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Measurements of the $\mathrm{t\bar{t}}$ production cross section in lepton+jets final states in pp collisions at 8 TeV and ratio of 8 to 7 TeV cross sections

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Abstract

A measurement of the top quark pair production ($\mathrm{t\bar{t}}$) cross section in proton-proton collisions at the centre-of-mass energy of 8 TeV is presented using data collected with the CMS detector at the LHC, corresponding to an integrated luminosity of 19.6 fb^{-1}. This analysis is performed in the $\mathrm{t\bar{t}}$ decay channels with one isolated, high transverse momentum electron or muon and at least four jets, at least one of which is required to be identified as originating from hadronization of a b quark. The calibration of the jet energy scale and the efficiency of b jet identification are determined from data. The measured $\mathrm{t\bar{t}}$ cross section is $228.5 \pm 3.8\,(\mathrm{stat}) \pm 13.7\,(\mathrm{syst}) \pm 6.0\,(\mathrm{lumi})$ pb. This measurement is compared with an analysis of 7 TeV data, corresponding to an integrated luminosity of 5.0 fb^{-1}, to determine the ratio of 8 TeV to 7 TeV cross sections, which is found to be $1.43 \pm 0.04\,(\mathrm{stat}) \pm 0.07\,(\mathrm{syst}) \pm 0.05\,(\mathrm{lumi})$. The measurements are in agreement with QCD predictions up to next-to-next-to-leading order.

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1 Introduction

Top quarks are abundantly produced at the CERN LHC. The predicted top quark pair production cross section ($\sigma_{t\bar{t}}$) in proton-proton (pp) collisions, at a centre-of-mass energy of 8 TeV, is 253 pb, with theoretical uncertainties at the level of 5–6%. A precise measurement of $\sigma_{t\bar{t}}$ is therefore an important test of perturbative quantum chromodynamics (QCD) at high energies. Furthermore, precision $t\bar{t}$ cross section measurements can be used to constrain the top quark mass m_t and QCD parameters, such as the strong coupling constant α_S [1], or the parton distribution functions (PDF) of the proton [2].

The $t\bar{t}$ production cross section was measured at the LHC at $\sqrt{s} = 7$ and 8 TeV [3–17]. In this paper, a measurement of the $t\bar{t}$ production cross section in the channel with one high transverse momentum lepton (muon or electron) and jets is presented using the 2012 data set at $\sqrt{s} = 8$ TeV, collected by the CMS experiment at the LHC and corresponding to an integrated luminosity of 19.6 fb^{-1}. To measure the cross section ratio, where several systematic uncertainties cancel, the 2011 data set at $\sqrt{s} = 7$ TeV, corresponding to an integrated luminosity of 5.0 fb^{-1}, has been concurrently analyzed with a similar strategy to the one developed for the cross section measurement at 8 TeV. The new measurement agrees very well with the previously published CMS result [4]. The larger statistical uncertainty of the present measurement with respect to the previous one is due to the simultaneous determination of the b tagging efficiency, as discussed in Section 6.

In the standard model, top quarks are predominantly produced in pairs via the strong interaction and decay almost exclusively into a W boson and a b quark. The event signature is determined by the subsequent decays of the two W bosons. This analysis uses $t\bar{t}$ semileptonic decays into muons or electrons, where one of the W bosons decays into two quarks and the other to a charged lepton and a neutrino. The W boson decays into tau leptons are not specifically selected. The top quark decaying into a b quark and a leptonically decaying W boson is defined in the following as the "leptonic top quark", while the other top quark is referred to as "hadronic". For the $t\bar{t}$ signal two of the four jets result from the hadronization of the b and $\bar{b}$ quarks (b jets), thus b tagging algorithms are employed for the identification of b jets in order to improve the purity of the $t\bar{t}$ candidate sample.

The technique for extracting the $t\bar{t}$ cross section consists of a binned log-likelihood fit of signal and background to the distribution of a discriminant variable in data showing a good separation between signal and background: the invariant mass of the b jet of the leptonic top quark and the lepton ($M_{\ell b}$). The mass of the three-jet combination with the highest transverse momentum in the event (M_3) is used as a discriminant in an alternative analysis. The $M_{\ell b}$ variable is related to the leptonic top quark mass, while M_3 is a measure for the hadronic top quark mass. These quantities provide a good separation between signal and background processes.

The analysis employs calibration techniques to reduce the experimental uncertainties related to b tagging efficiencies and jet energy scale (JES). The $t\bar{t}$ topology is reconstructed using a jet sorting algorithm in which the b jet originating from the leptonic top quark is identified. The b tagging efficiency is then determined from a b-enriched sample, in the mass region of the leptonic top quark, correcting for the contamination from non-b jets [18, 19]. The rate of jets that are wrongly tagged as originating from a b quark is also measured using data [20]. Independently, the JES is determined from the hadronically decaying W boson in the event by correcting the reconstructed mass of the W boson in the simulation to that determined from the data.

The results of the cross section measurements are given both for the visible region, i.e. for the phase space corresponding to the event selection, and for the full phase space. The visible region is defined by requiring the presence in the simulation of exactly one charged lepton, one neutrino, and at least four jets within the selection criteria, as presented in Section 5.

This paper is structured as follows: after a description of the CMS detector (see Section 2), the data and the simulated samples are discussed in Section 3, while Section 4 is dedicated to the event selection. The analysis technique and the impact of the systematic uncertainties are addressed in Section 5 and in Section 6. The results of the cross section measurements are discussed in Section 7. Section 8 describes the alternative analysis based on M_3, followed by a summary in Section 9.

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid, of 6 m internal diameter, providing an axial magnetic field of 3.8 T. Within the solenoidal field volume are a silicon pixel and strip tracker, which measures charged particle trajectories in the pseudorapidity range $|\eta| < 2.5$. Also within the field volume, the silicon detectors are surrounded by a lead tungstate crystal electromagnetic calorimeter ($|\eta| < 3.0$) and a brass and scintillator hadron calorimeter ($|\eta| < 5.0$) that provide high-resolution energy and direction measurements of electrons and hadronic jets. Muons are measured in gas-ionization detectors embedded in the steel magnetic flux-return yoke outside the solenoid. The muon detection systems provide muon detection in the range $|\eta| < 2.4$. A two-level trigger system selects the pp collision events for use in physics analysis. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found elsewhere [21].

3 Data and simulation

The cross section measurement is performed using the 8 TeV pp collisions recorded by the CMS experiment in 2012, corresponding to an integrated luminosity of $19.6 \pm 0.5\,\mathrm{fb}^{-1}$ [22], and the 2011 data set at $\sqrt{s} = 7\,\mathrm{TeV}$, corresponding to an integrated luminosity of $5.0 \pm 0.2\,\mathrm{fb}^{-1}$ [23].

The $\mathrm{t\bar{t}}$ events are simulated using the Monte Carlo (MC) event generators MADGRAPH (version 5.1.1.0) [24, 25] and POWHEG (v1.0 r1380) [26, 27]. In MADGRAPH the top quark pairs are generated at leading order (LO) with up to three additional high-p_{T} jets. The POWHEG generator implements matrix elements to next-to-leading order (NLO) in perturbative QCD, with up to one additional jet. The mass of the top quark is set to 172.5 GeV. The PYTHIA (v.6.426) [28] and HERWIG (v.6.520) [29] generators are used to model the parton showering. The PYTHIA shower matching is done using the MLM prescription [30, 31].

