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The Compact Muon Solenoid Experiment

Conference Report

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

29 August 2022 (v3, 12 September 2022)

Measurement of differential cross sections for the production of top quark pairs and of additional jets in pp collisions at $\sqrt{s} = 13$ TeV

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Abstract

Differential cross sections for top quark pair ($\mathrm{t\bar{t}}$) production are measured in proton-proton collisions at a centre-of-mass energy of 13 TeV using a sample of events containing two oppositely charged leptons. The data were recorded with the CMS detector at the LHC and correspond to an integrated luminosity of 138 fb^{-1}. Differential cross sections are measured as functions of kinematic observables of the $\mathrm{t\bar{t}}$ system, the top quark and antiquark and their decay products, and the number of additional jets in the event not originating from the $\mathrm{t\bar{t}}$ decay. These cross sections are measured as function of one, two, or three variables and are presented at the parton and particle levels. The measurements are compared to standard model predictions of Monte Carlo event generators with next-to-leading-order accuracy in quantum chromodynamics (QCD) at matrix-element level interfaced to parton showers. Some of the measurements are also confronted with predictions beyond next-to-leading-order precision in QCD. The nominal predictions from all calculations, neglecting theoretical uncertainties, do not describe well several of the measured cross sections, and the deviations are found to be largest for the multi-differential cross sections.

Presented at *The Tenth Annual Conference on Large Hadron Collider Physics - LHCP2022*

PROCEEDINGS OF SCIENCE

Measurement of differential cross sections for the production of top quark pairs and of additional jets in pp collisions at $\sqrt{s} = 13$ TeV

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

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1. Introduction

The top quark is the heaviest elementary particle, which would suggest a possible involvement in the production- and decay-modes of new physics processes at higher energy scales. Thus, differential measurements of top quark pair ($t\bar{t}$) production provide crucial tests of the Standard Model (SM) and are additionally sensitive to SM parameters like the top quark mass, the strong coupling constant and parton distribution functions (PDFs). In this analysis [1] normalized and absolute cross sections are measured in the dilepton channel at parton and/or particle level as functions of kinematic observables of the $t\bar{t}$ system, the top quark and antiquark and their decay products, and the number of additional jets in the event not originating from the $t\bar{t}$ decay. The measurements are based on pp collision data recorded by the CMS experiment from 2016 to 2018 at a center-of-mass energy of 13 TeV. This period is known as Run 2 and corresponds to an integrated luminosity of 138 fb^{-1}. Roughly 100 million $t\bar{t}$ have been produced throughout this time, which facilitates unprecedented precision in measurements of their kinematic distributions and topology.

2. Event selection and cross section measurements

The selection is performed in the dileptonic channel in which both top quarks decay to prompt ee, μμ and eμ final states, and where decay processes involving intermediate W boson decays via τ are vetoed and treated as background. Events with exactly two isolated leptons are selected using a combination of single and dilepton triggers and the leading (trailing) lepton must have $p_T \geq 25(20)$ GeV. A minimum of two jets with $p_T \geq 30$ GeV and at least one b-tag are also required.

The $t\bar{t}$ system is reconstructed from the visible decay objects and the top quark mass, W boson mass and missing transverse energy are applied as kinematic constraints in order to obtain the neutrino momenta. The major backgrounds constitute the single top tW process, Z+jets and non-signal $t\bar{t}$ events (labelled $t\bar{t}$ other). All remaining backgrounds are collectively labelled "Minor bg". The transverse momentum (invariant mass) of the $t\bar{t}$ system is shown on the left (right) in Fig. 1 after the full selection and kinematic reconstruction, where the data are shown by black dots with error bars representing the statistical uncertainties. The hatched band includes all shape uncertainties from systematic sources. The reference generator Powheg (version 2) [2–4] interfaced to Pythia8 ("POW+PYT") [5, 6] is generally observed to give a good description of the data.

