barrel ( $|\eta| < 1.479$ ) and the endcap ( $1.479 < |\eta| < 3$ ). The transition regions between the barrel and the endcaps,  $1.444 < |\eta| < 1.567$ , are not used for electron reconstruction. In the barrel region, the crystals are  $25.8 X_0$  long, where  $X_0$  is the radiation length, and conform to a granularity of  $\Delta\eta \times \Delta\phi = 0.0174 \times 0.0174$ . The endcap region is instrumented with a lead-silicon-strip preshower detector consisting of two orthogonal strip detectors with a strip pitch of 1.9 mm. One plane is at a depth of  $2X_0$  and the other at  $3X_0$ . The ECAL has an energy resolution of better than 0.5% for unconverted photons with transverse energies above 100 GeV. The energy resolution is 3% or better for the range of electron energies relevant for this analysis. The HCAL barrel and endcap regions cover the range  $|\eta| < 3$  and are subdivided into towers with a segmentation of  $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$ , corresponding to  $5 \times 5$  ECAL crystals in the barrel region. The HCAL forward region extends the calorimetry to  $|\eta| < 5$ .

The inner tracker measures charged particle tracks within the range  $|\eta| < 2.5$ . It consists of 1440 silicon pixel and 15148 silicon strip detector modules and provides an impact parameter resolution of  $\sim 15 \mu\text{m}$  and a transverse momentum resolution of about 1.5% for 100 GeV particles.

The muon barrel region is covered by drift tubes and the endcap regions by cathode strip chambers. In both regions resistive plate chambers provide additional coordinate and timing information. Muons can be reconstructed in the range  $|\eta| < 2.4$ , with a typical  $p_{\text{T}}$  resolution of 1% for  $p_{\text{T}} \approx 40$  GeV.

A more detailed description of CMS can be found in [11].

### 3 Lepton reconstruction and identification

Muons produced by  $\tau$  decays in the  $Z \rightarrow \tau^+\tau^-$  process are reconstructed in the tracker and muon chambers [12]. Quality cuts, based on the minimum number of hits in the silicon tracker, pixel detector, and muon chambers, are applied to suppress backgrounds from hadron punch-through and decay in flight.

Electrons are reconstructed by combining tracks produced by the Gaussian Sum Filter algorithm with ECAL clusters [13]. Requirements are imposed that distinguish prompt electrons from charged pions mimicking electron signatures, and from electrons produced by photon conversions.

The CMS particle flow (PF) algorithm [9] is used to form a mutually exclusive collection of reconstructed particles (muons, electrons, photons, and charged and neutral hadrons) by combining tracks and calorimeter clusters. These reconstructed particles are used to build composite objects such as  $\tau$ 's and jets, and to measure the missing transverse energy  $\cancel{E}_T$ .

Electrons and muons from  $\tau$  decays are expected to be isolated in the detector, while leptons from heavy-flavour (c and b) decays and decays in flight are expected to be found inside jets. A measure of isolation is used to discriminate the signal from the QCD multijet background, based on the charged hadrons, photons, and neutral hadrons falling within a cone  $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.4$  around the lepton momentum direction. In the  $\tau_\mu\tau_\mu$  final state, a cone of  $\Delta R = 0.3$  is used. A sum of the  $p_T$  for each particle type is made for charged hadrons with  $p_T > 0.5$  GeV and for photons and neutral hadrons with  $p_T > 1$  GeV; photons and neutral hadrons are excluded from the sum if they fall within inner cones of  $\Delta R = 0.05$  and  $\Delta R = 0.08$ , respectively. The relative isolation variable is  $I_{\text{rel}}^{\text{PF}} = \Sigma \left( p_T^{\text{charged}} + p_T^{\text{photon}} + p_T^{\text{neutral}} \right) / p_T^\ell$ , where  $p_T^{\text{charged}}$ ,  $p_T^{\text{photon}}$ , and  $p_T^{\text{neutral}}$  refer to the charged hadrons, photons, and neutral hadrons in the sum, respectively, and  $p_T^\ell$  refers to the  $p_T$  of the lepton  $\ell = e, \mu$ . For muons, it is required that  $I_{\text{rel}}^{\text{PF}} < 0.1$ , while for electrons it is required that  $I_{\text{rel}}^{\text{PF}} < 0.08$  in the barrel and  $I_{\text{rel}}^{\text{PF}} < 0.04$  in the endcaps. For the  $\tau_e\tau_\mu$  final state the isolation quantities are based directly on tracker and calorimeter information [7],  $I_{\text{rel}} = \Sigma (E_T(\text{ECAL}) + E_T(\text{HCAL}) + p_T(\text{tracks})) / p_T^\ell$ , calculated in a cone of  $\Delta R = 0.3$ . In this case, it is required that  $I_{\text{rel}} < 0.15$  for muons and  $I_{\text{rel}} < 0.1$  for electrons.

