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Observation of the associated production of a single top quark and a W boson in pp collisions at $\sqrt{s} = 8\,\text{TeV}$

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Abstract

The first observation of the associated production of a single top quark and a W boson is presented. The analysis is based on a data set corresponding to an integrated luminosity of 12.2 fb^{-1} of proton-proton collisions at $\sqrt{s} = 8\,\text{TeV}$ recorded by the CMS experiment at the LHC. Events with two leptons and a jet originating from a b quark are selected. A multivariate analysis based on kinematic and topological properties is used to separate the signal from the dominant $\text{t}\bar{\text{t}}$ background. An excess consistent with the signal hypothesis is observed, with a significance which corresponds to 6.1 standard deviations above a background-only hypothesis. The measured production cross section is $23.4 \pm 5.4\,\text{pb}$, in agreement with the standard model prediction.

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Since its discovery in 1995 [1, 2], studies of the top quark have raised great interest within high energy physics. As the heaviest of all standard model (SM) particles, the top quark potentially plays an important role in electroweak symmetry breaking as well as in physics beyond the SM. The measurement of the different mechanisms by which top quarks can be produced is instrumental in advancing the understanding of physics at the TeV scale.

Top quarks are produced predominantly in pairs via the strong interaction in proton-proton (pp) collisions but they can also be produced singly via electroweak interactions, involving a Wtb vertex. In the SM, single-top-quark production occurs mainly through three processes: *t*-channel (tqb), *s*-channel (tb), and associated production of a top quark and a W boson (tW). Single-top-quark production was first observed by the D0 [3] and CDF [4] experiments at the Tevatron. The *t*-channel production mode has been measured by D0 [5] and CDF [6] as well as at the Large Hadron Collider (LHC) by the Compact Muon Solenoid (CMS) [7] and ATLAS [8] experiments, while evidence for *s*-channel production was recently presented by the D0 [9] experiment. The tW production cross section is negligible at the Tevatron, but large enough at the LHC to make it accessible. Evidence for this process was presented by both the ATLAS [10] and CMS [11] experiments using the 7 TeV collision data, with significances of 3.6 and 4.0 σ respectively. This Letter presents the first observation of tW production at a significance of at least 5 σ, using data collected with the CMS experiment in pp collisions at $\sqrt{s} = 8$ TeV and corresponding to an integrated luminosity of 12.2 fb^{-1}.

In addition to testing the SM predictions at the electroweak scale, associated tW production is of interest because of its sensitivity to non-SM couplings of the Wtb vertex [12–16], while being relatively insensitive to scenarios that affect the other single-top-quark production channels.

The theoretical prediction for the cross section of tW production in pp collisions at $\sqrt{s} = 8$ TeV at approximate next-to-next-to-leading order (NNLO) is $22.2 \pm 0.6\,(\text{scale}) \pm 1.4\,(\text{PDF})$ pb [17], with the first uncertainty coming from factorization and renormalization scale variations and the second from variations in the parton distribution functions of the proton. At next-to-leading order (NLO) the definition of tW production in perturbative quantum chromodynamics mixes with top-quark pair production ($\mathrm{t\bar{t}}$) [18–20]. Two schemes for defining the tW signal to distinguish it from $\mathrm{t\bar{t}}$ production have been proposed: the "diagram removal" (DR) [18], in which all doubly-resonant NLO tW diagrams are removed, and the "diagram subtraction" (DS) [18, 21], where a gauge-invariant subtraction term modifies the NLO tW cross section to locally cancel the contribution from $\mathrm{t\bar{t}}$. In this Letter, the DR scheme is used for simulating the signal, but it was verified that the results are consistent between the two methods and any differences are accounted for in the systematic uncertainties.

