EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

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Measurement of the top quark pair production cross section in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$

The CMS Collaboration[*]

Abstract

The top quark pair production cross section is measured for the first time in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$ by the CMS experiment at the CERN LHC, using data corresponding to an integrated luminosity of $43\,\text{pb}^{-1}$. The measurement is performed by analyzing events with at least one electron and one muon of opposite charge, and at least two jets. The measured cross section is $746 \pm 58\,\text{(stat)} \pm 53\,\text{(syst)} \pm 36\,\text{(lumi)}\,\text{pb}$, in agreement with the expectation from the standard model.

*See Appendix B for the list of collaboration members

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The measurement of $t\bar{t}$ production at a center-of-mass energy not previously accessed has great discovery potential for physics beyond the standard model (SM), because new phenomena can significantly enhance the $t\bar{t}$ cross section. The increased energy also allows for a test of the production mechanism, dominated at the CERN LHC by gluon-gluon fusion, and of the validity of the theory of quantum chromodynamics (QCD). Furthermore, top quark production is an important source of background in many searches for physics beyond the SM, and its accurate evaluation is important. Previously, large samples of top quark events were collected in proton-proton collisions at the LHC at $\sqrt{s} = 7$ and 8 TeV and used to study $t\bar{t}$ production in different final states by the ATLAS [1–11] and CMS [12–20] collaborations.

This letter presents the first measurement of the $t\bar{t}$ production cross section $\sigma_{t\bar{t}}$ at $\sqrt{s} = 13$ TeV, utilizing data corresponding to an integrated luminosity of $43\,\mathrm{pb}^{-1}$ recorded by the CMS experiment. In the SM, top quarks are produced predominantly in $t\bar{t}$ pairs via the strong interaction, and each top quark decays almost exclusively to a W boson and a b quark. For this study, we select events that contain at least one electron and one muon of opposite charge, and at least two jets.

The central feature of the CMS detector [21] is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. A silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections, are located within the solenoid volume. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. A two-tier trigger system selects the most interesting pp collisions for offline analysis. A more detailed description of the CMS detector, together with a definition of its coordinate system and kinematic variables, can be found in Ref. [21].

We use several Monte Carlo (MC) generator programs to simulate signal and background processes. The next-to-leading-order (NLO) POWHEG (v2) [22, 23] generator is used to generate $t\bar{t}$ signal events, assuming a top quark mass of $m_t = 172.5$ GeV [24]. We utilize the NNPDF3.0 NLO [25] parton distribution functions (PDF) in the MC calculations. The events are interfaced to PYTHIA (v8.205) [26, 27] with the CUETP8M1 tune [28, 29] to simulate parton showering, hadronization, and the underlying event. An alternative sample is obtained using the HERWIG++ (v2.7.1) [30] program to model the parton shower. Another sample of $t\bar{t}$ events is generated using MG5_AMC@NLO (v5_2.2.2) [31] and MADSPIN [32] generators, and again PYTHIA (v8.205) for parton showering, hadronization, and the underlying event. The MC generators have been validated by comparing to unfolded differential distributions of $t\bar{t}$ production at $\sqrt{s} = 8$ TeV [33].

Background events are simulated by the MG5_AMC@NLO (v5_2.2.2) generator for W+jets production and Drell–Yan (DY) quark-antiquark annihilation into lepton-antilepton pairs through virtual photon or Z boson exchange, with normalization taken from data. Associated top quark and W boson production (tW) is simulated using POWHEG (v1) [34, 35] and PYTHIA (v8.205), and is normalized to the approximate next-to-next-to-leading-order (NNLO) cross section [36]. The contributions from WW, WZ and ZZ (referred to as VV) processes are simulated with PYTHIA (v8.205), and normalized to their NLO cross sections [37]. All other backgrounds are estimated from control samples extracted from collision data. The simulated samples include additional interactions per bunch crossing (pileup). On average, about 20 collisions per bunch crossing are present in our data.

The SM prediction for the $t\bar{t}$ production cross section at $\sqrt{s} = 13$ TeV is calculated with the TOP++ program [38] at NNLO in perturbative QCD, including soft-gluon resummation at next-to-next-to-leading-log order (NNLL) [39–44], assuming $m_t = 172.5$ GeV. The result is

$\sigma_{t\bar{t}}^{\text{NNLO+NNLL}} = 832^{+20}_{-29}\,(\text{scale}) \pm 35\,(\text{PDF} + \alpha_s)\,\text{pb}$. The expected yields for signal in all figures and tables are normalized to this value. The first uncertainty reflects uncertainties in the factorization and renormalization scales, μ_{F} and μ_{R}. The second uncertainty, associated with the PDFs and strong coupling constant α_s, is obtained by following the PDF4LHC prescription [45, 46] using the MSTW2008 68% CL NNLO [47, 48], CT10 NNLO [49, 50], and NNPDF2.3 5f FFN [51] PDF sets.