The  $\tau_{\text{had}}$  identification algorithm used in this measurement is known as the Hadrons Plus Strips algorithm [10]. The reconstruction starts with the clustering of all PF particles into jets with the anti- $k_t$  algorithm with a distance parameter  $R = 0.5$  [14]. For each jet, a charged hadron is combined with other nearby charged or neutral hadrons to reconstruct the decay modes, considering all possible combinations. The identification of  $\pi^0$  mesons is enhanced by clustering electrons and photons in "strips" along the bending plane to take into account possible broadening of calorimeter signatures by photon conversions. Then strips and charged hadrons are combined to reconstruct the combinations: single hadron, hadron plus a strip, hadron plus two strips and three hadrons. The hadron plus strip(s) decay modes require one charged hadron and one or two strips with a minimum  $E_T$  of 1 GeV. A constraint is applied on the strip mass to match the  $\pi^0$  mass and the invariant mass of the hadron plus strip(s) is calculated. This invariant mass should be compatible with the mass of the  $\rho(770)$  or  $a_1(1260)$  resonances. To reduce the contamination from

QCD jets, the  $\tau_{\text{had}}$ -candidate isolation is calculated in a cone of  $\Delta R = 0.5$  around the reconstructed  $\tau$ -momentum direction. It is requested that there be no charged hadrons with  $p_T > 1.0$  GeV and no photons with  $E_T > 1.5$  GeV in the isolation cone, other than the  $\tau$  constituents. The probability of a jet (electron) to be misidentified as a  $\tau_{\text{had}}$  is smaller than 2% (3%).