The top quark pair production cross section values are predicted to be $177.3^{+4.6}_{-6.0}$ (scale) $\pm$ 9.0 (PDF+α_S) pb at 7 TeV and $252.9^{+6.4}_{-8.6}$ (scale) $\pm$ 11.7 (PDF+α_S) pb at 8 TeV, as calculated with the TOP++ 2.0 program to next-to-next-to-leading order (NNLO) in perturbative QCD, including soft-gluon resummation to next-to-next-to-leading logarithmic (NNLL) order (Ref. [32] and references therein), and assuming $m_{\mathrm{t}} = 172.5\,\mathrm{GeV}$. The first uncertainty comes from the independent variation of the factorization and renormalization scales, while the second one is associated to variations in the PDF and α_S following the PDF4LHC prescription with the MSTW2008 68% confidence level NNLO, CT10 NNLO, and NNPDF2.3 5f FFN PDF sets (Refs. [33, 34] and references therein, and Refs. [35, 36]).

The top quark transverse momentum is reweighted in samples simulated with MADGRAPH and POWHEG, when interfaced to PYTHIA, in order to better describe the p_T distribution observed in the data. Based on a study of differential distributions [37, 38] in the top quark transverse momentum, an event weight $w = \sqrt{w_1 \cdot w_2}$ is applied, where the weights w_i of the two top quarks are given as a function of the generated top quark p_T values: $w_i = \exp(0.199 - 0.00166\, p_T^i/\text{GeV})$ at 7 TeV, and $w_i = \exp(0.156 - 0.00137\, p_T^i/\text{GeV})$ at 8 TeV. This reweighting is only applied to the phase space corresponding to the experimental selection.

The W/Z+jets events, i.e. the associated production of W/Z vector bosons with jets, with leptonic decays of the W/Z bosons, constitute the largest background. These are also simulated using MADGRAPH with matrix elements corresponding to at least one jet and up to four jets. The W/Z+jets events are generated inclusively with respect to the jet flavour. Drell–Yan production of charged leptons is generated for dilepton invariant masses above 50 GeV, as those events constitute the relevant background in the phase space of this analysis. The contribution from Drell-Yan events with dilepton invariant masses between 10 and 50 GeV is negligible. Single top quark production is simulated with POWHEG. The background processes are normalized to NLO and NNLO cross section calculations [39–43], with the exception of the QCD multijet background, for which the normalization is obtained from data in the M_3 analysis (see Section 8). In the $M_{\ell b}$ analysis the multijet background is reduced to a negligible fraction (see Section 4) and thus not considered further.

Pileup signals, i.e. extra activity due to additional pp interactions in the same bunch crossing, are incorporated by simulating additional interactions with a multiplicity matching the one inferred from data. The CMS detector response is modeled using GEANT4 [44]. The simulated events are processed by the same reconstruction software as the collision data.

4 Reconstruction and event selection

This analysis focuses on the selection of $t\bar{t}$ semileptonic decays in the muon and electron channels, with similar selection requirements applied for the two channels. Muons, electrons, photons, and neutral and charged hadrons are reconstructed and identified by the CMS particle-flow (PF) algorithm [45, 46]. The energy of muons is obtained from the corresponding track momentum using the combined information of the silicon tracker and the muon system [47]. The energy of electrons is determined from a combination of the track momentum at the primary collision vertex, the corresponding cluster energy in the electromagnetic calorimeter, and the energy sum of all bremsstrahlung photons associated to the track [48]. The vertex with the largest p_T^2 sum of the tracks associated to it is chosen as primary vertex.

Candidate $t\bar{t}$ events are first accepted by dedicated triggers requiring at least one muon or electron. Lepton isolation requirements are applied to improve the purity of the selected sample. At the trigger level the relative muon isolation, the sum of transverse momenta of other particles in a cone of size $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} < 0.4$ around the direction of the candidate muon divided by the muon transverse momentum, is required to be less than 0.2. Similarly, for electrons, the corresponding requirement is less than 0.3 in a cone of size 0.3. Events with a muon in the final state are triggered on the presence of a muon candidate with $p_T > 24$ GeV and $|\eta| < 2.1$. Events with an electron candidate with $|\eta| < 2.5$ are accepted by triggers requiring an electron with $p_T > 27$ GeV.

Tighter p_T requirements are applied in the offline selections. Muons are required to have a good quality [47] track with $p_T > 25$ GeV and $|\eta| < 2.1$. Electrons are identified using a combination of the shower shape information and track-electromagnetic cluster matching [48], and are required to have $p_T > 32\,\mathrm{GeV}$ and $|\eta| < 2.5$, with the exclusion of the transition region between the barrel and endcap electromagnetic calorimeter, $1.44 < |\eta| < 1.57$. Electrons coming from photon conversions are vetoed. Correction factors for trigger and lepton identification efficiencies have been determined with a tag-and-probe method [49] from data/simulation comparison as a function of the lepton p_T and η, and are applied to the simulation.

Signal events are required to have at least one good pp interaction vertex [50] and exactly one muon or electron with an origin consistent with the reconstructed vertex. Since the lepton from the W boson decay is expected to be isolated from other activity in the event, isolation requirements are applied. A relative isolation is defined as $I_{rel} = (I_{charged} + I_{photon} + I_{neutral})/p_T$, where p_T is the transverse momentum of the lepton and $I_{charged}$, I_{photon}, and $I_{neutral}$ are the sums of the transverse energies of the charged particles, the photons, and the neutral particles not identified as photons, in a cone $\Delta R < 0.4$ (0.3) for muons (electrons) around the lepton direction, excluding the lepton itself. The relative isolation I_{rel} is required to be less than 0.12 for muons and 0.10 for electrons. Events with more than one muon or electron candidate with relaxed requirements are vetoed in order to reject Z boson or $t\bar{t}$ decays into dileptons.

The missing energy in the transverse plane (E_T^{miss}) is defined as the magnitude of the projection on the plane perpendicular to the beams of the vector sum of the momenta of all PF candidates. It is required to be larger than 30 GeV in the muon channel and larger than 40 GeV in the electron channel, because of the larger multijet background.

Jets are clustered from the charged and neutral particles reconstructed with the PF algorithm, using the anti-k_T jet algorithm [51] with a distance parameter of 0.5. Particles identified as isolated muons and electrons are not used in the jet clustering. Jet energies are corrected for nonlinearities due to different responses in the calorimeters and for the differences between measured and simulated responses [52]. Furthermore, to account for extra activity within a jet cone due to pileup, jet energies are corrected [45, 46] for charged hadrons that belong to a vertex other than the signal primary vertex, and for the amount of pileup expected in the jet area from neutral jet constituents.

An additional global calibration factor of the jet energy scale is obtained by fitting the W boson mass distribution in the data and in the simulation. The scale factor is determined as the ratio of the W boson mass reconstructed from non-b-tagged jet pairs in data and in the simulation. This scale correction is applied in the simulation to all jets before the selection requirements are implemented. It largely reduces the systematic uncertainty related to the jet energy scale, discussed in Section 6.