At the trigger level, events are required to contain one electron and one muon, where the electron has transverse momentum $p_{\text{T}} > 12\,\text{GeV}$ and the muon has $p_{\text{T}} > 17\,\text{GeV}$, or the electron has $p_{\text{T}} > 17\,\text{GeV}$ and the muon has $p_{\text{T}} > 8\,\text{GeV}$. Offline, particle candidates are reconstructed with the CMS particle-flow (PF) algorithm [52, 53]. The PF algorithm reconstructs and identifies each individual particle using an optimized combination of information from the various elements of the CMS detector.

Events are selected to contain one electron [54] and one muon [55] of opposite charge, both of which are required to have $p_{\text{T}} > 20\,\text{GeV}$ and $|\eta| < 2.4$ (but excluding electrons within a small region of $|\eta|$ between the barrel and endcap sections of the ECAL). The electron and muon candidates are required to be sufficiently isolated from nearby jet activity as follows. For each electron and muon candidate, a cone of $\Delta R = 0.3$ and $\Delta R = 0.4$, respectively, is constructed around the direction of the track at the event vertex, where ΔR is defined as $\sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, and $\Delta\eta$ and $\Delta\phi$ are the distances in pseudorapidity and azimuthal angle. Excluding the contribution from the lepton candidate, the scalar sum of the p_{T} of all particle candidates that are inside ΔR and are consistent with arising from the chosen primary event vertex is calculated to define a relative isolation discriminant, I_{rel}, through the ratio of this sum to the p_{T} of the lepton candidate. The neutral-particle contribution to I_{rel} is corrected for pileup based on the average energy density deposited by neutral particles in the event. This corresponds to an average p_{T} from pileup determined event-by-event that is subtracted from the summed scalar p_{T} in the isolation cone. An electron and muon candidate is selected if they have respective values of $I_{\text{rel}} < 0.11$ and $I_{\text{rel}} < 0.12$.

In events with more than one pair of leptons passing the above selection, the two leptons of opposite charge and different flavor with the largest p_{T} are selected for further study. Events with τ leptons contribute to the measurement only if they decay to electrons or muons that satisfy the selection requirements, and are included in the MC simulations.

The efficiency of the lepton selection is measured using a "tag-and-probe" method in same-flavor dilepton events enriched in Z boson candidates, as described in Refs. [19, 56]. Differences in the event topology with respect to $t\bar{t}$ production are accounted for as a systematic uncertainty. In the current data set, the measured values for the combined identification and isolation efficiencies are typically 92% for muons and 77% for electrons. Based on a comparison of lepton selection efficiencies in data and simulation, the event yield in simulation is corrected using p_{T}- and η-dependent data-to-simulation scale factors (SF) to provide consistency with data. They have average values of 1.00 for muons and 0.96 for electrons.

Candidate events with dilepton invariant masses of $m_{\text{e}\mu} < 20\,\text{GeV}$ are removed to suppress backgrounds, mainly from low-mass DY processes. Jets are reconstructed from the PF particle candidates using the anti-k_{T} clustering algorithm [57] with a distance parameter of 0.4, optimized for the running conditions at higher center-of-mass energy. The jet energy is corrected for pileup in a manner similar to that used to find the energy within the lepton isolation cone. Jet energy corrections are also applied as a function of jet p_{T} and η [58] to data and simulation. Events are required to have at least two reconstructed jets with $p_{\text{T}} > 30\,\text{GeV}$ and $|\eta| < 2.4$.

Backgrounds in this analysis arise primarily from tW, DY, and VV events in which at least two leptons are produced. Background yields from tW and VV events are estimated from simulation. The $e^{\pm}\mu^{\mp}$ DY background normalization is estimated from data using the "$R_{out/in}$" method [19, 59, 60], where events with e^+e^- and $\mu^+\mu^-$ final states are explored as follows. A data-to-simulation normalization factor is estimated from the number of events within the Z boson mass window in data, and extrapolated to the number of events outside the Z mass window with corrections based on control regions in data enriched in DY events. This factor is found to be 1.04 ± 0.16 (stat).