The analysis is performed using the dilepton decay channels, in which the W boson produced in association with the top quark and the W boson from the decay of the top quark both decay leptonically into a muon or an electron, and a neutrino. This leads to a final state composed of two oppositely charged isolated leptons, a jet resulting from the fragmentation of a b quark, and two neutrinos. The neutrinos escape detection and are only discernible by the presence of missing transverse energy ($E_{\mathrm{T}}^{\text{miss}}$), defined as the magnitude of the vector sum of the transverse momentum of all reconstructed particles. The primary background to tW production in this final state comes from $\mathrm{t\bar{t}}$ production, with $\mathrm{Z}/\gamma^{\star}$ events being the next most significant.

The analysis uses a multivariate technique, exploiting kinematic and topological differences to distinguish the tW signal from the dominant $\mathrm{t\bar{t}}$ background. To assess the robustness of the result, two additional analyses were conducted. One involves a fit to a single kinematic variable, the other is based on event counts.

The central feature of the CMS apparatus [22] is a superconducting solenoid with an internal diameter of 6 m, providing a magnetic field of 3.8 T. Within the bore of the solenoid are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass/scintillator hadron calorimeter. Muons are measured in gas-ionization detectors embedded in the steel flux return yoke outside the magnet. In addition, CMS has extensive forward calorimetry. The detector covers a region of $|\eta| < 5.0$, where the pseudorapidity η is defined as $\eta = -\ln[\tan(\theta/2)]$, where θ is the polar angle.

Data samples are selected based on triggers requiring two leptons (either an electron or muon), one with transverse momentum, p_T, of at least 17 GeV and a second with p_T of at least 8 GeV. All events are required to have a well reconstructed primary vertex [23]. The primary vertex with the largest sum of p_T^2 of associated tracks is chosen.

Electrons are reconstructed from energy deposits in the electromagnetic calorimeter matched to tracks in the silicon tracker. Muons, E_T^{miss}, and jets are reconstructed using the CMS particle flow (PF) algorithm [24, 25], which performs a global event reconstruction. Electrons and muons are required to have $p_T > 20$ GeV and fall within the pseudorapidity range of $|\eta| < 2.5$ for electrons and $|\eta| < 2.4$ for muons. Exactly two oppositely charged, isolated leptons are required in the event, and events with additional leptons passing looser criteria are rejected. In order to limit the contribution from low mass dilepton resonances, the invariant mass of the dilepton system, $m_{\ell\ell}$ ($\ell = \mathrm{e}$ or μ), is required to be greater than 20 GeV. Events in the ee and $\mu\mu$ final states are rejected if $m_{\ell\ell}$ is between 81 and 101 GeV, to suppress the $\mathrm{Z} \to \ell\ell$ process in the same-flavor final states. Additionally, a requirement of $E_T^{miss} > 50$ GeV is applied for these final states.

Jets are reconstructed by clustering PF candidates using the anti-k_T algorithm [26] with a distance parameter of 0.5. Selected jets must be within $|\eta| < 2.4$ and have $p_T > 30$ GeV. Corrections are made to the jet energies for detector response as a function of η and p_T [27]. Additional corrections are made to subtract energy in the jet from multiple pp collisions (pileup). Jets originating from the decay of a b quark are tagged based on the presence of a secondary vertex, identified using a multivariate algorithm combining tracking information in a discriminant [28]. A working point is chosen, corresponding to a b-tagging efficiency of approximately 70% and with a misidentification rate of 1–2%. Loose jets are defined as jets failing the requirements on p_T and η, but passing the less restrictive selection requirement of $p_T > 20$ GeV and $|\eta| < 4.9$, while still passing all other selection criteria. In particular, loose jets that fall within $|\eta| < 2.4$ are classified as central loose jets.

For events passing the dilepton and E_T^{miss} criteria described above, a region in which the tW signal is enhanced (signal region) and two regions dominated by background (control regions) are defined. The signal region contains events with exactly one jet passing the selection requirements, which is b-tagged (1j1t region). Two control regions enriched in $\mathrm{t\bar{t}}$ background are defined as having exactly two jets with either one or both b-tagged (2j1t and 2j2t regions, respectively).