At least four jets are required with $p_T > 40\,\mathrm{GeV}$ and $|\eta| < 2.5$. To reduce contamination from background processes, at least one of the jets has to be identified as a b jet. The b tagging algorithm used is the "combined secondary vertex" (CSV) algorithm at the medium working point [18, 19], corresponding to an efficiency of about 1% for light jets (mistag rate) and an efficiency for b jets in the range 60–70% depending on the jet p_T and pseudorapidity. Figure 1 shows kinematic distributions after applying the b tagging requirement. Good agreement between data and simulation is observed.

The $M_{\ell b}$ analysis uses control samples in data for the estimation of the b tagging efficiency, as described in Refs. [18–20]. Among the four leading jets, three are assigned to the hadronically decaying top quark through a χ^2 sorting algorithm using top quark and W boson mass constraints. The remaining fourth jet is the b jet candidate assigned to the leptonically decaying top quark. The b tagging algorithm is only applied to this b jet candidate.

Owing to differences in the triggers and in the centre-of-mass energies, in the 7 TeV analysis slightly different selection criteria are applied on the charged-lepton p_T and E_T^{miss}. The muon transverse momentum is required to be larger than 26 GeV, while the electron p_T has to be larger than 30 GeV. No explicit E_T^{miss} requirement is needed in the muon channel. Events with $E_T^{miss} > 30$ GeV are selected in the electron channel.

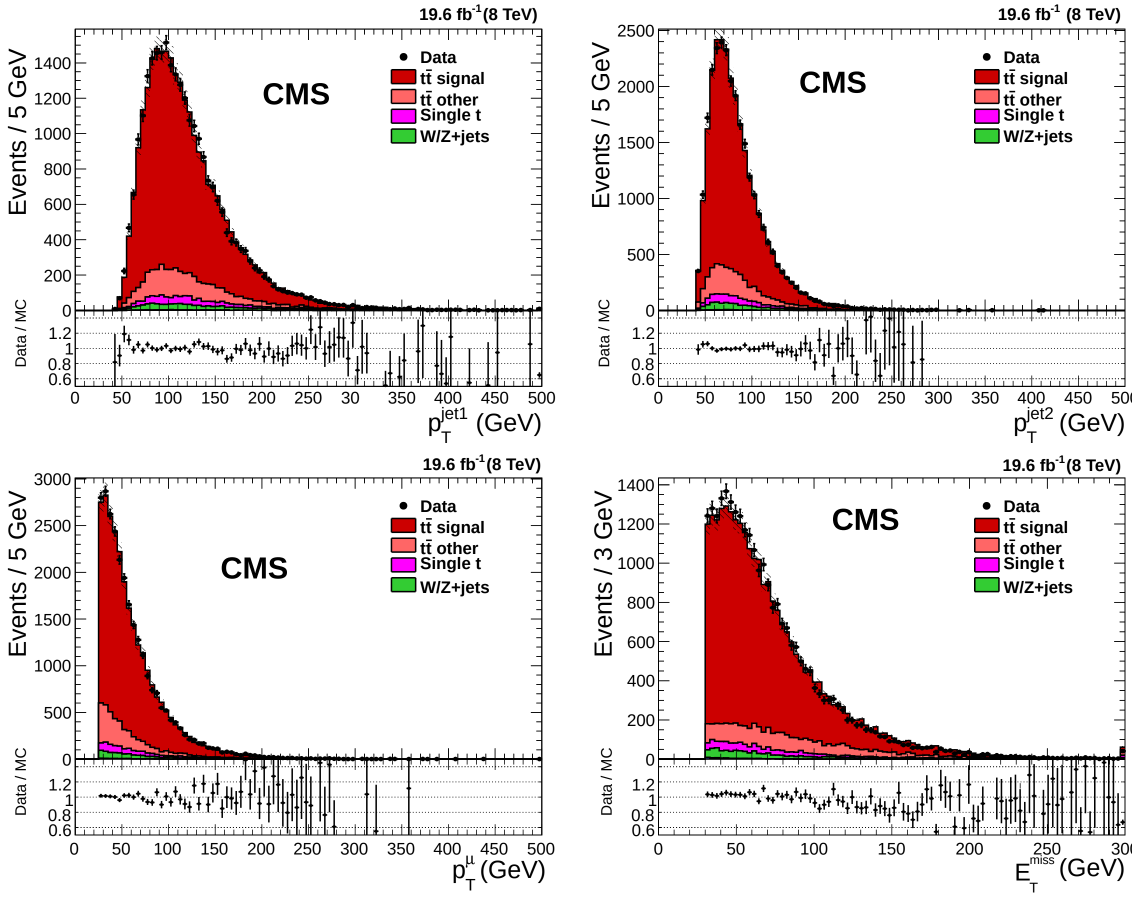

Figure 1: Transverse momentum distributions of the first- and second-leading jet (top), the muon and E_T^{miss} distribution (bottom) for all relevant processes in the muon+jets channel with the requirement of at least one b-tagged jet. The simulation is normalized to the standard model cross section values and p_T-reweighting is applied to the $t\bar{t}$ contribution. The multijet background is negligible and not shown. The distributions are already corrected for the b tagging efficiency scale factor. The hashed area shows the uncertainty in the luminosity measurement and the b tagging systematic uncertainty. The ratio between data and simulation is shown in the lower panels for bins with non-zero entries.

5 Visible and total cross section measurements

The $t\bar{t}$ visible ($\sigma_{t\bar{t}}^{vis}$) and total ($\sigma_{t\bar{t}}$) production cross sections are extracted from the number of $t\bar{t}$ events observed in the data using the equations

$$\sigma_{t\bar{t}}^{vis} = \frac{N_{t\bar{t}}}{L\,\varepsilon_{t\bar{t}}}, \qquad \sigma_{t\bar{t}} = \frac{\sigma_{t\bar{t}}^{vis}}{A}, \tag{1}$$

where $N_{t\bar{t}}$ is the number of selected $t\bar{t}$ events (including both signal events from the semileptonic channel considered and events from other decay channels), L is the integrated luminosity,

A is the $\mathrm{t\bar{t}}$ acceptance, and $\varepsilon_{\mathrm{t\bar{t}}}$ is the $\mathrm{t\bar{t}}$ selection efficiency within the acceptance requirements outlined in the next section. Results are presented for both the visible and total cross section, in order to separate experimental uncertainties from theoretical assumptions as much as possible.

The number of $\mathrm{t\bar{t}}$ events is determined with a binned maximum-likelihood fit of distributions (templates), describing signal and background processes, to the data sample passing the final selection, by fitting $M_{\ell \mathrm{b}}$, the invariant mass distribution of the b jet and the lepton.

One template is used for $\mathrm{t\bar{t}}$ events (both for the $\mathrm{t\bar{t}}$ signal events and the other $\mathrm{t\bar{t}}$ events passing the selection criteria) and one template for all background processes (W/Z+jets and single top quark production). Figure 2 shows the result for the fit to the data distributions in the muon and electron channels.