Other background sources, such as $t\bar{t}$ or W+jets events with decays into one lepton and jets, can contaminate the signal sample if a jet is incorrectly reconstructed as a lepton, or an event contains a lepton from the decay of bottom or charm hadrons. These are grouped into the nonprompt-lepton category, together with contributions that can arise, for example, from the decays of mesons, photon conversions to e^+e^- pairs in the material of the detector, or effects from detector resolution. The nonprompt-lepton background is estimated from an extrapolation of a control region of same-sign (SS) dilepton events to the signal region of opposite-sign (OS) dileptons. The SS control region is defined using the same criteria as used for the nominal signal region, except requiring $e\mu$ pairs of the same charge. The SS dilepton events predominantly contain at least one misidentified lepton. Other SM processes, such as DY, tW, VV and $t\bar{t}$ dilepton production have significantly smaller contributions, and are estimated using simulation. The scaling from the SS control region in data to the signal region is performed using an extrapolation factor, extracted from MC simulation, given by the ratio of the number of OS events with misidentified leptons to the number of SS events with misidentified leptons. From the eight same-sign events observed in data, the expected contamination of 1.7 ± 0.4 events due to DY, tW, VV and $t\bar{t}$ dilepton production is subtracted, and the result is multiplied by the OS to SS ratio of 1.4 ± 0.3 to obtain an estimate of 8.5 ± 4.4 nonprompt lepton events contaminating the signal, including statistical and systematic uncertainties. This agrees with predictions from MC simulations of semileptonic $t\bar{t}$ and W+jets events.

Figure 1 shows (left) the multiplicity of jets and (right) the scalar p_T sum of all jets (H_T) for events passing the dilepton criteria. Agreement is observed between data and the predictions for signal and background.
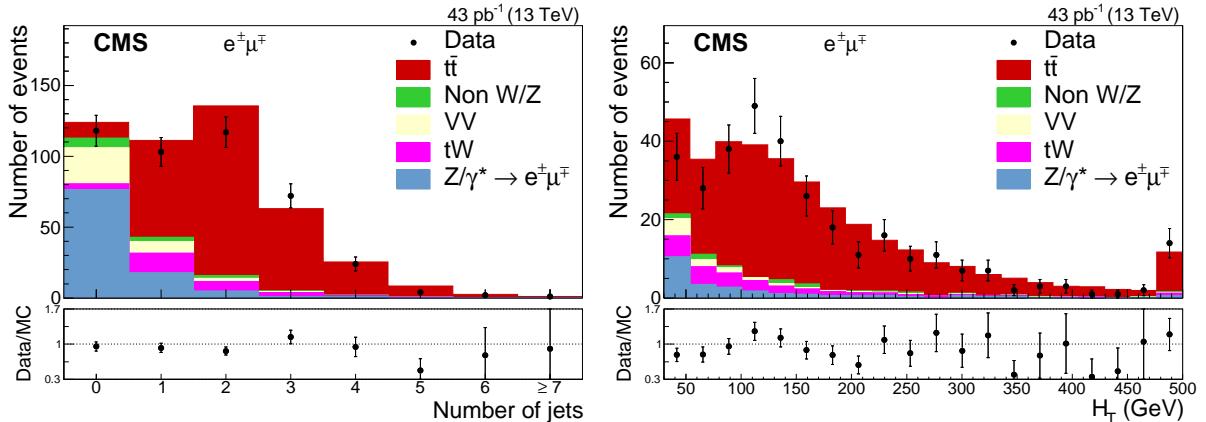

Figure 1: The distributions in (left) the jet multiplicity, and (right) H_T in events passing the dilepton criteria. The expected distributions for $t\bar{t}$ signal and individual backgrounds are shown after implementing data-based corrections; the last bin contains the overflow in events. The ratios of data to the sum of the expected yields are given at the bottom of each panel.