Events from Monte Carlo simulation are used to estimate the contributions and kinematics of signal and background processes. Single-top-quark events are simulated at NLO with the POWHEG 1.0 event generator [29–32]; MADGRAPH 5.1.3 is used for simulating $\mathrm{t\bar{t}}$ and single-boson events (V+jets, where $\mathrm{V} = \mathrm{W}, \mathrm{Z}$) [33]. Samples are produced using a top-quark mass $m_t = 172.5$ GeV, consistent with its current best measurement [34]. Diboson backgrounds are simulated using PYTHIA 6.426 [35]. In all samples, fragmentation and hadronization are modeled with PYTHIA, and TAUOLA v27.121.5 is used to simulate τ decays [36]. The CTEQ6L1 and CTEQ6.6M PDF sets [37] are used for samples simulated at leading-order and NLO, respec-

Table 1: Event yields in the signal and control regions. Yields from simulation are shown with statistical (first) and systematic (second) uncertainties.

	1j1t	2j1t	2j2t
tW	1500±20±130	790±20±80	220±10±30
$\mathrm{t\bar{t}}$	7090±60±900	12910±80±1320	7650±60±1020
$\mathrm{Z}/\gamma^{\star}$, other	670±30±90	370±30±60	36±7±12
Tot. sim.	9260±70±1040	14070±90±1410	7910±70±1020
Data	9353	13479	7615

tively. A full simulation of the response of the CMS detector is performed for all generated events using a GEANT4-based model [38]. The simulation includes modeling of pileup, with the distribution of the number of interactions in simulation matching that in data. Simulated samples are normalized to the NNLO cross sections for $\mathrm{t\bar{t}}$ ($\sigma_{\mathrm{t\bar{t}}} = 245.8^{+6.2}_{-8.4}\,(\text{scale})^{+6.2}_{-6.4}\,(\text{PDF})\,\text{pb}$) [39], $\mathrm{Z}/\gamma^{\star}$, and W+jets processes, with approximate NNLO cross sections used for single top quark [17] and NLO for diboson processes. The $\mathrm{Z}/\gamma^{\star}$ simulation is reweighted to reproduce the $E_{\mathrm{T}}^{\text{miss}}$ distribution observed in data, using events with $m_{\ell\ell}$ in the vicinity of the Z-boson mass (81 to 101 GeV) to derive scale factors.

After the selection, the simulated samples in the 1j1t signal region contain predominantly tW and $\mathrm{t\bar{t}}$ events (comprising 16% and 76% of the events, respectively), with a smaller contribution from $\mathrm{Z}/\gamma^{\star}$ events (6%). The two control regions are dominated by $\mathrm{t\bar{t}}$ production. Event yields in simulation and data in the signal and control regions are shown in Table 1.

In order to separate the tW signal from the $\mathrm{t\bar{t}}$ background, a multivariate analysis based on boosted decision trees (BDT) [40] is used, implemented with the toolkit for multivariate data analysis [41]. The BDT analyzer is trained using 13 variables, chosen for their separation power in distinguishing tW and $\mathrm{t\bar{t}}$, as well as being well-modeled in simulation when checked in control regions. The most powerful variables are those involving loose jets in the event: the number of loose jets, number of central loose jets, and the number of loose jets that are b-tagged. Other variables with significant separation power are related to the kinematics of the system comprised of the leptons, jets and $E_{\mathrm{T}}^{\text{miss}}$: the scalar sum of their transverse momenta (H_{T}), the magnitude of the vector sum of their transverse momenta ($p_{\mathrm{T}}^{\text{sys}}$), and invariant mass of the system. A complete list of the variables used can be found in the Supplemental Material (Appendix A). The distributions of the number of loose jets and the p_{T} of the system in the 1j1t signal region are shown in Fig. 1 for all three final states (ee, eμ, and $\mu\mu$) combined.