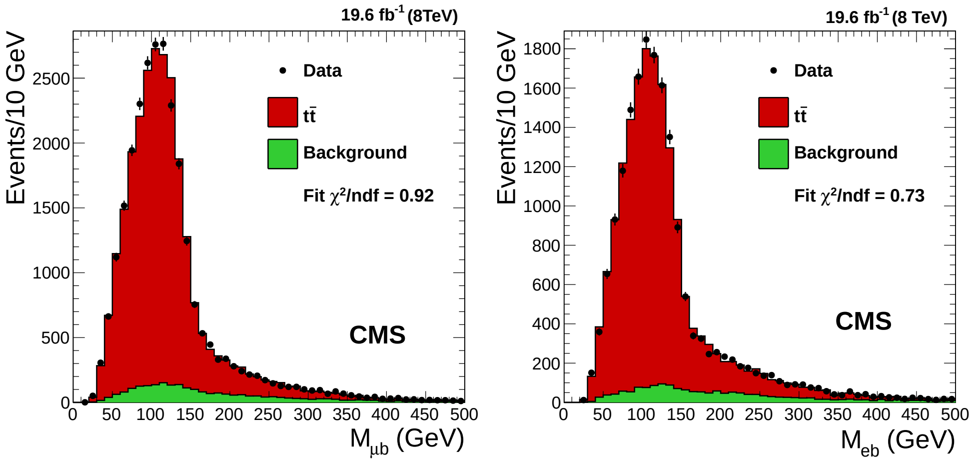

Figure 2: Distributions of the lepton-jet mass in the muon+jets (left) and electron+jets (right) channels, rescaled to the fit results.

5.1 Acceptance

The $\mathrm{t\bar{t}}$ acceptance A corresponding to the visible phase space depends on the theoretical model and it is determined at the generator level by requiring the presence of exactly one charged lepton, one neutrino, and at least four jets, passing p_{T} and $|\eta|$ selection criteria similar to the ones delineated in Section 4. For simplicity a single acceptance definition, corresponding to the tightest selection criteria, is used for both channels at each centre-of-mass energy: exactly one muon or electron with $p_{\mathrm{T}} > 32\,\mathrm{GeV}$ and $|\eta| < 2.1$, one neutrino with $p_{\mathrm{T}} > 40\,\mathrm{GeV}$, and at least four jets with $p_{\mathrm{T}} > 40\,\mathrm{GeV}$ and $|\eta| < 2.5$.

The acceptance values include contributions from other $\mathrm{t\bar{t}}$ decay channels, in particular from the dilepton channel, at the level of about 9%.

The acceptance values are provided in Table 1 for the two generators used in this analysis, MADGRAPH and POWHEG. The acceptance values are in agreement at the 1–2% level at 8 TeV and at better than 5% at 7 TeV. This different level of agreement is due to the fact that the common acceptance definition described above corresponds the tightest p_{T} criteria, i.e. to the the p_{T} requirements of the electron channel at $\sqrt{s} = 8\,\mathrm{TeV}$. The reweighted acceptance is determined as the number of reweighted $\mathrm{t\bar{t}}$ events in the visible phase space, i.e. the sum of the weights, divided by the total number of (non-reweighted) $\mathrm{t\bar{t}}$ events.

The statistical uncertainty in the acceptance calculations is below 3%. The theoretical systematic uncertainties due to variations of the PDFs or of the matching thresholds are in the range 0.1–

0.2%. Variation of the factorization and renormalization scale induces a variation of up to 2% in the acceptance. Those variations are already included in the systematic uncertainties quoted in Section 6.

In the following, top quark p_T-reweighting [37, 38] is always applied to the visible phase space as it provides a better agreement between data and simulation. On the other hand, given that the event weights were only determined in the phase space corresponding to the experimental selection, they have not been used for the extrapolation to the total cross section. Therefore, the non-reweighted acceptance is used to determine the total cross section. However, rescaling by the ratio of the values provided in Table 1 would allow a determination of the total cross section with the reweighted acceptance. The visible cross section does not depend on the acceptance A.

Table 1: Average acceptance values for the muon and electron channels obtained with MADGRAPH and POWHEG at $\sqrt{s} = 7$ and 8 TeV, without and with top quark p_T-reweighting applied. The statistical uncertainty is 0.0004, i.e. below 3%. The theoretical uncertainties are at the level of 2%, as discussed in the text.

Generator	A ($\sqrt{s} = 7$ TeV)		A ($\sqrt{s} = 8$ TeV)	
	no rew.	with rew.	no rew.	with rew.
MADGRAPH	0.0158	0.0156	0.0166	0.0162
POWHEG	0.0151	0.0149	0.0163	0.0161

5.2 Selection efficiency

The selection efficiency within the acceptance, $\varepsilon_{t\bar{t}}$, is reported in Table 2. It is determined from the p_T-reweighted MADGRAPH simulated sample as the number of events passing the selection criteria outlined in Section 4, over the number of events passing the phase space requirements defined above. The selection efficiency includes the effects of trigger requirements, lepton and jet identification criteria, and b tagging efficiency, which is determined from data. A signal selection efficiency of 32% in the muon channel and 21% in the electron channel is determined. Compatible values (37% and 22%, respectively) are obtained at $\sqrt{s} = 7$ TeV. For the muon channel the common acceptance requirements used for both channels are tighter than the selection requirements, thus the muon channel efficiency is significantly larger than the electron channel efficiency. The $t\bar{t}$ selection efficiency, $A\varepsilon_{t\bar{t}}$, is the number of selected $t\bar{t}$ events out of all produced $t\bar{t}$ pairs, in all decay channels.

Table 2: Signal selection efficiencies, at $\sqrt{s} = 8$ TeV, determined from simulation using MADGRAPH. The non-reweighted acceptance from Table 1 is used. The relative statistical uncertainty on these numbers is below 3%.

Channel	$\varepsilon_{t\bar{t}}$ ($\sqrt{s} = 7$ TeV)	$A\varepsilon_{t\bar{t}}$ ($\sqrt{s} = 7$ TeV)	$\varepsilon_{t\bar{t}}$ ($\sqrt{s} = 8$ TeV)	$A\varepsilon_{t\bar{t}}$ ($\sqrt{s} = 8$ TeV)
μ+jets	37%	0.58%	32%	0.53%
e+jets	22%	0.36%	21%	0.35%

6 Systematic uncertainties

Systematic uncertainties are determined by varying each source within its estimated uncertainty and by propagating the variation to the cross section measurement. Template shapes and signal efficiencies are varied together according to the systematic uncertainty considered. The uncertainty is given by the shift in the fitted cross section and is cross-checked by repeating its estimation with pseudo-experiments using simulation. The systematically varied template shapes are fit to pseudo-data generated using the nominal template shapes and normalizations. Most systematic uncertainties, except the ones related to b tagging and to the estimation of the multijet background, are common to both the $M_{\ell\mathrm{b}}$ and the M_3 measurements.

