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Measurement of the $t\bar{t}$ production cross section in the dilepton channel in pp collisions at $\sqrt{s} = 8$ TeV

The CMS Collaboration*

Abstract

The top-antitop quark ($t\bar{t}$) production cross section is measured in proton-proton collisions at $\sqrt{s} = 8$ TeV with the CMS experiment at the LHC, using a data sample corresponding to an integrated luminosity of 5.3 fb^{-1}. The measurement is performed by analysing events with a pair of electrons or muons, or one electron and one muon, and at least two jets, one of which is identified as originating from hadronisation of a bottom quark. The measured cross section is $239 \pm 2\,(\text{stat.}) \pm 11\,(\text{syst.}) \pm 6\,(\text{lum.})$ pb, for an assumed top-quark mass of 172.5 GeV, in agreement with the prediction of the standard model.

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*See Appendix A for the list of collaboration members

1 Introduction

A precise measurement of the $t\bar{t}$ production cross section can be used to test the theory of quantum chromodynamics (QCD) at next-to-next-to-leading-order (NNLO) level. It can be also used in global fits of the parton distribution functions (PDF) at NNLO, and allows an estimation of $\alpha_s(M_Z)$ as described in [1, 2]. Furthermore, top-quark production is an important source of background in many searches for physics beyond the standard model (SM). A large sample of top-quark events has been collected at the Large Hadron Collider (LHC), and studies of top-quark production have been conducted in various decay channels as well as searches for deviations from the SM predictions [3–9].

This paper presents a measurement of the $t\bar{t}$ production cross section, $\sigma_{t\bar{t}}$, based on the dilepton channel (e^+e^-, $\mu^+\mu^-$, and $e^\pm\mu^\mp$) in a data sample of proton-proton collisions at $\sqrt{s} = 8$ TeV corresponding to an integrated luminosity of 5.3 fb^{-1} recorded by the Compact Muon Solenoid (CMS) experiment. In the SM, top quarks are predominantly produced in $t\bar{t}$ pairs via the strong interaction and decay almost exclusively to a W boson and a bottom quark. We measure the $t\bar{t}$ production cross section selecting final states that contain two leptons of opposite electric charge, momentum imbalance associated to the neutrinos from the W boson decays, and two jets of particles resulting from the hadronisation of two b quarks.

2 The CMS detector and simulation

The CMS detector [10] has a superconducting solenoid occupying the central region that provides an axial magnetic field of 3.8 T. The silicon pixel and the strip tracker cover $0 < \phi < 2\pi$ in azimuth and $|\eta| < 2.5$ in pseudorapidity, where η is defined as $\eta = -\ln[\tan(\theta/2)]$, with θ being the polar angle measured with respect to the anticlockwise-beam direction. The lead-tungstate crystal electromagnetic calorimeter and the brass/scintillator hadron calorimeter are located inside the solenoid. Muons are measured in gas-ionisation detectors embedded in the steel flux return yoke outside the solenoid. The detector is nearly hermetic, thereby providing reliable measurement of momentum imbalance in the plane transverse to the beams. A two-tier trigger system selects the most interesting pp collisions for offline analysis.

Several MC event generators are used to simulate signal and background events: MADGRAPH (v. 5.1.4.8) [11], POWHEG (r1380) [12] and PYTHIA (v. 6.424) [13], depending on the process considered. The MADGRAPH generator with spin correlations is used to model $t\bar{t}$ events with a top-quark mass of 172.5 GeV and combined with PYTHIA to simulate parton showering, hadronisation, and the underlying event. The MADGRAPH generator is also used to simulate the W+jets and Drell–Yan (DY) processes. Single-top-quark events are simulated using POWHEG. Inclusive production of the WZ and ZZ diboson final states is simulated with PYTHIA. Production of WW fully leptonic final states is simulated with MADGRAPH. Decays of τ leptons are handled with TAUOLA (v. 2.75) [14]. The contributions from WW, WZ and ZZ (referred to as "VV") and single-top-quark production are taken from MC simulations with appropriate next-to-leading order (NLO) cross sections. All other backgrounds are estimated from control samples extracted from collision data.