The BDT analyzer provides a single discriminant value for each event. The distributions of the BDT discriminant in data and simulation are shown in Fig. 2 for the 1j1t, 2j1t, and 2j2t regions, combining all three final states together.

The uncertainty from all systematic sources is determined by estimating their effect on the normalization and shape of the BDT discriminant for all regions and final states. The dominant systematic uncertainties come from the choice of thresholds for the matrix element and parton showering (ME/PS) matching in simulation of $\mathrm{t\bar{t}}$ production and the renormalization/factorization scale. The effect of these uncertainties were estimated by producing simulated samples with the value of the ME/PS matching thresholds and renormalization/factorization scale doubled and halved from their respective initial values of 20 GeV and $m_{\mathrm{t}}^{2} + \sum p_{\mathrm{T}}^{2}$ (where the sum is over all additional final state partons), contributing a 14% and 12% uncertainty, respectively, to the measured cross section. The uncertainty due to the value of the top-quark mass used in simulation is estimated by simulating tW and $\mathrm{t\bar{t}}$ processes with a varied value for m_{t}, resulting in a

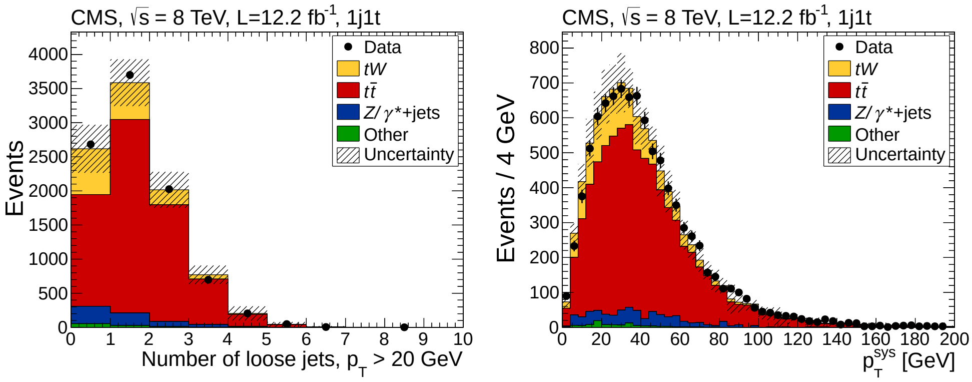

Figure 1: The number of loose jets in the event and the p_T of the system (p_T^{sys}) composed of the jet, leptons, and E_T^{miss}, in the signal region (1j1t) for all final states combined. Shown are data (points) and simulation (histogram). The hatched band represents the combined effect of all sources of systematic uncertainty.