The effect of uncertainties in the JES is evaluated by varying the JES up and down within the p_{T}- and η-dependent uncertainties given in Ref. [52]. The final JES of the simulation is matched to that in data by applying an additional global correction factor α to all jet momenta before selection. The α calibration values are individually determined for each sample. In addition to the selection described in Section 4, two b-tagged jets are required in order to increase the signal purity. The mass of the hadronically decaying W boson is reconstructed as the dijet invariant mass from all combinations of non b-tagged jets. The dijet invariant mass distributions are fitted in data and in simulation with a function describing the W boson signal peak and the dijet combinatorial background. The α values are determined as the ratios of the fitted W boson masses in data and in simulation. In the $M_{\ell\mathrm{b}}$ analysis $\alpha = 1.011 \pm 0.004$ is obtained with the nominal samples both in the muon and electron channels, with variations of the order of $\pm 1.5\%$ for the samples with down and up variations of the JES. The same values are determined by the M_3 analysis. This additional calibration reduces the size of the JES systematic uncertainty by approximately 60%. The JES uncertainty, reported in Table 3, consists of several sources, all propagated individually. Details of the individual contributions are explained in [53].

Table 3: Components (in %) of the JES uncertainty at 8 TeV in the muon and electron channels. The correlation coefficients used in their combination are also shown.

Source	μ+jets	e+jets	Correlation
Absolute scale	± 0.33	± 0.40	0.0
Global jet scale factor	± 0.59	± 0.39	0.0
Radiation modeling	± 0.46	± 0.41	1.0
Relative p_{T} extrapolation	± 0.67	± 0.57	1.0
Parton flavour mixture	± 1.84	± 1.79	1.0
b jet fragmentation	± 0.50	± 0.46	1.0
B jet semileptonic decay fraction	± 0.11	± 0.16	1.0
High-p_{T} extrapolation	± 0.18	± 0.23	1.0
High-p_{T} single-jet response	± 0.21	± 0.27	1.0
Pileup random-cone simulation	± 0.35	± 0.31	1.0
Time-dependent detector effects	± 0.17	± 0.24	1.0
Total JES	± 2.23	± 2.13	0.9

The impact of the jet energy resolution (JER) is estimated by applying η-dependent variations with an average of $\pm 10\%$. The JES and JER variations are propagated to the $E_{\mathrm{T}}^{\mathrm{miss}}$. In addition, the contribution to $E_{\mathrm{T}}^{\mathrm{miss}}$ arising from energy depositions not contained in jets is varied by $\pm 10\%$ [52]. The uncertainty related to the pileup modeling is determined by propagating a $\pm 5\%$ variation [54] to the central value of the inelastic cross section. Variations in the composition of the main background processes, W+jets and Z+jets, are conservatively evaluated by varying independently their cross sections by $\pm 30\%$. The resulting effects are added in quadrature. The variation of the single top quark background gives a negligible contribution. The trigger efficiency and lepton identification correction factors are determined with a tag-and-probe method [49] in dilepton events and are varied within their p_T- and η-dependent uncertainties.

Uncertainties from the b tagging efficiency and mistag rate are evaluated in the M_3 analysis by varying the correction factors within their uncertainties [18, 19] quoted in Section 8. In the $M_{\ell b}$ analysis, on the other hand, the b tagging efficiency for b jets is measured from data, using the technique described in Refs. [18–20], on the same selected event sample as that for the cross section determination, but before b tagging. The $M_{\ell b}$ variable is used not only as a cross section estimator, but also as a b tagging discriminator. The statistical and systematic uncertainties in the b tagging and mistag efficiencies are propagated into the statistical and systematic uncertainties in the cross section measurements. For this reason the statistical uncertainty obtained by the $M_{\ell b}$ analysis is larger than the one of the M_3 analysis. A systematic uncertainty is assigned to the choice, based on simulation, of the b-enriched (for $M_{\ell b}$ values below 140 GeV) and of the b-depleted (for $M_{\ell b}$ in the range 140–240 GeV) regions, by shifting the windows by ± 30 GeV. Since the b tagging efficiency and mistag rate are derived from data and since they are re-determined when evaluating the effect of the various systematic uncertainties, no additional uncertainties are included. The method is shown [18–20] to be stable for different b tagging algorithms and working points.

Theoretical uncertainties are taken from detailed studies performed on simulated samples. They include the common factorization and renormalization scales, which are varied by a factor of 1/4 and 4 from the default value equal to the Q^2 for the $t\bar{t}$ or W/Z+jet events. The effect of the jet-parton matching threshold on $t\bar{t}$ and W+jets events is studied by varying the threshold used for matching the matrix element level to the particles created in the parton showering by a factor of 0.5 or 2. Uncertainties from the choice of PDF are evaluated by using the Hessian method [55] with the parameters of the CTEQ6.6 PDF set [56]. Other PDF sets yield very similar uncertainties. The PDFs and their uncertainties are determined from a fit to collision data yielding the Hessian matrix. Each of the 22 eigenvectors obtained by diagonalizing the matrix is varied up and down within its uncertainties. The differences with respect to the nominal prediction are determined independently for each eigenvector and are added in quadrature. The systematic uncertainty due to the top quark p_T-reweighting procedure described in Section 3 is evaluated as the difference with respect to the measurement obtained with the non-reweighted sample. Only the variation due to the template shape is considered, as the correction is meant to modify the shape only.

A "signal modeling" uncertainty is attributed to the choice of the generators. It comprises changes in matrix element and parton shower implementation. The effect of the matrix element generator is evaluated by using POWHEG (instead of MADGRAPH) interfaced to PYTHIA, while the parton shower modeling is evaluated with POWHEG and HERWIG instead of POWHEG and PYTHIA. For 7 TeV the same values determined for 8 TeV are used. As discussed in Section 7, the "signal modeling" uncertainty is symmetrized by taking the larger of the two contributions ($\pm 4.4\%$).

An uncertainty of 2.6% [22] (2.2% [23]) is assigned to the determination of the 2012 (2011) integrated luminosity. Tables 4 and 5 provide an overview of the contributions to the systematic uncertainty on the combined cross section measurements in the $M_{\ell b}$ measurements at 7 and 8 TeV.

Table 4: Overview of the systematic uncertainties in the measurement of the $t\bar{t}$ cross sections at 8 TeV, both for the total and the visible cross sections. For the "signal modeling" uncertainty the larger between the matrix element (ME) and parton shower (PS) uncertainties is taken, as explained in Section 6. The correlations assumed for the combination of the muon and electron channels are also given.