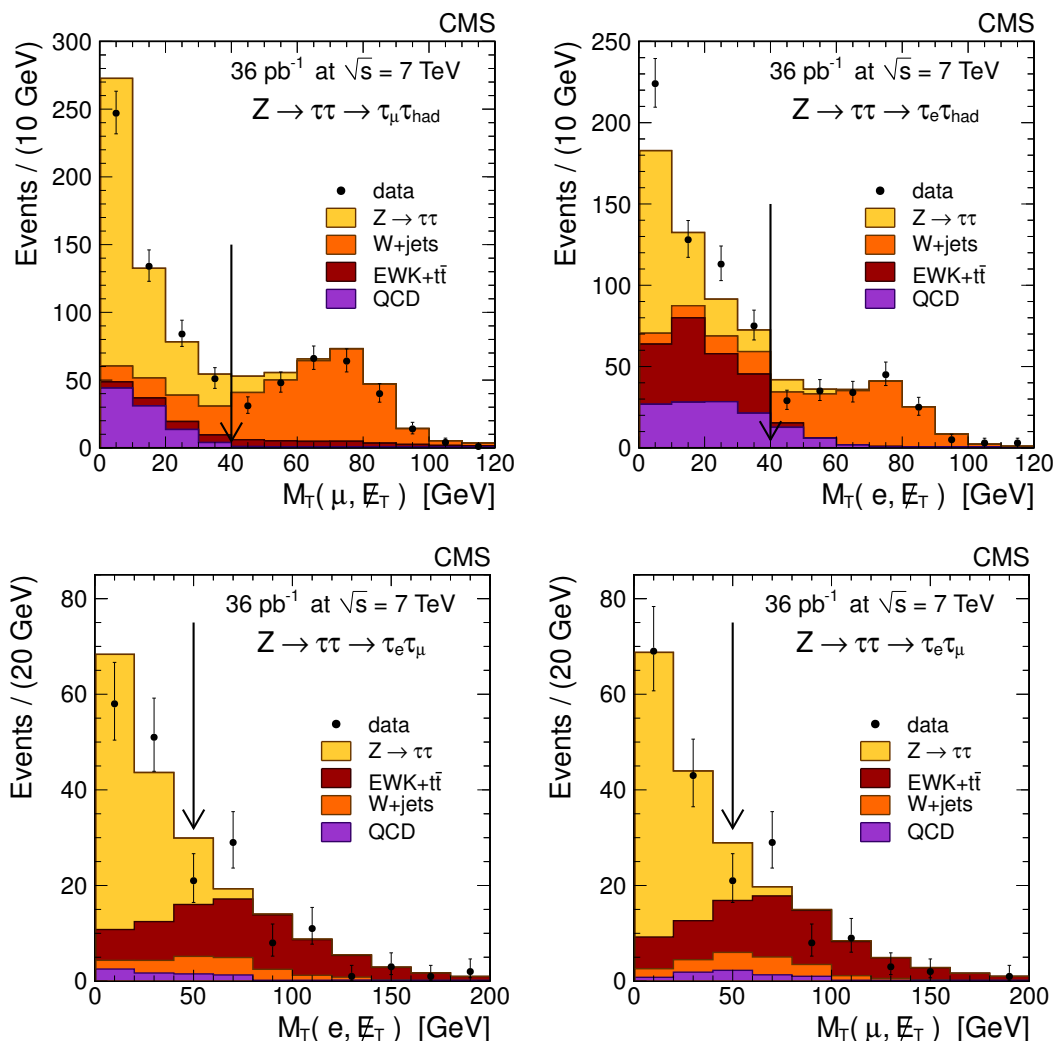
## 4 Event selection

The events preselected for this analysis in the  $\tau_\mu\tau_{\text{had}}$ ,  $\tau_e\tau_\mu$ , and  $\tau_\mu\tau_\mu$  final states are required to pass the single-muon Level-1 (L1) trigger with a  $p_T$  threshold of 7 GeV and the single muon High Level Trigger (HLT) [15], with a threshold varying from 9 GeV to 15 GeV, depending on the instantaneous luminosity. Events in the  $\tau_e\tau_{\text{had}}$  final state are selected using the single-electron L1 trigger with a threshold of 8 GeV in the transverse energy, and a single-electron HLT trigger with a threshold of 12 GeV at higher instantaneous luminosity. At the end of the 2010 data taking period, a combined  $e+\tau$  trigger was used to maintain efficiency as the instantaneous luminosity increased. The trigger has the same L1 requirements as the electron trigger, but the HLT requires the presence of an electron of transverse energy larger than 12 GeV and a hadronic tau decay with  $p_T$  larger than 15 GeV, tagged with a simplified version of the tau reconstruction algorithm with a less restrictive selection than the one used in the offline analysis. The tau reconstruction at HLT is performed using PF objects. Jets are reconstructed with an iterative cone algorithm and tracking is performed only for jets with  $E_T$  above 8 GeV. All charged particles are treated as pions, e.g. no muon or electron identification was applied. It is required that there is at least one track of  $p_T > 1$  GeV in a cone of radius 0.2 and no additional charged hadrons (tracks) with  $p_T$  above 1.5 GeV in a cone of  $\Delta R = 0.4$ . The efficiency of the L1+HLT to trigger on  $\tau$  leptons is measured from data and is found to be  $\approx 93\%$  for a  $\tau_{\text{had}}$  identified by the full offline algorithm with a reconstructed  $p_T$  above 15 GeV.

Offline event selection starts with the requirement of a well-defined primary vertex [16]. For the  $\tau_\mu\tau_{\text{had}}$  and  $\tau_e\tau_{\text{had}}$  final states, one isolated muon or electron is required with  $p_T > 15$  GeV and  $|\eta| < 2.1$ . The associated  $\tau_{\text{had}}$  must be oppositely charged, with  $p_T > 20$  GeV and  $|\eta| < 2.3$ . In order to reject events coming from the W+jets background, the transverse mass of the lepton and the  $\cancel{E}_T$ ,  $M_T(\ell, \cancel{E}_T) = \sqrt{2p_T^\ell \cancel{E}_T \cdot (1 - \cos \Delta\phi)}$ , is required to be less than 40 GeV, where  $\Delta\phi$  is the difference in azimuthal angle between the lepton and  $\cancel{E}_T$  vectors. The  $M_T$  distribution and the selection requirement applied are illustrated in figure 1 for the  $\tau_\mu\tau_{\text{had}}$ ,  $\tau_e\tau_{\text{had}}$  and  $\tau_e\tau_\mu$  final states.

For the  $\tau_e\tau_\mu$  final state, one isolated muon with  $|\eta| < 2.1$  and one oppositely charged isolated electron with  $|\eta| < 2.4$  are required, both with  $p_T > 15$  GeV. Further background suppression is achieved by requiring  $M_T(\mu, \cancel{E}_T) < 50$  GeV and  $M_T(e, \cancel{E}_T) < 50$  GeV.

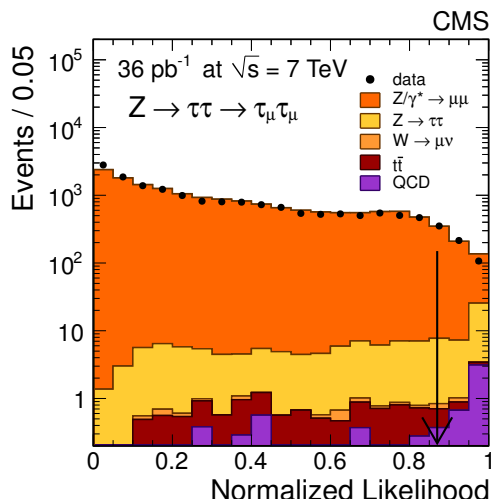
For the  $\tau_\mu\tau_\mu$  final state, events with two oppositely charged isolated muons with  $|\eta| < 2.1$  are selected if one satisfies  $p_T > 19$  GeV and the other  $p_T > 10$  GeV. The requirement  $\cancel{E}_T < 50$  GeV suppresses  $t\bar{t}$  and W+jets backgrounds, and a requirement on the azimuthal angle difference between the muons,  $\Delta\phi_{\mu\mu} > 2$ , rejects QCD background events, for muons originating from the same quarkonia decay or from a decay chain of heavy-flavour hadrons.