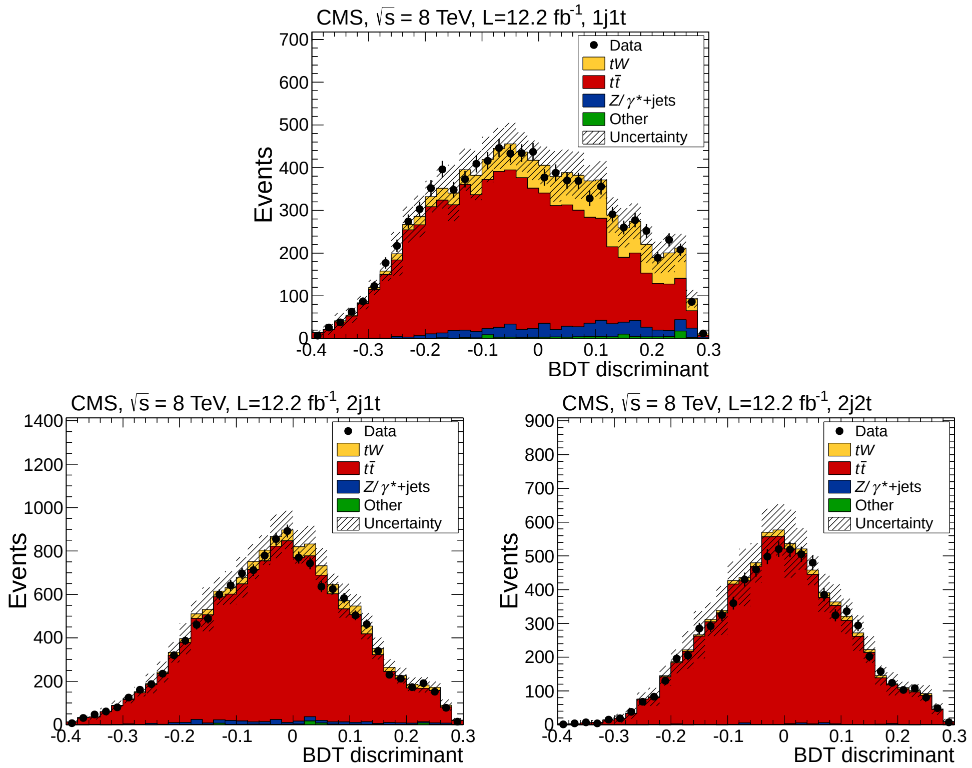

Figure 2: The BDT discriminant, in the signal region (1j1t) and control regions (2j1t and 2j2t) for all final states combined. Shown are data (points) and simulation (histogram). The hatched band represents the combined effect of all sources of systematic uncertainty.

9% effect on the cross section. The complete list of systematic uncertainties and corresponding effects on the cross section can be found in the Supplemental Material (Appendix A).

A simultaneous binned likelihood fit to the rate and shape of the BDT distributions of the three final states in the three regions is performed. The two control regions are included in the fit to allow for better determination of the $t\bar{t}$ contribution. The distributions for signal and background are taken from simulation. In the likelihood function, for each source of systematic uncertainty u, a nuisance parameter θ_u is introduced. The excess of events is quantified based on the score statistic q, chosen to enhance numerical stability, defined as

$$q = \frac{\partial}{\partial \mu} \ln \mathcal{L}(\mu = 0, \hat{\theta}_0 | \text{data})$$

where μ is the signal strength parameter (defined as the signal cross section in units of the SM prediction) and $\hat{\theta}_0$ is the set of nuisance parameters that maximizes the likelihood $\mathcal{L}$ for a background-only hypothesis ($\mu = 0$). The score statistic is evaluated for sets of four billion pseudo-experiments using a background-only hypothesis. The significance is determined based on the probability of producing a score statistic value in the background-only hypothesis as high or higher than that observed in data. The expected significance is evaluated using the median and central 68% interval of the score statistic values obtained in pseudo-experiments generated under a signal-plus-background hypothesis. A profile likelihood method is used to determine the signal cross section and 68% confidence level (CL) interval.

We observe an excess of events above the expected background with a p-value of 5×10^{-10} corresponding to a significance of $6.1\,\sigma$, compared to an expected significance from simulation of $5.4 \pm 1.4\,\sigma$. The measured cross section is found to be 23.4 ± 5.4 pb, where the uncertainty is mainly systematic, in agreement with the predicted SM value of $22.2 \pm 0.6\,(\text{scale}) \pm 1.4\,(\text{PDF})$ pb.

The cross section measurement is used to determine the absolute value of the Cabibbo-Kobayashi-Maskawa matrix element $|V_{tb}|$, assuming $|V_{tb}| \gg |V_{td}|$ and $|V_{ts}|$:

$$|V_{tb}| = \sqrt{\sigma_{tW}/\sigma_{tW}^{th}} = 1.03 \pm 0.12\,(\text{exp}) \pm 0.04\,(\text{th.})$$

where σ_{tW}^{th} is the theoretical prediction of the tW cross section assuming $|V_{tb}| = 1$, and the uncertainties are separated into experimental and theoretical values. Using the SM assumption $0 \leq |V_{tb}|^2 \leq 1$, a lower bound $|V_{tb}| > 0.78$ at 95% CL is found using the approach of Feldman and Cousins [42].