The $t\bar{t}$ production cross section amounts to $\sigma_{t\bar{t}} = 252.9^{+6.4}_{-8.6}\,(\text{scale}) \pm 11.7\,(\text{PDF} + \alpha_s)$ pb as calculated with the TOP++ program [15] at NNLO in perturbative QCD, including soft-gluon resummation at next-to-next-to-leading-log order [16], and assuming a top-quark mass $m_t = 172.5$ GeV. The first uncertainty comes from the independent variation of the factorisation and renormalisation scales, μ_F and μ_R, while the second one is associated to variations in the PDF and α_s following the PDF4LHC prescriptions [17]. Expected signal yields in figures and tables are normalised to that value unless otherwise stated.

The simulated samples include additional interactions per bunch crossing (pileup), with the distribution matching that observed in data.

3 Event selection

Event selection is similar to that used for the measurement of the $\mathrm{t\bar{t}}$ dilepton cross section at $\sqrt{s} = 7\,\mathrm{TeV}$ [4]. At trigger level, events are required to have two electrons, two muons, or one electron and one muon, where one of these leptons has transverse momentum $p_{\mathrm{T}} > 17\,\mathrm{GeV}$ and the other has $p_{\mathrm{T}} > 8\,\mathrm{GeV}$. Events are then selected with two oppositely charged leptons reconstructed with the CMS particle-flow (PF) algorithm [18], both with $p_{\mathrm{T}} > 20\,\mathrm{GeV}$ and $|\eta| < 2.5$ for electrons and $|\eta| < 2.1$ for muons. In events with more than one pair of leptons passing these selections, the pair of opposite-sign leptons with the largest value of total transverse momentum is selected. Events with τ leptons contribute to the measurement only if they decay to electrons or muons that satisfy the selection requirements. The efficiency for dilepton triggers is measured in data through triggers based on transverse momentum imbalance. The trigger efficiency is approximately 90% to 93% for the three final states. Using the measured dilepton trigger efficiency in data, the corresponding efficiencies in the simulation are corrected by p_{T} and η multiplicative data-to-simulation scale factors (SFs), which have an average value of 0.96 and uncertainties in the range 1 to 2%.

Charged-lepton candidates from W-boson decays are usually isolated from other particles in the event. For each electron or muon candidate, a cone of $\Delta R < 0.3$ is constructed around the track direction at the event vertex, where ΔR is defined as $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, and $\Delta\eta$ and $\Delta\phi$ are the differences in pseudorapidity and azimuthal angle between any energy deposit and the axis of the lepton track. The scalar sum of the p_{T} of all particles reconstructed with the PF algorithm, consistent with the chosen primary vertex and contained within the cone, is calculated, excluding the contribution from the lepton candidate itself. The relative isolation discriminant, I_{rel}, is defined as the ratio of this sum to the p_{T} of the lepton candidate. The neutral component is corrected for pileup based on the average energy density deposited by neutral particles in the event: an average transverse energy due to pileup is determined event by event and is subtracted from the transverse energy in the isolation cone. A lepton candidate is rejected if $I_{\mathrm{rel}} > 0.15$. The efficiency of the lepton selection is measured using a "tag-and-probe" method in dilepton events enriched in Z-boson candidates, as described in [4, 19]. The measured values for the combined identification and isolation efficiencies are typically of 96% for muons and 90% for electrons. Based on a comparison of lepton selection efficiencies in data and simulation, the event yield in simulation is corrected by p_{T}-and η-dependent SFs, which have an average value of 0.99 and uncertainties in the range 1 to 2% to provide consistency with data. Considering also the dilepton trigger, the combined factors have an average value of 0.96 and uncertainties around 2% for the three $\mathrm{t\bar{t}}$ final states.

Dilepton candidate events with an invariant mass $M_{\ell\ell} < 20\,\mathrm{GeV}$ ($\ell = \mathrm{e}$ or μ) are removed to suppress backgrounds from heavy-flavour resonances, as well as contributions from low-mass DY processes. Events with dilepton invariant masses within $\pm 15\,\mathrm{GeV}$ of the Z mass are also rejected in the same-flavour channels.

Jets are reconstructed from the PF particle candidates using the anti-k_{T} clustering algorithm [20] with a distance parameter of 0.5. The jet energy is corrected for pileup in a manner similar to the correction of the energy inside the lepton isolation cone. Jet energy corrections are also applied as a function of the jet p_{T} and η [21]. Events are required to have at least two reconstructed jets with $p_T > 30\,\text{GeV}$ and $|\eta| < 2.5$.