After requiring at least two jets, we obtain the plots presented in Fig. 2, where (left) shows the

distribution in the invariant dilepton mass $m_{e\mu}$, which is sensitive to the existence of a new heavy object decaying into a $t\bar{t}$ pair. Figure 2 (right) shows the difference in azimuthal angle between the two leptons, $\Delta\phi(e, \mu)$, and explores the correlation between the t and $\bar{t}$ spins [61–66]. For both distributions, data are in agreement with the SM expectations.
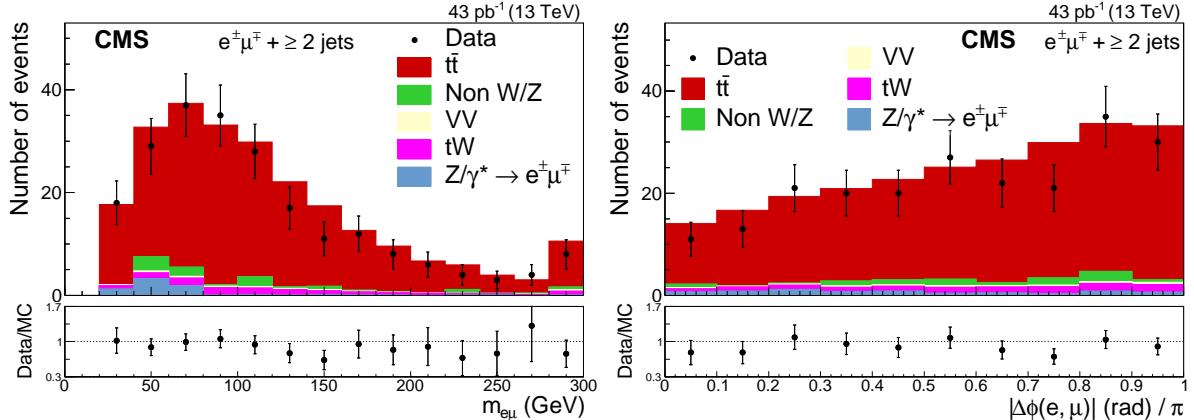

Figure 2: The distributions in (left) the dilepton invariant mass, and (right) the difference in the azimuthal angle between the two leptons after all selections. The last bin in (left) contains the overflow events. The ratios of data to the sum of the expected yields are given at the bottom of each panel.

The dominant uncertainty is due to the preliminary integrated luminosity, which is estimated from x-y beam-beam scans performed in July 2015 utilizing the methods of Ref. [67]. The resulting uncertainty in the integrated luminosity is 4.8%.

Smaller uncertainties arise from the measured trigger efficiency, and the lepton identification and isolation efficiencies. After the offline dilepton selection, the trigger efficiency is measured in data to be $(91 \pm 4)\%$ using triggers based on the p_T imbalance in the event. This efficiency is applied to the MC simulations and the uncertainty is taken as a global uncertainty. The uncertainties on the electron and muon identification and isolation efficiencies are estimated by changing the p_T- and η-dependent SF values by one standard deviation ($\pm 1\sigma$). The modeling of lepton energy scales is studied using $Z \to ee$ and $\mu\mu$ events in data and in simulation, yielding an uncertainty in the electron energy scale of 1%, and in the muon energy scale of 0.5%. The impact of the uncertainty in the jet energy scale (JES) is estimated by changing the p_T- and η-dependent JES SF by $\pm 1\sigma$, and the uncertainty in jet energy resolution (JER) uncertainty is estimated through similar η-dependent $\pm 1\sigma$ changes in the JER SF. The maximum of each of the deviations is taken as the uncertainty.

The distribution of the number of vertices per beam crossing is compared between data and simulation. The results indicate agreement of the total pp inelastic cross section within 10%. The result of varying this cross section by $\pm 10\%$ for all MC samples is used to obtain the systematic uncertainty due to pileup.

Theory uncertainties on $t\bar{t}$ production involve the systematic bias related to the missing higher-order diagrams in POWHEG, and is estimated through studies of the signal acceptance by changing the renormalization and factorization scales in POWHEG simultaneously within the range $[\mu/2, 2\mu]$ ($\mu = \mu_R = \mu_F$). In addition, the predictions of the NLO generators MG5_AMC@NLO (v5_2.2.2) and POWHEG are compared for $t\bar{t}$ production, where both use PYTHIA (v8.205) for hadronization, parton showering, and simulation of the underlying event. The uncertainty arising from the hadronization model mainly affects the JES and the fragmentation of jets. The uncertainty in the JES already contains a contribution from the uncertainty in the hadroniza-

tion. The hadronization uncertainty is also determined by comparing samples of events generated with POWHEG, where the hadronization is either modeled with PYTHIA (v8.205) or HERWIG++ (v2.7.1). This also includes differences in parton showering, and the underlying event, and is called $t\bar{t}$ modeling uncertainty. All theory uncertainties on $t\bar{t}$ production are taken as the maximum difference found in the results. The uncertainty from the choice of PDF is determined by reweighting the sample of simulated $t\bar{t}$ events according to the 26 CT10 NLO [49, 50] and the 100 NNPDF3.0 sets [25] of PDF uncertainties.