Using the same selection as in the BDT analysis, two cross-check analyses are performed. Events containing any b-tagged loose jets are rejected. Additionally, a requirement of $H_T > 160$ GeV is added in the $e\mu$ final state, where no E_T^{miss} requirement is applied. The effects of systematic uncertainties are taken into account in the same way as for the BDT analysis, and the same method for extraction of the significance and cross section is used. The first cross-check analysis is based on the distribution of p_T^{sys} rather than the BDT discriminant, and results in an observed significance of $4.0\,\sigma$ above a background-only hypothesis, with an expected significance of $3.2^{+0.4}_{-0.9}\,\sigma$, and a measured cross section of 24.3 ± 8.6 pb. The second cross-check analysis is based only on event counts after selection, and an excess of events is observed above the background with a significance of $3.6\,\sigma$, with an expected significance based on simulation of $2.8 \pm 0.9\,\sigma$, and a measured cross section of 33.9 ± 8.6 pb. Event yields in data and simulation for this analysis are shown in Fig. 3, with the simulation scaled to the result of the statistical fit. The results of both analyses are consistent with those found in the BDT analysis, but with larger, mostly systematic, uncertainties.

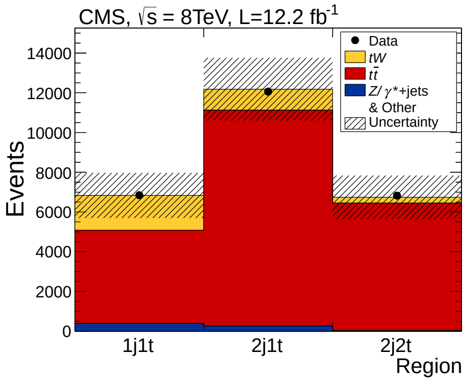

Figure 3: Event yields in data and simulation for events passing additional requirements from the cross-check analyses. Yields are shown in the 1j1t signal regions and 2j1t and 2j2t control regions for a combination of all three final states, with the simulation scaled to the outcome of the statistical fit from the event-count analysis. The hatched band represents the combined effect of all systematic uncertainties on the event yields.

In summary, the production of a single top quark in association with a W boson is observed for the first time. The analysis uses data collected by the CMS experiment in pp collisions at $\sqrt{s} = 8\,\text{TeV}$, corresponding to an integrated luminosity of $12.2\,\text{fb}^{-1}$. An excess of events above background is found with a significance of $6.1\,\sigma$, and a tW production cross section of $23.4 \pm 5.4\,\text{pb}$ is measured, in agreement with the standard model prediction.

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centres and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); MoER, SF0690030s09 and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); NRF and WCU (Republic of Korea); LAS (Lithuania); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS and RFBR (Russia); MESTD (Serbia); SEIDI and CPAN (Spain); Swiss Funding Agencies (Switzerland); NSC (Taipei); ThEPCenter, IPST, STAR and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

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A Supplemental Material

Two additional tables are provided giving details on the variables used in the BDT analysis and additional information on the sources of systematic uncertainty. Table 2 gives the definition of the thirteen variables used as inputs to the training of the BDT analyzer. Table 3 presents the contribution of each of the sources of systematic uncertainty in the analysis to the measured cross section uncertainty, as well as a brief description of the systematic uncertainty. The contribution due to each source are estimated by fixing the nuisance parameters associated with each of the sources one at a time, and measuring the effect on the uncertainty on the cross section.