Systematic uncertainty	8 TeV			
	μ+jets (%)	e+jets (%)	corr.	comb.(%)
Jet energy scale	±2.2	±2.1	0.9	±2.2
Jet energy resolution	±0.8	±0.9	1.0	±0.8
E_T^{miss} unclustered energy	±0.1	±0.3	1.0	±0.1
Pileup	±0.5	±0.4	1.0	±0.5
Lepton ID / Trigger eff. corrections	±0.4	±0.5	0.0	±0.5
b tagging method	±0.3	±0.7	1.0	±0.3
Background composition	±0.2	±0.3	1.0	±0.2
Factorization/renormalization scales	±1.7	±2.6	1.0	±1.7
ME-PS matching threshold	±1.3	±2.3	1.0	±1.2
Top quark p_T-reweighting	±1.1	±1.2	1.0	±1.1
Signal modeling for $\sigma_{t\bar{t}}$ ($\sigma_{t\bar{t}}^{vis}$)	$\pm4.4(\pm2.2)$	$\pm4.4(\pm2.4)$	1.0	$\pm4.4(\pm2.3)$
PDF uncertainties	±2.1	±1.9	1.0	±2.1
Sum for $\sigma_{t\bar{t}}$ ($\sigma_{t\bar{t}}^{vis}$)	$\pm6.0(\pm4.6)$	$\pm6.5(\pm5.4)$		$\pm6.0(\pm4.7)$
Integrated luminosity	±2.6	±2.6	1.0	±2.6
Total for $\sigma_{t\bar{t}}$ ($\sigma_{t\bar{t}}^{vis}$)	$\pm6.5(\pm5.3)$	$\pm7.0(\pm6.0)$		$\pm6.5(\pm5.3)$

Table 5: Overview of the systematic uncertainties in the measurement of the $t\bar{t}$ cross sections at 7 TeV, both for the total and the visible cross sections. For the "signal modeling" uncertainty the larger between the matrix element (ME) and parton shower (PS) uncertainties is taken, as explained in Section 6. The correlations assumed for the combination of the muon and electron channels are also shown.

Systematic uncertainty	7 TeV			
	μ+jets (%)	e+jets (%)	corr.	comb.(%)
Jet energy scale	±4.8	±5.2	0.9	±4.4
Jet energy resolution	±1.4	±1.1	1.0	±1.1
E_{T}^{miss} unclustered energy	< 0.05	±0.3	1.0	±0.2
Pileup	±0.4	±0.6	1.0	±0.5
Lepton ID / Trigger eff. corrections	±1.4	±1.7	0.0	±0.8
b tagging method	±0.5	±0.6	1.0	±0.6
Background composition	±0.5	±0.4	1.0	±0.5
Factorization/renormalization scales	±3.7	±0.4	1.0	±2.1
ME-PS matching threshold	±2.0	±1.7	1.0	±1.8
Top quark p_{T}-reweighting	±1.1	±1.2	1.0	±1.1
Signal modeling for $\sigma_{t\bar{t}}$ ($\sigma_{t\bar{t}}^{vis}$)	±4.4(±2.2)	±4.4(±2.4)	1.0	±4.4(±2.3)
PDF uncertainties	±2.3	±1.9	1.0	±2.2
Sum for $\sigma_{t\bar{t}}$ ($\sigma_{t\bar{t}}^{vis}$)	±8.4(±7.5)	±7.7(±6.8)		±7.4(±6.4)
Integrated luminosity	±2.2	±2.2	1.0	±2.2
Total for $\sigma_{t\bar{t}}$ ($\sigma_{t\bar{t}}^{vis}$)	±8.7(±7.8)	±8.0(±7.1)		±7.7(±6.7)

7 Results and combination

The results in the muon and electron channels, shown in Tables 6 and 7, are in good agreement. The combination of the channel results is performed using the best linear unbiased estimator (BLUE) method [57–59]. Asymmetric systematic uncertainties are symmetrized for the use with BLUE by taking half of the full range, except for the "signal modeling" uncertainty, where the maximum, 4.4%, is taken for $\sigma_{t\bar{t}}$. Full correlation is assumed for all systematic uncertainties between the two channels, except for lepton identification and trigger uncertainties, which are assumed to be uncorrelated.

Owing to the additional jet energy calibration from data, a correlation coefficient of 0.9 is obtained for the overall JES uncertainty. This correlation is determined from the correlation coefficients in Table 3 and it is compatible with the value inferred by comparing the combined result with and without the additional calibration. Varying the JES correlation coefficient between 0 and 1 has only a minor effect on the combined results. For example, the total cross section at 8 TeV varies by less than 0.5%, and the cross section ratio varies only by approximately 0.1%. A combination based on the relative statistical precision of the two channels would also yield compatible results. Variations of the correlations of other experimental systematic uncertainties have negligible effect on the combined results.

The integrated luminosity and the pileup uncertainties are assumed to be fully correlated between channels at the same centre-of-mass energy, and uncorrelated between 7 and 8 TeV for the cross section ratio.

7.1 Results at $\sqrt{s} = 8$ TeV

The visible cross section obtained from the fit to the $M_{\ell b}$ distribution, using MADGRAPH signal templates for $m_t = 172.5$ GeV, is

$$\sigma_{t\bar{t}}^{vis}(\text{combined}) = 3.80 \pm 0.06\,(\text{stat}) \pm 0.18\,(\text{syst}) \pm 0.10\,(\text{lumi})\,\text{pb}.$$

The statistical uncertainty includes the contribution from the simultaneous determination of the b tagging efficiency (see Section 6). There is excellent agreement with the measurement of the visible cross section using POWHEG for the efficiency within the kinematic acceptance selected by this analysis.

Using the acceptance values of Table 1, the visible cross section measurements in the electron and muon channels are first extrapolated to the full phase space and then combined to obtain the following total cross section measurement

$$\sigma_{t\bar{t}}(\text{combined}) = 228.5 \pm 3.8\,(\text{stat}) \pm 13.7\,(\text{syst}) \pm 6.0\,(\text{lumi})\,\text{pb}.$$

The measurements are in good agreement with the theoretical prediction

$$\sigma_{t\bar{t}}^{th.}\,(8\,\text{TeV}) = 252.9^{+6.4}_{-8.6}(\text{scale}) \pm 11.7(\text{PDF}+\alpha_S)\,\text{pb}$$

(see Section 3), for $m_t = 172.5$ GeV.

The BLUE combination yields the following relative weights of the muon and electron channels, and their correlations, respectively. At 8 TeV they are: 1.07 (1.09), −0.07 (−0.09), with correlation coefficient 0.88 (0.91) for the total (visible) cross section, while at 7 TeV they are: 0.50 (0.51), 0.50 (0.49), with correlation coefficient 0.71 (0.65). The negative weights of the electron channel in the combination of the total and visible cross section at 8 TeV depend on the choice of the JES correlation coefficient (0.9) used in the combination. Smaller JES correlation coefficients (0.5 for the total cross section and 0.2 for the visible cross section) would yield positive BLUE weights. The negative weights causes the combined central value, 228.5 pb, to lie outside the interval of the two individual measurements, as summarized in Tables 6 and 7.

Alternatively, using POWHEG instead of MADGRAPH, the combined total cross section at 8 TeV shifts by +8.6 pb. The difference, at the level of less than 4%, is mainly ascribed to the different acceptance for the two generators.

All results are summarized in Tables 6 and 7 for $m_t = 172.5$ GeV. For POWHEG the same relative systematic uncertainties as determined for MADGRAPH are used.

7.2 Dependence on the top quark mass at $\sqrt{s} = 8$ TeV

Using simulation, the dependence of the measured cross section on the top quark mass is determined to be linear in the m_t range from 161.5 to 184.5 GeV. The top quark mass value used for the central results is 172.5 GeV. The slope values reported in Table 8 can be used to linearly adjust the channel results to other mass values. For $m_t = 173.3$ GeV [60] the adjusted results of the two channels yield a combined cross section value

$$\sigma_{t\bar{t}}(\text{combined}) = 227.4 \pm 3.8\,(\text{stat}) \pm 13.7\,(\text{syst}) \pm 6.0\,(\text{lumi})\,\text{pb}.$$

Table 6: Visible cross section measurements at $\sqrt{s} = 7$ and 8 TeV with the reference analysis $M_{\ell\mathrm{b}}$ and the alternative analysis M_3 (described in Section 8). Results obtained for $m_\mathrm{t} = 172.5$ GeV with MADGRAPH and with POWHEG are shown. The uncertainties are in the order: statistical, systematic, and due to the luminosity determination.