**Figure 1.** Lepton+ $\cancel{E}_T$  transverse mass for the final states  $\tau_\mu\tau_{\text{had}}$  (top left),  $\tau_e\tau_{\text{had}}$  (top right) and  $\tau_e\tau_\mu$  (bottom). The arrow shows the final selection criteria applied.

Effective suppression of the Drell-Yan background is achieved with a multivariate likelihood ratio technique. For each event, the relative probabilities to belong to two event classes ( $Z \rightarrow \tau^+\tau^- \rightarrow \tau_\mu\tau_\mu$  and  $Z/\gamma^* \rightarrow \mu^+\mu^-$ ) are computed, exploiting the following set of discriminating variables: the ratio of the transverse momentum of the dimuon system to the scalar sum of the momenta of the two muons; the significance of the distance of closest approach (DCA) between the two muon helix tracks; the pseudorapidity of the dimuon system; and the azimuthal angle between the positive muon momentum and  $\cancel{E}_T$ . A normalized likelihood discriminant is computed and is shown in figure 2. Events with a likelihood discriminant value larger than 0.87 are kept in the final sample.

For the plots in figures 1 and 2, the QCD multijet, W and diboson backgrounds were simulated with PYTHIA [17], the Drell-Yan signal and background with the next-to-leading order (NLO) Monte Carlo generator POWHEG [18–20], and the top samples



**Figure 2.** Likelihood discriminant for the  $\tau_\mu\tau_\mu$  final state. The arrow shows the final selection criterion applied.

with Madgraph [21]. The tau decays were performed with Tauola [22]. The samples were normalized using the cross section at next-to-next-to-leading order (NNLO) for Drell-Yan and W, at leading order (LO) for QCD, and NLO for the  $t\bar{t}$  sample. The EWK label in the figure refers to the  $Z \rightarrow e^+e^-, \mu^+\mu^-$ , and diboson backgrounds.

## 5 Background estimation

The  $Z \rightarrow \tau^+\tau^-$  signal is established using the visible mass, which is the reconstructed mass of the  $\ell\tau_{\text{had}}$  system in the  $\tau_\ell\tau_{\text{had}}$  final states, and the dilepton invariant mass for the  $\tau_e\tau_\mu$  and  $\tau_\mu\tau_\mu$  final states. Due to the presence of neutrinos in the final state, the  $Z \rightarrow \tau^+\tau^-$  visible mass peak extends across the range 30–100 GeV, which is considerably broader than the Z resonance itself. The backgrounds generally span the same mass range, so an accurate determination of the signal yield requires effective background estimation techniques. The main background sources are QCD multijet processes, W+jets, and  $Z \rightarrow \ell^+\ell^-$ , with small contributions from top-quark decays and dibosons. All backgrounds are measured in control regions where their contributions are enhanced and extrapolated to the signal selection region using selection efficiencies determined either from data or the Monte Carlo simulation. In the  $\tau_\ell\tau_{\text{had}}$  final state, the QCD multijet background is estimated using samples of same-sign (SS) and opposite-sign (OS) events from data, for which the electron or muon isolation requirement is inverted; the QCD background estimate is based on the ratio of OS to SS yields. The visible mass distribution of the SS events is used to describe the background in the signal region. The W contribution is extracted from the region  $M_T(\ell, \cancel{E}_T) > 60 \text{ GeV}$ , where it dominates the sample. In the  $\tau_e\tau_\mu$  final state, the background contributions are expected to be small and are estimated from the simulation. The large-transverse-mass region is used to check the estimated background contributions from W, diboson, and  $t\bar{t}$  backgrounds. For the  $\tau_\mu\tau_\mu$  final state, the Drell-Yan muon-pair



	$\tau_\mu\tau_{\text{had}}$	$\tau_e\tau_{\text{had}}$	$\tau_e\tau_\mu$	$\tau_\mu\tau_\mu$ ( $M_{\mu\mu} < 70 \text{ GeV}$ )
$Z \rightarrow \ell^+\ell^-$ , jet misidentified as $\tau$	$6.4 \pm 2.4$	$15.0 \pm 6.2$	-	
$Z \rightarrow \ell^+\ell^-$ , lepton misidentified as $\tau$	$12.9 \pm 3.5$	$109 \pm 28$	$2.4 \pm 0.3$	$20.1 \pm 1.3$
$t\bar{t}$	$6.0 \pm 3.0$	$2.6 \pm 1.3$	$7.1 \pm 1.3$	$0.15 \pm 0.03$
$W \rightarrow \ell\nu$	$54.9 \pm 4.8$	$30.6 \pm 3.1$	$1.5 \pm 0.5$	$2.5 \pm 2.5$
$W \rightarrow \tau\nu$	$14.7 \pm 1.3$	$7.0 \pm 0.7$		
QCD multijet	$132 \pm 14$	$181 \pm 23$		
WW/WZ/ZZ	$1.6 \pm 0.8$	$0.8 \pm 0.4$	$3.0 \pm 0.4$	-
Total background	$228 \pm 16$	$346 \pm 37$	$14.0 \pm 1.8$	$22.8 \pm 2.8$
Total data	517	540	101	58

**Table 1.** Numbers of expected background events and number of data events passing all the selection criteria in the four final states. The uncertainties shown include the statistical and systematic uncertainties added in quadrature.

production events are selected with a reduced likelihood without including the muon DCA significance, and the resulting muon DCA significance distribution is fitted with signal and background shapes. The QCD multijet background estimate is obtained from a sample of SS dimuon events.