An uncertainty of 30% in cross sections for tW and VV backgrounds are taken from measurements [68–76]. For DY production, a global cross section uncertainty of 15% is applied, which is derived from the variation of the SF for events passing the dilepton criteria and events passing all selection cuts. The systematic uncertainty in the estimated nonprompt lepton background is given mainly by the systematic uncertainty in the ratio of OS to SS events with misidentified leptons in the MC simulations. We checked how well the simulation models the production of misidentified leptons by examining additional control regions, with the observed discrepancy used to assign an uncertainty of 23% to the method.

Table 1 summarizes the magnitude of the statistical and systematic uncertainties from different sources contributing to the $t\bar{t}$ production cross section. All sources of uncertainties are added in quadrature.

Table 1: Summary of individual contributions to the systematic uncertainty in the $\sigma_{t\bar{t}}$ measurement. The uncertainties are given in pb, and as relative uncertainties. The separate total systematic uncertainty without integrated luminosity, the part attributed to the integrated luminosity, and the statistical contributions are added in quadrature to obtain the total uncertainty.

Source	$\Delta\sigma_{t\bar{t}}$ (pb)	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)
Trigger efficiencies	33	4.4
Lepton efficiencies	25	3.4
Lepton energy scale	<1	≤0.1
Jet energy scale	11	1.5
Jet energy resolution	<1	≤0.1
Pileup	5.2	0.7
QCD scales	1.4	0.2
NLO generator of $t\bar{t}$ signal	14	1.9
Modeling of $t\bar{t}$ signal	13	1.8
PDF	18	2.4
Single top tW background	13	1.8
VV background	3.5	0.5
Drell-Yan background	4.1	0.5
Nonprompt leptons background	7.6	1.0
Total systematic (w/o luminosity)	53	7.2
Integrated luminosity	36	4.8
Statistical uncertainty	58	7.8
Total	87	12

Table 2 shows the total number of events observed in data, together with the total number of background events expected from simulation or estimated from data. The mean acceptance multiplied by the selection efficiency and the branching fraction, as estimated from simulation at $m_{\mathrm{t}} = 172.5\,\mathrm{GeV}$, is $\epsilon = (0.60 \pm 0.04)\%$, including statistical and systematic uncertainties. The

measured fiducial cross section for $t\bar{t}$ production with two leptons (one electron and one muon) in the range $p_T > 20\,\text{GeV}$ and $|\eta| < 2.4$, is $\sigma_{t\bar{t}}^{\text{fid}} = 12.4 \pm 1.0\,(\text{stat}) \pm 1.0\,(\text{syst}) \pm 0.6\,(\text{lumi})\,\text{pb}$. After applying all corrections, the inclusive cross section is measured to be $\sigma_{t\bar{t}} = 746 \pm 58\,(\text{stat}) \pm 53\,(\text{syst}) \pm 36\,(\text{lumi})\,\text{pb}$.

Table 2: The number of eμ events after final event selection expected for background, and observed in data. The uncertainties represent the statistical and systematic components added in quadrature.

Source	Number of events $e^{\pm}\mu^{\mp}$
Drell–Yan	6.9 ± 1.2
Nonprompt leptons	8.5 ± 4.4
tW	10.9 ± 3.4
VV	2.7 ± 0.9
Total background	29.1 ± 5.7
Data	220

A linear parametrization of the acceptance dependence on m_t in the range 169.5–175.5 GeV results in a cross section reduction of $\approx 0.7\%$ at $m_t = 173.34\,\text{GeV}$, the current world average of the top quark mass [24].

In an alternative analysis, the selected sample is split into events with 0, 1, 2, and > 2 b quark jets, and 0, 1, 2, and >2 additional light-flavor or gluon jets (i.e., not identified as b quark jets). Jets are identified as b quark jets using the combined secondary vertex (CSV) algorithm [77]. A maximum likelihood fit of the yields in different input samples is performed to extract simultaneously $\sigma_{t\bar{t}}$ and the b tagging efficiency. Systematic uncertainties are implemented through nuisance parameters [78]. This result is within 1% of the nominal analysis.