Analysis	Generator	Channel	$\sigma_{\mathrm{t\bar{t}}}^{\mathrm{vis}}$ at $\sqrt{s} = 8$ TeV
		μ+jets	$3.80 \pm 0.06 \pm 0.18 \pm 0.10$ pb
$M_{\ell\mathrm{b}}$	MADGRAPH	e+jets	$3.90 \pm 0.07 \pm 0.21 \pm 0.10$ pb
		Combined	$3.80 \pm 0.06 \pm 0.18 \pm 0.10$ pb
$M_{\ell\mathrm{b}}$	POWHEG	Combined	$3.83 \pm 0.06 \pm 0.18 \pm 0.10$ pb
		μ+jets	$3.79 \pm 0.05 \pm 0.24 \pm 0.10$ pb
M_3	MADGRAPH	e+jets	$3.75 \pm 0.04 \pm 0.26 \pm 0.10$ pb
		Combined	$3.78 \pm 0.04 \pm 0.25 \pm 0.10$ pb
M_3	POWHEG	Combined	$3.88 \pm 0.05 \pm 0.27 \pm 0.10$ pb
Analysis	Generator	Channel	$\sigma_{\mathrm{t\bar{t}}}^{\mathrm{vis}}$ at $\sqrt{s} = 7$ TeV
		μ+jets	$2.48 \pm 0.09 \pm 0.19 \pm 0.06$ pb
$M_{\ell\mathrm{b}}$	MADGRAPH	e+jets	$2.62 \pm 0.10 \pm 0.18 \pm 0.06$ pb
		Combined	$2.55 \pm 0.09 \pm 0.18 \pm 0.06$ pb

7.3 Results at $\sqrt{s} = 7$ TeV and cross section ratio

At $\sqrt{s} = 7$ TeV the measured cross section, with MADGRAPH, is

$$\sigma_{\mathrm{t\bar{t}}}(\text{combined}) = 161.7 \pm 6.0\,(\text{stat}) \pm 12.0\,(\text{syst}) \pm 3.6\,(\text{lumi})\,\text{pb}.$$

The measurements are in good agreement with the theoretical expectation

$$\sigma_{\mathrm{t\bar{t}}}^{\text{th.}}\,(7\,\text{TeV}) = 177.3^{+4.6}_{-6.0}\,(\text{scale}) \pm 9.0\,(\text{PDF}+\alpha_S)\,\text{pb [2, 61]}$$

at 7 TeV, for a top quark mass of 172.5 GeV.

From the measurements of the total cross section at the two centre-of-mass energies, a cross section ratio $R^{8/7}$ is determined. In the ratio the experimental uncertainties, which are correlated between the two analyses (at $\sqrt{s} = 7$ or 8 TeV, in each channel) cancel out, leading to an improved precision in comparison to the individual measurements at 7 or 8 TeV. The ratio is first determined in the individual muon (1.45 ± 0.09) and electron (1.41 ± 0.09) channels and then combined. The measured ratio is

$$R^{8/7} = 1.43 \pm 0.04\,(\text{stat}) \pm 0.07\,(\text{syst}) \pm 0.05\,(\text{lumi}). \quad (2)$$

In the combination of the ratios in the two channels the theoretical uncertainties, and the jet-related uncertainties are assumed to be 100% correlated, except the JES uncertainty, which is taken as 90% correlated. The other experimental uncertainties are assumed to be uncorrelated. The expected cross section ratio, $R^{8/7}_{\text{th.}} = 1.429 \pm 0.001$ (scale) $\pm\, 0.004$ (PDF) $\pm\, 0.001$ ($\mathrm{ff_s}$) $\pm\, 0.001$ (m_t) [2], is in good agreement with the measurement.

8 Alternative approach at $\sqrt{s} = 8$ TeV using M_3

In the M_3 analysis similar requirements for the selection of $\mathrm{t\bar{t}}$ semileptonic decays are used, with slightly different p_T-threshold values. Only the differences with respect to the main selec-

Table 7: Total cross section measurements at $\sqrt{s} = 7$ and 8 TeV with the reference analysis $M_{\ell b}$ and the alternative analysis M_3 (described in Section 8). Results obtained for $m_t = 172.5$ GeV with MADGRAPH and with POWHEG are shown. The uncertainties are in the order: statistical, systematic, and due to the luminosity determination.

Analysis	Generator	Channel	$\sigma_{t\bar{t}}$ at $\sqrt{s} = 8$ TeV
$M_{\ell b}$	MADGRAPH	μ+jets	$228.9 \pm 3.4 \pm 13.7 \pm 6.0$ pb
		e+jets	$234.6 \pm 3.9 \pm 15.2 \pm 6.2$ pb
		Combined	$228.5 \pm 3.8 \pm 13.7 \pm 6.0$ pb
$M_{\ell b}$	POWHEG	Combined	$237.1 \pm 3.9 \pm 14.2 \pm 6.2$ pb
M_3	MADGRAPH	μ+jets	$228.7 \pm 2.6 \pm 19.0 \pm 6.0$ pb
		e+jets	$225.8 \pm 2.4 \pm 19.1 \pm 5.9$ pb
		Combined	$227.1 \pm 2.5 \pm 19.1 \pm 6.0$ pb
M_3	POWHEG	Combined	$238.4 \pm 2.8 \pm 20.0 \pm 6.2$ pb
Analysis	**Generator**	**Channel**	**$\sigma_{t\bar{t}}$ at $\sqrt{s} = 7$ TeV**
$M_{\ell b}$	MADGRAPH	μ+jets	$157.7 \pm 5.5 \pm 13.2 \pm 3.4$ pb
		e+jets	$165.8 \pm 6.5 \pm 12.8 \pm 3.6$ pb
		Combined	$161.7 \pm 6.0 \pm 12.0 \pm 3.6$ pb

Table 8: Slope values for the muon and electron channels obtained with linear fits to the cross section values at $\sqrt{s} = 8$ TeV as a function of the top quark mass. The MADGRAPH generator is used. The change in sign is due to the acceptance A.

Channel	Slope (%/GeV) of $\sigma_{t\bar{t}}^{vis}$	Slope (%/GeV) of $\sigma_{t\bar{t}}$
μ+jets	$+0.50 \pm 0.06$	-0.66 ± 0.05
e+jets	$+0.30 \pm 0.04$	-0.94 ± 0.05

tion are summarized in the following.

At least four jets are required within $|\eta| < 2.5$ and with $p_{\mathrm{T}} > 50$, 40, 30, and 30 GeV in the muon channel, and $p_{\mathrm{T}} > 50$, 45, 35, and 30 GeV in the electron channel. Muons are required to have transverse momentum larger than 26 GeV. In the muon channel no explicit requirement is applied on the missing energy in the transverse plane, while $E_{\mathrm{T}}^{\mathrm{miss}}$ has to be larger than 20 GeV in the electron channel.