The numbers of selected events and the expected background contributions are summarized in table 1. The statistical and systematic uncertainties in the methods used are also given, where the uncertainties are added in quadrature. The uncertainty is dominated by the statistical precision of the data samples used to obtain the estimates of the number of background events.

## 6 Systematic uncertainties

The efficiencies for electron and muon reconstruction, identification, and isolation, as well as the trigger efficiencies are obtained from data. Correction factors for the values extracted from the simulation are determined using the method described in ref. [7] (*tag-and-probe* method). The measured efficiencies have a small dependence on  $p_T$  and cover the full range of  $p_T$  used in the analysis. Typical Monte Carlo to data correction factors for muon (electron) trigger and reconstruction efficiencies are 0.97 (1.01) and 1.01 (0.98) respectively. The uncertainties on the correction factors are in the range of 0.2–1.1%.

A similar technique is used to estimate the hadronic tau identification efficiency. A data sample of taus is selected using  $Z \rightarrow \tau^+\tau^- \rightarrow \tau_\mu\tau_{\text{had}}$  events. The events are preselected without applying the full tau identification but only kinematic cuts and a set of requirements to suppress the background from  $Z \rightarrow \mu^+\mu^-$ , W, and QCD events. The efficiency is then calculated as a ratio of the number of events that pass the tau identification requirement to the number of all preselected events. The total uncertainty of the measurement arises from the statistical uncertainty of the sample and the systematic uncertainties

related to the understanding of the backgrounds in the preselection sample and amounts to 23% [10].

To estimate the efficiency of the  $M_T$  selection and the likelihood selection efficiency for the  $\tau_\mu\tau_\mu$  final state, an embedded sample is used where the muons in a  $Z \rightarrow \mu^+\mu^-$  data sample are replaced by simulated tau decays with the original muon momentum. The estimated uncertainties amount to 2%, which comes from the statistical precision of the selected  $Z \rightarrow \mu^+\mu^-$  data and the difference seen between the efficiency obtained with the embedded sample and a genuine  $Z \rightarrow \tau^+\tau^-$  MC sample.

To estimate the effect of the energy-scale uncertainties on the acceptance, the energies of all reconstructed objects (electrons, muons, taus, and jets) are varied within their respective uncertainty. After each independent shift, the missing transverse energy is recalculated and the event selection is repeated. The event yield is compared to the nominal value and the relative difference is quoted as the systematic uncertainty. The systematic uncertainties are in the range from 1% to 3.5%.

To obtain the acceptance corrections, the D6T and Z2 PYTHIA tunes [23] were used in the simulation. The effect of the use of different tunes on the final extracted cross section is smaller than 1% and is not included in the systematic uncertainties.

The numbers of background events from various sources have been estimated from data and are given in table 1. The uncertainties are dominated by the statistical precision of the data samples used in the estimation.

The luminosity has been measured with an uncertainty of 4% [24].

The main source of theoretical uncertainty in the calculation of the experimental acceptance comes from the parton distribution functions (PDFs). The central acceptance value is obtained with the CT10 PDF [25]. The uncertainty is estimated using the error sets of the PDFs: CT10, MSTW2008NLO [26], and NNPDF2.0 [27], following the PDF4LHC prescription [28], and amounts to 2%.

The experimental and theoretical uncertainties are summarized in table 2.

## 7 Cross section measurement

The cross section is obtained for each final state with the following formula:

$$\sigma(\text{pp} \rightarrow ZX) \times \mathcal{B}(Z \rightarrow \tau^+\tau^-) = \frac{N}{\mathcal{A} \epsilon \mathcal{B}' \mathcal{L}} \quad , \quad (7.1)$$

where  $N$  is the number of extracted signal events,  $\mathcal{A}$  is the acceptance of signal events,  $\epsilon$  is the signal selection efficiency,  $\mathcal{B}'$  is the branching fraction of the  $\tau$ -decay mode considered [29], and  $\mathcal{L}$  is the integrated luminosity [24].