The missing transverse energy, E_T^{miss}, is defined as the magnitude of the momentum imbalance, which is the negative sum of the momenta of all reconstructed particles in the plane transverse to the beams. A value of $E_T^{miss} > 40\,\text{GeV}$ is required in the e^+e^- and $\mu^+\mu^-$ channels while no E_T^{miss} requirement is imposed for the $e^\pm\mu^\mp$ mode, as there is very little contamination from DY events in this channel.

Since $t\bar{t}$ events contain jets from hadronisation of b quarks, requiring their presence can reduce background from events without b quarks. Jets are identified as b jets using the combined secondary vertex algorithm (CSV) [22]. The operating point chosen for CSV corresponds to an identification efficiency of about 85% and a misidentification (mistag) probability of about 10% [23] for light-flavour jets (u, d, s and gluons). The selection requires the presence of at least one b jet in the event.

Figure 1 shows the p_T distributions of the highest-p_T lepton and jet after jet multiplicity selection, for all three final states combined. In this and the following figures the signal yields refer to an assumed top-quark mass of 172.5 GeV. The hatched regions correspond to the total statistical uncertainties in the predicted event yields. The ratio of the data to the sum of simulations and data-based predictions for the signal and backgrounds is shown in the bottom panels. A detailed description of the different background estimates is given in section 4. The multiplicities of selected jets and b jets are shown in figure 2 for the $e^\pm\mu^\mp$ channel, which is expected to have less background contamination. A similar level of agreement is obtained with the e^+e^- and $\mu^+\mu^-$ channels.

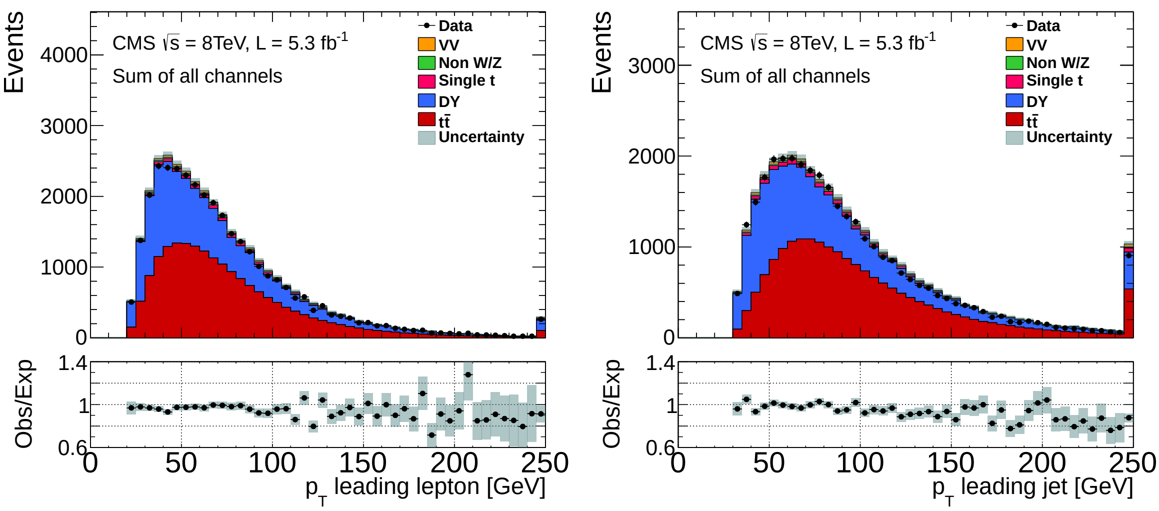

Figure 1: The p_T distributions of the highest-p_T lepton (left) and jet (right) after the jet multiplicity selection, for all three final states. The expected distributions for $t\bar{t}$ signal and individual backgrounds are shown after data-based corrections are applied; the last bin contains the overflow events. The hatched bands correspond to the total statistical uncertainty in the event yields for the sum of the $t\bar{t}$ and background predictions. The ratios of data to the sum of the expected yields are given at the bottom.

