Available on CMS information server **CMS CR -2022/158**

**The Compact Muon Solenoid Experiment**

**Conference Report**

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

**27 September 2022 (v3, 03 October 2022)**

# $t\bar{t}$ Production at CMS

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**Abstract**

The most recent inclusive and differential measurements of top quark pair production are presented. Data collected with the CMS experiment in proton-proton collisions at the LHC at different centre-of-mass energies are used and the results are compared to the standard model predictions.

Presented at *LHCP2022 10th Annual Large Hadron Collider Physics Conference*

PROCEEDINGS OF SCIENCE

# $t\bar{t}$ Production at CMS

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*The Tenth Annual Conference on Large Hadron Collider Physics - LHCP2022*
*16-20 May 2022*
*online*

*Speaker

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## 1. Introduction

Top quarks are produced at a high rate at the CERN LHC, more than 100 million top quark pairs ($t\bar{t}$) were produced in Run 2. While the dominant top quark production channels of pair production ($\sigma \approx 830$ fb) and $t$ channel single production ($\sigma \approx 220$ fb) have been measured with high precision, other more rare production modes are becoming fully accessible. This document provides a review of the latest experimental studies of measurements of $t\bar{t}$ production with the CMS detector [1] at the LHC proton-proton (pp) collider at different centre-of-mass energies ($\sqrt{s}$). The results are compared to the standard model (SM) predictions.

## 2. Differential $t\bar{t}$ production cross sections using lepton+jets events

Measurements of differential and double-differential $t\bar{t}$ production cross sections have been presented as a function of many kinematic properties of the top quarks and the $t\bar{t}$ system at the parton and particle levels, where the latter reduces extrapolations based on theoretical assumptions [2]. In addition, the number of additional jets and kinematic variables in bins of jet multiplicities have been measured at the particle level. The data correspond to an integrated luminosity of 137 fb$^{-1}$. The $t\bar{t}$ cross sections are measured in the lepton+jets channel with a single electron or muon, and jets in the final state. For the first time, the full spectra of differential cross sections are determined using a combination of resolved and boosted $t\bar{t}$ topologies, in which the $t\bar{t}$ decay products can be either identified as separated jets and isolated leptons or as collimated and overlapping jets, respectively. The combination of multiple reconstruction categories provides constraints on the systematic uncertainties and results in a significantly improved precision with respect to previous measurements. For a top quark transverse momentum $p_T < 500$ GeV the uncertainty is reduced by about 50% compared with previous CMS measurements. The dominant sources of systematic uncertainties are the jet energy scale, integrated luminosity, and $t\bar{t}$ modeling.

Most differential distributions are found to be compatible with the SM predictions of the event generators POWHEG [3] + PYTHIA [4], POWHEG + HERWIG [5], and MG5_aMC@NLO [6] + PYTHIA. In addition, the parton-level cross sections are compared to the next-to-next-to-leading-order (NNLO) quantum chromodynamics calculations obtained with MATRIX [7] that come with a significantly reduced theoretical uncertainty. A softer top quark $p_T$ spectrum is observed compared to most of the next-to-leading-order (NLO) predictions. Deviations between the predictions and data are observed when the top quark $p_T$ is measured in bins of the $t\bar{t}$ invariant mass and $p_T$. The POWHEG + HERWIG and MG5_aMC@NLO + PYTHIA simulations do not give a good description of the observed jet multiplicities and related observables such as the scalar $p_T$ sum of additional jets. The total $t\bar{t}$ production cross section is measured to be $\sigma = 791 \pm 25$ pb, which constitutes the most precise measurement in the lepton+jets channel to date.