The visible mass distributions of the  $\tau_\mu\tau_{\text{had}}$ ,  $\tau_e\tau_{\text{had}}$ ,  $\tau_e\tau_\mu$  and  $\tau_\mu\tau_\mu$  final states are shown in figure 3. To estimate the number of signal events, a fit is performed using the visible mass shapes from the simulation, except for the QCD multijet and  $Z \rightarrow \ell^+\ell^-$  backgrounds, which are obtained from data. For the simulation shapes, a variation of the electron and tau energy scales within their uncertainties is considered. The effect of the muon energy scale is negligible. The background normalizations correspond to the numbers listed in

Source	$\tau_\mu\tau_{\text{had}}$	$\tau_e\tau_{\text{had}}$	$\tau_e\tau_\mu$	$\tau_\mu\tau_\mu$
Trigger	0.2%	3%	0.2%	0.3%
Lepton identification and isolation	1.0%	1.1%	1%	1%
$\tau_{\text{had}}$ identification	23%		-	
Efficiency of $M_T$ selection	2%		-	
Likelihood selection efficiency	-			2%
Acceptance due to $\tau_{\text{had}}$ energy scale, 3%	3.5%		-	
Acceptance due to e energy scale, 2%	-	1.6%	1.6%	-
Acceptance due to $\mu$ momentum scale, 1%	1%	-	1%	2%
Luminosity	4%			
Parton distribution functions	2%			

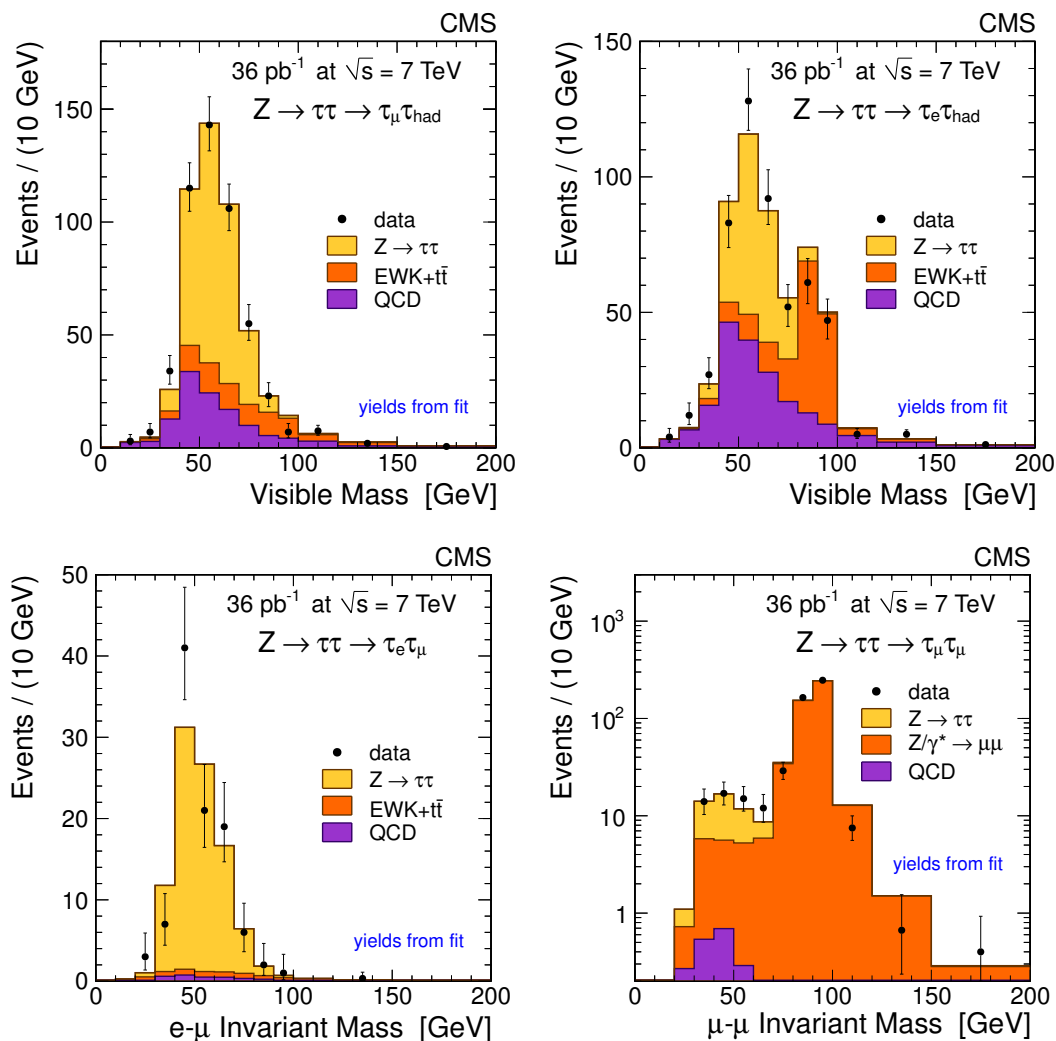
**Table 2.** Summary of the sources of systematic uncertainties and their estimated effect on the measured  $Z \rightarrow \tau^+\tau^-$  cross section.