The M_3 analysis uses a correction factor of (0.95 ± 0.02) [18, 19] to the simulated events to reproduce the different b tagging efficiency in data and simulation, and a correction factor of $(1.11 \pm 0.01 \pm 0.12)$ [18, 19] to take into account the different probability that a light-quark or gluon jet is identified as a b jet. These correction factors are determined following Refs. [18, 19]. No correction factors are applied in the $M_{\ell\mathrm{b}}$ analysis, where these efficiencies are determined from data.

Different strategies to take into account the multijet background are developed for the $M_{\ell\mathrm{b}}$ and M_3 analyses. In the former, this background is reduced to a negligible level thanks to tighter selection requirements on $E_{\mathrm{T}}^{\mathrm{miss}}$ and on the transverse momenta of the third and fourth jets. In the M_3 analysis, looser selection cuts are chosen and the multijet background is considered further in the analysis. Since MC simulation can not adequately reproduce the shape and normalization of multijet events, this background is thus estimated from data.

Selected multijet events mostly consist of semileptonic heavy-flavour decays and, in the electron channel, events in which pions in jets are misidentified as electrons. Such events feature lepton candidates not coming from W boson decay and thus not truly isolated. The shape of the accepted multijet background is extracted from a sideband data sample where leptons have large relative isolation, greater than 0.17 in the muon channel and 0.2 in the electron channel. The data sample is selected such that it is rich in multijet background and poor in $\mathrm{t\bar{t}}$ signal and in other processes such as W+jets. The remaining $\mathrm{t\bar{t}}$, W+jets and Z+jets contamination is removed using simulation. Other backgrounds, for example single top quark production, are neglected because of their smaller contributions. The nominal multijet shape is taken as the distribution measured in the sideband after subtracting the components described above.

The template fit is performed by using one single template for $\mathrm{t\bar{t}}$ events (both for the $\mathrm{t\bar{t}}$ signal events and the other $\mathrm{t\bar{t}}$ events passing the selection requirements) and individual templates for each background process. The $\mathrm{t\bar{t}}$, single top quark, W+jets, and Z+jets templates, used in the likelihood maximization, are taken from simulation, while the multijet template is estimated from data as described above. The single top quark contribution is constrained by a Gaussian distribution of 30% width to its expected value. The choice of the constraint has a negligible effect on the final result. The normalization of the signal and background processes, including the multijet background, is determined by the fit itself. The muon and electron channels are combined with the BLUE method to obtain the quoted combined result.

The measured cross section with the M_3 template fit is

$$\sigma_{\mathrm{t\bar{t}}}(\text{combined}) = 227.1 \pm 2.5\,(\text{stat}) \pm 19.1\,(\text{syst}) \pm 6.0\,(\text{lumi})\,\text{pb}.$$

The M_3 distributions in the muon and electron channels are shown in Fig. 3. Good agreement is observed between data and the templates. The results are compatible with those of the $M_{\ell\mathrm{b}}$ analysis and are summarized in Tables 6 and 7. The main contributions to the systematic uncertainties of the combined result are, in decreasing order: signal modeling (4.4%), factorization and renormalization scales (2.9%), multijet background subtraction (2.2%), JES (2.1%), PDF (1.6%), and b tagging efficiency and mistag rate (1.5%).

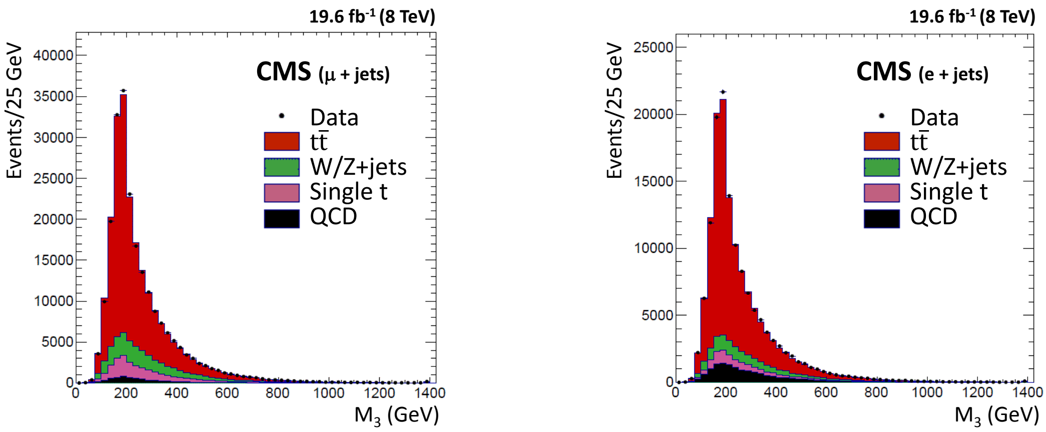

Figure 3: Distributions of the M_3 mass in the 8 TeV data, for the muon+jets (left) and electron+jets (right) channels, rescaled to the template likelihood fit results.

9 Summary

A measurement of the $t\bar{t}$ production cross section at $\sqrt{s} = 8$ TeV is presented, using the data collected with the CMS detector and corresponding to an integrated luminosity of $19.6\,\mathrm{fb}^{-1}$. The analysis is performed in the $t\bar{t}$ semileptonic decay channel with one muon or electron and at least four jets in the final state with at least one b-tagged jet. The $t\bar{t}$ cross section is extracted using a binned maximum-likelihood fit of templates from simulated events to the data sample. The results from the two semileptonic channels are combined using the BLUE method.

Techniques based on control samples in data are used to determine the b tagging efficiency and to calibrate the jet energy scale. These techniques allow for a better determination of the corresponding systematic uncertainties, particularly for the JES, which is a dominant source of experimental uncertainty.

In the kinematic range defined in the simulation with exactly one muon or electron with $p_T > 32$ GeV and $|\eta| < 2.1$, one neutrino with $p_T > 40$ GeV, and at least four jets with $p_T > 40$ GeV and $|\eta| < 2.5$, the measured visible $t\bar{t}$ cross section at $\sqrt{s} = 8$ TeV is $3.80 \pm 0.06\,(\text{stat}) \pm 0.18\,(\text{syst}) \pm 0.10\,(\text{lumi})$ pb.

Using the MadGraph generator for the extrapolation to the full phase space, the total $t\bar{t}$ cross section at 8 TeV is $228.5 \pm 3.8\,(\text{stat}) \pm 13.7\,(\text{syst}) \pm 6.0\,(\text{lumi})$ pb. The result of an alternative analysis, which makes use of the observable M_3, is in good agreement with this value.

Furthermore, the analysis performed using data at $\sqrt{s} = 7$ TeV, yields a total cross section measurement of $161.7 \pm 6.0\,(\text{stat}) \pm 12.0\,(\text{syst}) \pm 3.6\,(\text{lumi})$ pb. The measured cross section ratio, where a number of experimental uncertainties cancel out, is $1.43 \pm 0.04\,(\text{stat}) \pm 0.07\,(\text{syst}) \pm 0.05\,(\text{lumi})$.

All measurements are in agreement with the NNLO theoretical predictions.

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