## 3. Differential cross sections for the production of top quark pairs and additional jets

A measurement of differential $t\bar{t}$ production cross sections was presented, performed with events containing two oppositely charged leptons (electrons or muons) [8]. The data used in this analysis correspond to an integrated luminosity of 138 $fb^{-1}$. Differential cross sections are measured as functions of kinematical observables of the $t\bar{t}$ system, the top quark and antiquark and their decay products, and the total number of additional jets in the event not originating from the $t\bar{t}$ decay. The measurements are performed as function of one observable, or simultaneously as functions of two or three kinematic variables. The differential cross sections are defined both with particle-level objects in a fiducial phase space close to that of the detector acceptance and with parton-level top quarks in the full phase space. Overall, both the statistical and the systematic uncertainties in the measurements are improved by a factor of about 2 compared to previous analyses based on the 2016 data only.

Predictions of several NLO Monte Carlo event generators that differ in the hard matrix element, parton shower, and hadronization models, were compared to the data. The predictions of these MC models, without taking theoretical uncertainties into account, generally fail to describe a large fraction of the measured cross sections. The calculations predict the top quark and antiquark to have harder transverse momentum and more-central rapidity distributions than observed in the data. The invariant mass and rapidity distributions of the $t\bar{t}$ system are reasonably well described by the models overall. For the $t\bar{t}$ $p_T$ spectrum, the predictions exhibit larger differences and none of them provides a good description of the data. Double- and triple-differential cross sections show enhanced model-to-data discrepancies, for instance the effect of a harder $p_T(t)$ spectrum in the models is pronounced at high $m(t\bar{t})$. Cross sections as functions of kinematic observables of the leptons and b jets originating from the decay of the top quark and antiquark are measured with high precision. Overall, the observed trends for these objects follow those for the top quarks and antiquarks, with the models predicting harder transverse momentum spectra than seen in the data. For the leptons, this effect is somewhat enhanced and also the dilepton invariant mass spectrum is harder in the models than in the data. The studies of the $t\bar{t}$ and top quark and antiquark kinematical distributions as a function of the jet multiplicity show multiplicity-dependent shape differences between data and models. There is an indication that the trend of harder $p_T(t)$ distributions in the models is localized at small jet multiplicities.

Selected kinematic spectra were also compared to a variety of predictions beyond NLO precision. For observables of the top quark and the $t\bar{t}$ systems, these predictions provide descriptions of the data that are of similar or improved quality, compared to the MC models, except for kinematic spectra where the theory scale uncertainties are large. For observables of the leptons and b jets, the tested NNLO model provides a data description quality that is on average comparable but not better than that of the NLO MC models.

## 4. Search for central exclusive production of top quark pairs with tagged protons

We have searched for the central exclusive production of $t\bar{t}$ pairs in pp interactions, for the first time using tagged intact protons, reconstructed by the CMS-TOTEM Precision Proton Spectrometer [9]. The $t\bar{t}$ pairs are reconstructed by the CMS detector either in the dilepton or the lepton+jets decay modes: the search is conducted separately for the two modes, and the results are then combined. With a data sample at a centre-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 29.4 $fb^{-1}$, results consistent with predictions from the SM are obtained, and an upper limit of 0.59 pb at the 95% confidence level is set on the central exclusive production of $t\bar{t}$ pairs.

## 5. Inclusive $t\bar{t}$ production cross section at $\sqrt{s}$ = 5.02 TeV

A measurement of the $t\bar{t}$ production cross section at a centre-of-mass energy of 5.02 TeV is presented for events with one electron and one muon of opposite charge, and at least two jets, using pp collisions collected by the CMS experiment corresponding to an integrated luminosity of 302 $pb^{-1}$ [10]. The measured cross section is found to be $\sigma$ = 60.7 ± 5.0 (stat) ± 2.8 (syst) ± 1.1 (lumi) pb. To reduce the statistical uncertainty, a combination with the single lepton + jets measurement, using a data set collected in 2015 at the same centre-of-mass energy and corresponding to an integrated luminosity of 27.4 $pb^{-1}$ [11], is performed. A measurement of 63.0 ± 4.1 (stat) ± 3.0 (syst+lumi) pb is obtained, in agreement with the prediction from the SM of $66.8^{+2.9}_{-3.1}$ pb.

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