	$\tau_\mu\tau_{\text{had}}$	$\tau_e\tau_{\text{had}}$	$\tau_e\tau_\mu$	$\tau_\mu\tau_\mu$
Acceptance $\mathcal{A}$	0.128	0.116	0.074	0.163
Selection efficiency $\epsilon$	0.35	0.22	0.55	0.173
Mass window correction $f_{\text{out}}$	0.03	0.03	0.02	0.01
$N_{\text{fit}}$	306	205	90.5	35
Integrated luminosity $\mathcal{L}$ ( $\text{pb}^{-1}$ )	35.7	35.7	35.5	35.7

**Table 3.** Acceptance, selection efficiency, fraction of selected events outside the generator-level mass window, number of extracted signal events from the fit and integrated luminosity, for the four final states considered.

table 1 and are allowed to vary within the estimated uncertainties. The background yields and signal shapes shown in figure 3 are those obtained from the fitting procedure.

The acceptances were obtained with the NLO QCD program POWHEG in the  $Z \rightarrow \tau^+\tau^-$  mass region  $60 < M_{\tau^+\tau^-} < 120$  GeV. For the acceptance calculation, events with an electron or muon with  $p_T > 15$  GeV and  $|\eta| < 2.1$  and a visible  $\tau_{\text{had}}$   $p_T > 20$  GeV and  $|\eta| < 2.3$  are used in the  $\tau_e\tau_{\text{had}}$  and  $\tau_\mu\tau_{\text{had}}$  final states. For the  $\tau_e\tau_\mu$  final state, events with an electron with  $p_T > 15$  GeV and  $|\eta| < 2.3$  and a muon with  $p_T > 15$  GeV and  $|\eta| < 2.1$  are used. For the  $\tau_\mu\tau_\mu$  final state, events are requested to have two muons of  $p_T > 19$  GeV and  $p_T > 10$  GeV with  $|\eta| < 2.1$ . The momentum and  $\eta$  are taken for muons and electrons after final state radiation. Table 3 shows the acceptances and the selection efficiencies for the different final states considered. The number of extracted events from the fit,  $N_{\text{fit}}$ , is corrected for the fraction of signal events outside the generator-level mass window,  $f_{\text{out}}$ , where  $N = N_{\text{fit}} \cdot (1 - f_{\text{out}})$  in eq. 7.1. The number of extracted events and correction factors used are also shown in table 3.



**Figure 3.** Visible mass distributions of the  $\tau_\mu\tau_{\text{had}}$  (top left),  $\tau_e\tau_{\text{had}}$  (top right),  $\tau_e\tau_\mu$  (bottom left), and  $\tau_\mu\tau_\mu$  (bottom right) final states.

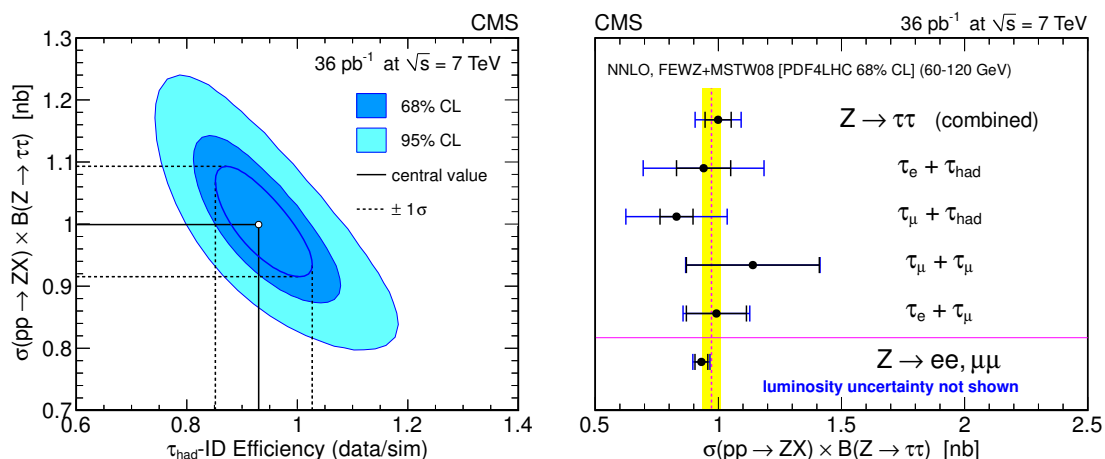
The measured values of the cross section from the four final states considered are shown in table 4, where the uncertainties shown are due to statistical, systematic, integrated luminosity and  $\tau$  identification uncertainties.

The measured values are compatible with each other and with the NNLO theoretical prediction, obtained with the program FEWZ and the MSTW08 set of PDFs,  $0.972 \pm 0.042$  nb [30]. They are also consistent with the CMS measurement based on  $Z \rightarrow e^+e^-$ ,  $\mu^+\mu^-$  events [7].