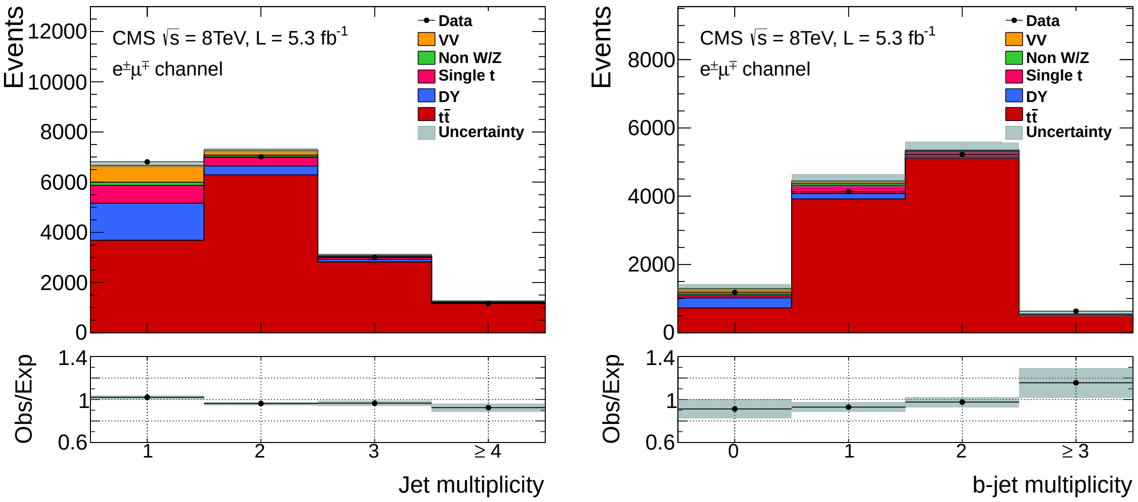

Figure 2: Jet multiplicity (left) in events passing the dilepton criteria, and (right) b-jet multiplicity in events passing the full event selections but before the b-jet requirement, for the $e^{\pm}\mu^{\mp}$ channel. In the right figure, the hatched bands show the total statistical and b-jet systematic uncertainties in the event yields for the sum of the $t\bar{t}$ and background predictions. The hatched bands in the left figure show only the total statistical uncertainty on the predicted event yields. The ratios of data to the sum of the expected yields are given at the bottom.

4 Background determination

Backgrounds in this analysis arise from single-top-quark, DY and VV events, in which at least two prompt leptons are produced from Z or W decays. Other background sources, such as $t\bar{t}$ or W+jets events with decays into lepton+jets and where at least one jet is incorrectly reconstructed as a lepton (which mainly happens for electrons) or a lepton from the decay of bottom or charm hadrons (which mainly happens for muons), are grouped into the non-W/Z lepton category. Background yields from single-top-quark and VV events are estimated from simulation, while all other backgrounds are estimated from data.

The DY background is estimated using the "$R_{\text{out/in}}$" method [3, 4, 24] in which the events outside of the Z mass window are obtained by normalising the event yield from simulation to the observed number of events inside the Z mass window. The data-to-simulation scale factor is found to be 1.3 ± 0.4 for the $e^{\pm}\mu^{\mp}$ channel. This value is compatible with 1.5 ± 0.5, which is estimated using a template fit as described in [4]. For the $e^{+}e^{-}$ and $\mu^{+}\mu^{-}$ channels the factors are found to be 1.7 ± 0.5 and 1.6 ± 0.5, respectively.

Non-prompt leptons can arise from decays of mesons or heavy-flavour quarks, jet misidentification, photon conversions, or finite resolution detector effects whereas prompt leptons usually originate from decays of W or Z bosons and are isolated and well identified. Backgrounds with non-prompt leptons are estimated [25] from a control sample of collision data in which leptons are selected with relaxed identification and isolation requirements defining the loose lepton candidate, while the set of signal selection cuts described in section 3 defines the tight lepton candidate. The prompt and non-prompt lepton ratios are defined as the ratio of the number of tight candidates to the number of loose ones as measured from samples enriched in leptonic decays of Z bosons or in QCD dijet events, respectively. These ratios, parametrized as a function of p_T and η of the lepton, are then used to weight the events in the loose-loose dilepton sample, to obtain the estimated contribution from the non-prompt lepton background in the signal region. The systematic uncertainty comes from the jet p_T spectrum in dijet events and amounts, together with the statistical one, to 40% of the estimated yield.

5 Sources of systematic uncertainty

Simulated events are scaled according to the lepton efficiency correction factors, which are typically close to one, measured using control samples in data, leading to a 1 to 2% uncertainty in the $t\bar{t}$ selection efficiency.