Figure 1 in Appendix A presents a summary of results for $\sigma_{t\bar{t}}$ from the combination of the Tevatron measurements at 1.96 TeV [79], from CMS measurements at $\sqrt{s} = 7$ and 8 TeV [14, 19], and from the measurement presented here at $\sqrt{s} = 13\,\text{TeV}$, compared to the NNLO+NNLL predictions as a function of $\sqrt{s}$ for p$\bar{\text{p}}$ and pp collisions [44].

In summary, the first measurement of the $t\bar{t}$ production cross section in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$ is presented for events containing an electron-muon pair and at least two jets. The measurement is obtained through an event-counting analysis based on a data sample corresponding to an integrated luminosity of $43\,\text{pb}^{-1}$. The result is $\sigma_{t\bar{t}} = 746 \pm 58\,(\text{stat}) \pm 53\,(\text{syst}) \pm 36\,(\text{lumi})\,\text{pb}$, with a total relative uncertainty of 12%. This measurement is consistent with the SM prediction of $\sigma_{t\bar{t}}^{\text{NNLO+NNLL}} = 832^{+40}_{-46}\,\text{pb}$ for a top quark mass of 172.5 GeV.

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A $t\bar{t}$ production cross section in $p\overline{p}$ and pp collisions as a function of $\sqrt{s}$
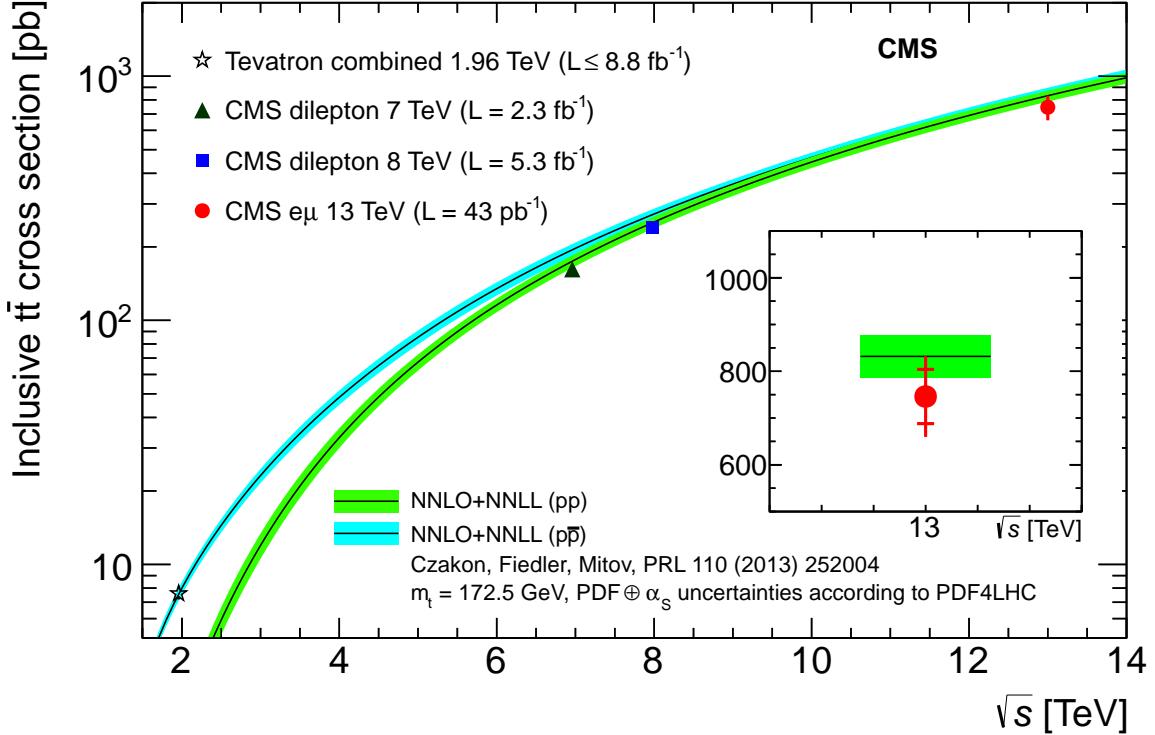
Figure A.1: The $t\bar{t}$ production cross section in $p\overline{p}$ and pp collisions as a function of $\sqrt{s}$. The Tevatron combination is given at $\sqrt{s} = 1.96$ TeV [79], as are the CMS results at 7 and 8 TeV in the dilepton channels [14, 19]. The CMS result at 13 TeV is also shown in the figure where the inner error bar corresponds to the statistical uncertainty and the outer one to the total uncertainty. The measurements are compared to NNLO+NNLL theoretical predictions [44].

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