The dominant uncertainty on the  $Z \rightarrow \tau^+\tau^-$  cross section measurement comes from the  $\tau_{\text{had}}$  reconstruction and identification efficiency. A simultaneous fit to all four final states is performed to obtain the cross section and a scale factor for the  $\tau_{\text{had}}$  efficiency, which is the ratio of the efficiency in the data to that in the simulation. The result of the global fit is shown in figure 4 (left), where the likelihood contours for the best estimates

Final state	$\sigma(\text{pp} \rightarrow ZX) \times \mathcal{B}(Z \rightarrow \tau^+\tau^-)$ nb	stat.	syst.	lumi.	$\tau_{\text{had}} - \text{ID}$
$\tau_\mu\tau_{\text{had}}$	0.83	0.07	0.04	0.03	0.19
$\tau_e\tau_{\text{had}}$	0.94	0.11	0.03	0.04	0.22
$\tau_e\tau_\mu$	0.99	0.12	0.06	0.04	
$\tau_\mu\tau_\mu$	1.14	0.27	0.04	0.05	

**Table 4.** The measured values of the cross section from the four final states considered. The statistical, systematic and luminosity uncertainties are given. The uncertainty associated to the  $\tau_{\text{had}}$  reconstruction and identification efficiency,  $\tau_{\text{had}} - \text{ID}$ , is shown separately.



**Figure 4.** Likelihood contours for the joint parameter estimation of the cross section and the  $\tau$ -identification (left). The fitted central values (solid line) and their estimated  $1\sigma$  uncertainties (dashed lines) are also shown. Summary of the measured  $Z \rightarrow \tau^+\tau^-$  cross sections in the  $\tau_\mu\tau_{\text{had}}$ ,  $\tau_e\tau_{\text{had}}$ ,  $\tau_e\tau_\mu$ , and  $\tau_\mu\tau_\mu$  final states, in the invariant mass range of  $60 < M_{\tau^+\tau^-} < 120$  GeV (right). The inner error bar represents the statistical uncertainty. The extracted cross section from the combined fit and the NNLO theoretical prediction are also shown.

of the cross section and the  $\tau_{\text{had}}$  efficiency scale factor are shown. In addition to the one-standard-deviation contour, the contours for which the likelihood  $L$  is reduced by  $2\Delta \ln L = 2.30$  and  $6.18$  compared to the maximum value are also shown, corresponding to a coverage of 68% and 95% in the two-parameter plane, respectively. The value of the cross section extracted from the fit is

$$\sigma(\text{pp} \rightarrow ZX) \times \mathcal{B}(Z \rightarrow \tau^+\tau^-) = 1.00 \pm 0.05 (\text{stat.}) \pm 0.08 (\text{syst.}) \pm 0.04 (\text{lumi.}) \text{ nb},$$

which is compared to the individual final state measurements in figure 4 (right). The value for the cross section is dominated by the dilepton final states which have smaller systematic uncertainties. In the simultaneous fit, the  $\tau_{\text{had}} - \text{ID}$  scale factor is measured to be  $0.93 \pm 0.09$ .

A more precise value of the hadronic tau reconstruction efficiency can be obtained by performing a fit of the  $\tau_\mu\tau_{\text{had}}$  and  $\tau_e\tau_{\text{had}}$  final states, where the cross section is fixed to the value measured by CMS in the electron and muon decay channels,  $\sigma(\text{pp} \rightarrow ZX) \times \mathcal{B}(Z \rightarrow e^+e^-, \mu^+\mu^-) = 0.931 \pm 0.026 (\text{stat.}) \pm 0.023 (\text{syst.}) \pm 0.102 (\text{lumi.}) \text{ nb}$  [7]. The

extracted value of the  $\tau_{\text{had-ID}}$  scale factor is  $0.96 \pm 0.07$ , which corresponds to a tau identification efficiency of  $(47.4 \pm 3.3)\%$  in data, for hadronically decaying tau leptons in the  $Z \rightarrow \tau^+\tau^-$  sample with visible  $p_T > 20$  GeV within the detector acceptance.

## 8 Conclusions

A measurement of the cross section for the process  $pp \rightarrow ZX$  with  $Z \rightarrow \tau^+\tau^-$  has been performed, based on the  $\tau_\mu\tau_{\text{had}}$ ,  $\tau_e\tau_{\text{had}}$ ,  $\tau_e\tau_\mu$ , and  $\tau_\mu\tau_\mu$  final states. A clear signal is established in the visible mass distributions for all channels. The measured cross section,  $\sigma(pp \rightarrow ZX) \times \mathcal{B}(Z \rightarrow \tau^+\tau^-) = 1.00 \pm 0.05$  (stat.)  $\pm 0.08$  (syst.)  $\pm 0.04$  (lumi.) nb, is consistent with theoretical expectations, and the CMS measurements in the  $Z \rightarrow e^+e^-$  and  $\mu^+\mu^-$  decay channels, made with lower integrated luminosity. A global fit of the  $\tau_\mu\tau_{\text{had}}$  and  $\tau_e\tau_{\text{had}}$  channels provides a 7% constraint on the efficiency for reconstructing hadronic tau decays in CMS. The results presented in this paper constitute the first measurement of the Z production cross section with the full luminosity collected by CMS in 2010.

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