The impact of uncertainty in the jet energy scale (JES) and jet energy resolution (JER) are estimated from the change observed in the number of selected MC $t\bar{t}$ events after varying the jet momenta within the JES uncertainties [21], and in the case of JER by an η-dependent correction with an average of $\pm 10\%$. For the e^+e^- and $\mu^+\mu^-$ channels these uncertainties are also propagated to $\not\!\!E_T$ resulting in a larger uncertainty than for the $e^\pm\mu^\mp$ channel.

The uncertainties on the b jet scale factors in $t\bar{t}$ signal events are approximately 2% for b jets and 10% for mistagged jets [22, 23], depending on the p_T of the jets. They are propagated to the $t\bar{t}$ selection efficiency in simulated events.

The uncertainty assigned to the pileup simulation amounts to 0.8%, as obtained by varying the inelastic cross section by 5%. The uncertainty in the integrated luminosity is 2.6% [26].

The systematic effects related to the missing higher-order diagrams in MADGRAPH are estimated with two different methods. The uncertainty in the signal acceptance is determined by varying the renormalisation and factorisation scales simultaneously up and down by a factor of two using MADGRAPH, and the uncertainty is taken as the maximum difference after the final event selection. The effect on the calculated $t\bar{t}$ production cross section is 2.3%, which is the value used in the analysis for this uncertainty. This estimate is cross-checked by comparing the predictions of the leading-order and NLO generators MADGRAPH and POWHEG, where both use PYTHIA for hadronisation and extra radiation. The systematic uncertainty is found to be 2.2%, comparable with the above estimate.

The matching between the matrix elements (ME) and the parton shower (PS) evolution is done by applying the MLM prescription [27]. Changing the thresholds that control the matching of partons from the matrix element with those from PS by factors of 0.5 and 2.0 for one of the parameters (minimum k_T measure between partons) and 0.75 and 1.5 for the other (jet matching threshold for the k_T-MLM scheme) compared to the default thresholds, produces a 1.6% variation in the $t\bar{t}$ event selection efficiency.

The uncertainty arising from the hadronisation model affects mainly the JES and the fragmentation of b jets. As the b-jet efficiencies and mistagging rates are taken from data, no additional uncertainty is expected from this source. The uncertainty in the JES already contains a contribution from the uncertainty in the hadronisation. The hadronisation uncertainty is also determined by comparing samples of events generated with POWHEG where the hadronisation is modelled with PYTHIA or HERWIG, and the effect on the calculated $t\bar{t}$ cross section is 1.4%, which is well within the JES uncertainty.

Uncertainties in the selected number of single-top-quark and VV events are calculated following the same prescription as for the signal yield. In addition, an uncertainty in the cross sections for single-top-quark and VV backgrounds, taken from measurements and estimated to be approximately 20% [28–36], is added in quadrature.

Table 1 summarizes the magnitude of the systematic uncertainties on the $t\bar{t}$ production cross section from the different sources.

Table 1: Summary of the individual contributions to the systematic uncertainty on the $\sigma_{t\bar{t}}$ measurement. The uncertainties are given in pb. The statistical uncertainty on the result is given for comparison.

Source	e^+e^-	$\mu^+\mu^-$	$e^\pm\mu^\mp$
Trigger efficiencies	4.1	3.0	3.6
Lepton efficiencies	5.8	5.6	4.0
Lepton energy scale	0.6	0.3	0.2
Jet energy scale	10.3	10.8	5.2
Jet energy resolution	3.2	4.0	3.0
b-jet tagging	1.9	1.9	1.7
Pileup	1.7	1.5	2.0
Scale (μ_F and μ_R)	5.7	5.5	5.6
Matching partons to showers	3.9	3.8	3.8
Single top quark	2.6	2.4	2.3
VV	0.7	0.7	0.5
Drell–Yan	10.8	10.3	1.5
Non-W/Z leptons	0.9	3.2	1.9
Total systematic	18.6	18.6	11.4
Integrated luminosity	6.4	6.1	6.2
Statistical	5.2	4.5	2.6

6 Results

The $t\bar{t}$ production cross section is measured by counting events after applying the selection criteria described in section 3. Table 2 shows the total number of events observed in data and the number of signal and background events expected from simulation or estimates from data. Table 3 lists the mean acceptance (which contains contributions from $W \to \tau\nu_\tau$, with leptonic τ decays) multiplied by the selection efficiency and the branching fraction in the dilepton final state, and the measured cross section for each of the three final states, e^+e^-, $\mu^+\mu^-$, and $e^\pm\mu^\mp$, which give compatible results. The e^+e^- and $\mu^+\mu^-$ channels have two additional sources of uncertainty, arising from the DY background estimation and from the propagation of the JES to the $E\!\!\!/_T$ estimation, which limit the precision of the measurement of $\sigma_{t\bar{t}}$ in those final states.