Table 2: Variables used for BDT training

Variable Name	Description
# of loose jets	Number of loose jets, $p_\mathrm{T} > 20\,\mathrm{GeV}$, $\lvert\eta\rvert < 4.9$
# of central loose jets	Number of loose jets, $p_\mathrm{T} > 20\,\mathrm{GeV}$, $\lvert\eta\rvert < 2.4$
# of b-tagged loose jets	Number of loose jets, $p_\mathrm{T} > 20\,\mathrm{GeV}$, $\mathrm{q_b}$-tagged, $\lvert\eta\rvert < 2.4$
$p_\mathrm{T}^\mathrm{sys}$	Vector sum of p_T of leptons, jet, and $E_\mathrm{T}^\mathrm{miss}$
H_T	Scalar sum of p_T of leptons, jet, and $E_\mathrm{T}^\mathrm{miss}$
$p_\mathrm{T}(\mathrm{jet})$	p_T of the leading, tight, b-tagged jet
$p_\mathrm{T}(\text{loose jet})$	p_T of leading loose jet, defined as 0 for events with no loose jet present
$p_\mathrm{T}^\mathrm{sys}/H_\mathrm{T}$	Ratio of $p_\mathrm{T}^\mathrm{sys}$ to H_T for the event
m_sys	Invariant mass of the combination of the leptons, jet, and $E_\mathrm{T}^\mathrm{miss}$
$\mathrm{Centrality}(\mathrm{j}\ell\ell)$	Centrality of jet and leptons, defined as ratio of transverse to total energy
$p_\mathrm{T}(\mathrm{leptons})/H_\mathrm{T}$	Ratio of scalar sum of p_T of the leptons to the H_T of full system
$p_\mathrm{T}(\mathrm{j}\ell\ell)$	Vector sum of p_T of jet and leptons
$E_\mathrm{T}^\mathrm{miss}$	Missing transverse energy in the event

Table 3: Contributions to the systematic uncertainty in the measured cross section. The values are estimated by fixing each source one at a time and evaluating the change in the measured cross section uncertainty. Systematic uncertainties apply to all processes unless specifically noted.

Systematic uncertainty	$\Delta\sigma$ (pb)	$\Delta\sigma/\sigma$	Notes
ME/PS matching thresholds	3.3	14%	Matching threshold 2× and 1/2× nominal 20 GeV value in $\mathrm{t\bar{t}}$ simulation
Renormalization/factorization scale	2.9	12%	Scale value 2× and 1/2× nominal value of $m_\mathrm{t}^2 + \sum p_\mathrm{T}^2$ in $\mathrm{t\bar{t}}$ and tW simulation
Top-quark mass	2.2	9%	m_t varied in tW and $\mathrm{t\bar{t}}$ simulation by $\pm 2\,\mathrm{GeV}$
Fit statistical	1.9	8%	Remaining uncertainty in fit when all other systematic uncertainties are removed
Jet energy scale	0.9	4%	Jet energy scale varied up/down
Luminosity	0.7	3%	2.6% uncertainty in the measured luminosity
Z+jets data/simulation scale factor	0.6	3%	Varying scale factors used for correcting Z+jets $E_\mathrm{T}^\mathrm{miss}$ simulation
tW DR/DS scheme	0.5	2%	Difference between DR and DS scheme used for defining tW signal
$\mathrm{t\bar{t}}$ cross section	0.4	2%	Uncertainty in the cross section of $\mathrm{t\bar{t}}$ production
Lepton identification	0.4	2%	Uncertainty in scale factors for lepton efficiencies between data/simulation
PDF	0.4	2%	From choice of PDF
Jet energy resolution	0.2	1%	Energy resolution for jets varied up/down
b-tagging data/simulation scale factor	0.2	<1%	Variations in scale factors
$\mathrm{t\bar{t}}$ spin correlations	0.1	<1%	Difference between $\mathrm{t\bar{t}}$ simulation with/without spin correlations
Pileup	0.1	<1%	Varying effect of pileup
Top-quark p_T reweighting	0.1	<1%	Uncertainty due to differences in top quark p_T between data and $\mathrm{t\bar{t}}$ simulation
$E_\mathrm{T}^\mathrm{miss}$ modeling	0.1	<1%	Uncertainty in amount of unclustered $E_\mathrm{T}^\mathrm{miss}$
Lepton energy scale	0.1	<1%	Uncertainty in energy of leptons
Total	5.5	24%	

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