A combination of the three final states using the BLUE method [37] yields a measured cross section of $\sigma_{t\bar{t}} = 239.0 \pm 2.1\,(\text{stat.}) \pm 11.3\,(\text{syst.}) \pm 6.2\,(\text{lum.})$ pb for a top-quark mass of 172.5 GeV. In the combination, the systematic uncertainties are 100% correlated across channels, except those associated to the lepton efficiencies, which have a correlation coefficient of 0.64 for e^+e^- with $e^\pm\mu^\mp$ and 0.55 for $\mu^+\mu^-$ with $e^\pm\mu^\mp$. Finally, the uncertainties associated with the data-based estimates and the statistical uncertainties are taken as uncorrelated.

In this analysis the dependence of the acceptance on the top-quark mass is found to be quadratic within the present uncertainty of the top-quark mass [38]. The cross-section dependence in the range 160–185 GeV can be parametrized as

$$\sigma_{t\bar{t}}/\sigma_{t\bar{t}}\,(m_t = 172.5) = 1.00 - 0.009 \times (m_t - 172.5) - 0.000168 \times (m_t - 172.5)^2 \qquad (1)$$

where m_t is given in GeV. Assuming a top-quark mass value of 173.2 GeV [38], a cross section value $\sigma_{t\bar{t}} = 237.5 \pm 13.1$ pb is obtained.

Figure 3 shows the distributions of $M_{\ell\ell}$, $\not\!\!E_T$ and the difference of the azimuthal angle between the two selected leptons ($\Delta\phi_{\ell\ell}$) and their ratios to expectations for the $e^{\pm}\mu^{\mp}$ channel, which dominates the combination.

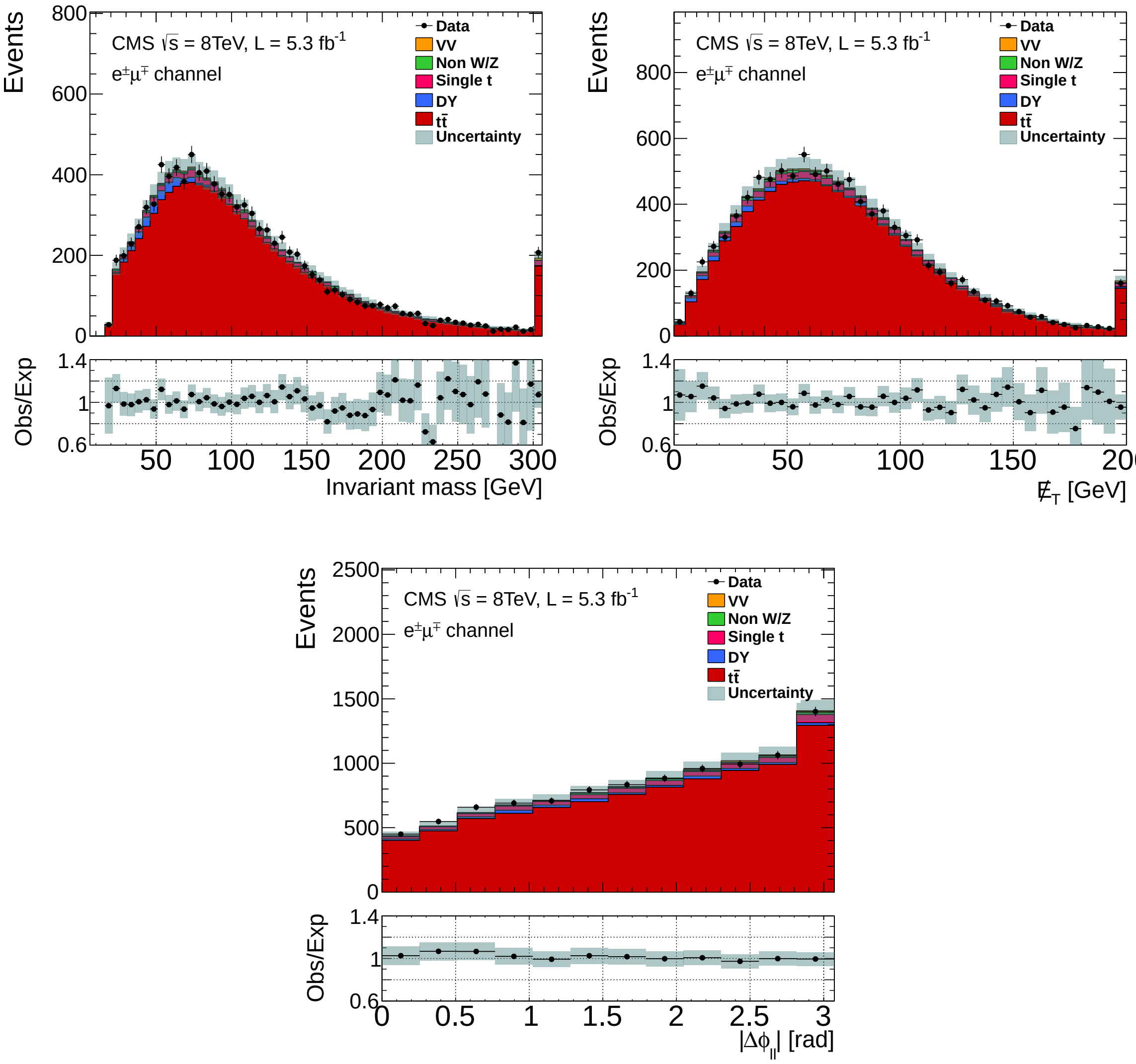

Figure 3: Distributions of (upper left) the dilepton invariant-mass, (upper right) the $\not\!\!E_T$, and (lower) the difference of the azimuthal angle between the two selected leptons, after the b-jet multiplicity selection and for the $e^{\pm}\mu^{\mp}$ channel. For the first two plots the last bin contains the overflow events. The expected distributions for $t\bar{t}$ signal, in this case, are normalised to the measured $t\bar{t}$ cross section. The hatched bands correspond to the total uncertainty in the predicted event yields for the sum of the $t\bar{t}$ and background predictions. The ratios of data to the sum of the expected yields are given at the bottom.

7 Summary

A measurement of the $t\bar{t}$ production cross section in proton-proton collisions at $\sqrt{s} = 8$ TeV is presented for events containing a lepton pair (e^+e^-, $\mu^+\mu^-$, $e^{\pm}\mu^{\mp}$), at least two jets with at least one tagged as b jet, and a large imbalance in transverse momentum in the final state. The measurement is obtained through an event-counting analysis based on a data sample corresponding to 5.3 fb^{-1}. The result obtained by combining the three final states is $\sigma_{t\bar{t}} = 239 \pm 2\,(\text{stat.}) \pm 11\,(\text{syst.}) \pm 6\,(\text{lum.})$ pb, in agreement with the prediction of the standard model for a top-quark mass of 172.5 GeV.

Table 2: Number of dilepton events after applying the event selection and requiring at least one b jet. The results are given for the individual sources of background, $t\bar{t}$ signal with a top-quark mass of 172.5 GeV and $\sigma_{t\bar{t}} = 252.9$ pb, and data. The uncertainties correspond to the statistical and systematic components added in quadrature.

	Number of events		
Source	e^+e^-	$\mu^+\mu^-$	$e^\pm\mu^\mp$
Drell–Yan	386±116	492±148	194±58
Non-W/Z leptons	25±10	114±46	185±72
Single top quark	127±28	157±34	413±88
VV	30±8	39±10	94±21
Total background	569±120	802±159	886±130
$t\bar{t}$ dilepton signal	2728±182	3630±250	9624±504
Data	3204	4180	9982

Table 3: The total efficiencies ϵ_{total}, i.e. the products of event acceptance, selection efficiency and branching fraction for the respective $t\bar{t}$ final states, as estimated from simulation for a top-quark mass of 172.5 GeV, and the measured $t\bar{t}$ production cross sections, where the uncertainties are from statistical, systematic and integrated luminosity components, respectively.

	e^+e^-	$\mu^+\mu^-$	$e^\pm\mu^\mp$
ϵ_{total} (%)	0.203 ± 0.012	0.270 ± 0.017	0.717 ± 0.033
$\sigma_{t\bar{t}}$ (pb)	244.3 ± 5.2 ± 18.6 ± 6.4	235.3 ± 4.5 ± 18.6 ± 6.1	239.0 ± 2.6 ± 11.4 ± 6.2

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