The normalized differential cross section is defined as

$$\frac{1}{\sigma}\frac{d\sigma_i}{dX} = \frac{1}{\Delta_i^X}\frac{x_i}{\sum_i x_i}$$

for an observable X, where σ is the total cross section, x_i is the observed number of signal events in bin i after unfolding and Δ_i^X is the corresponding bin width. Background is subtracted from the data after the full selection and kinematic reconstruction, and the data is subsequently corrected for detector effects such as resolutions, efficiencies and acceptances in the unfolding procedure with the TUnfold package [7], where Tikhonov regularization [8], based on second order derivatives, is used and the bias vector is estimated from the nominal $t\bar{t}$ simulation. Measurements are performed for two different definitions of the top quark at generator level, namely at parton level in the full phase space and at particle level in the fiducial phase space, where the selection of the latter is chosen to mimic the selection at detector level in order to minimize extrapolation effects.

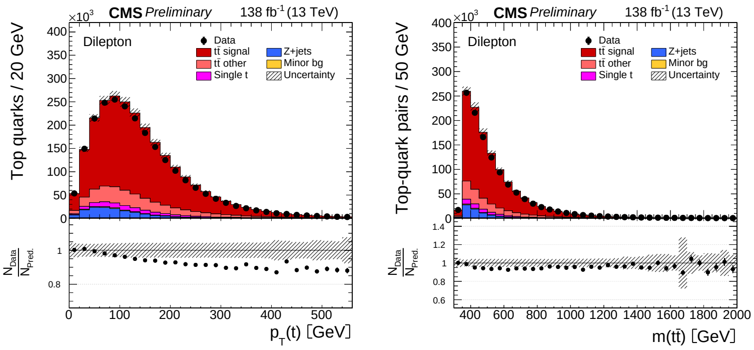

Figure 1: Control plots are shown for $p_{\mathrm{T}}(\mathrm{t})$ (left) and $m(\mathrm{t\bar{t}})$ (right) after the full selection.

3. Results

Figure 2 (3) shows normalized differential $\mathrm{t\bar{t}}$ production cross sections measured at parton (particle) level in the full (fiducial) phase space. Comparisons are done to next-to-leading order Monte Carlo models (NLO MC) and state of the art SM predictions at beyond-NLO accuracy in QCD. The former set also includes the alternative generators MG5_aMC@NLO[FxFx] [9, 10] and Powheg (version 2) interfaced to Pythia8 and Herwig7 [11], denoted by “FXFX+PYT” and “POW+HER”, respectively. The latter set is constituted by $a\mathrm{N}^3\mathrm{LO}$[12], Matrix (NNLO) [13–20], Stripper (NNLO) [21–24] and MiNNLOPS (NNLOPS) [25–27]. The data is shown by black dots and the predictions by coloured markers, where error bars on “POW+PYT” (all beyond-NLO models) illustrate all theoretical uncertainties (only scale uncertainties). The grey and yellow bands illustrate the statistical uncertainty and the total systematic and statistical uncertainties added in quadrature, respectively. The total uncertainty is generally within 2 to 20%, where the dominant contribution comes from the jet energy scale. All predictions use the PDF set NNPDF3.1 [28] at NNLO accuracy and assume a value of m_t = 172.5 GeV for the top quark mass.

The NLO MC models are observed to have harder $p_{\mathrm{T}}(\mathrm{t})$ spectra when compared with data and the beyond-NLO models. Overall “FXFX+PYT” provides the least accurate predictions, however, no single model at NLO or beyond-NLO precision can describe the data well for all of the measured cross sections. The beyond-NLO models show similar or improved performance when compared with the reference generator “POW+PYT”, as seen for e.g. $p_{\mathrm{T}}(\mathrm{t})$, but fail to describe the data for observables that exhibit a large impact from scale variations, e.g. $p_{\mathrm{T}}(\mathrm{t\bar{t}})$. The model Stripper exhibits fluctuations around the nominal data distribution for $||\eta(\mathrm{l\bar{l}})|, p_{\mathrm{T}}(\mathrm{l\bar{l}})|$, which is a general trend observed for this model and double-differential spectra at particle level.

4. Summary

A selected number of cross sections were presented from the preliminary publication [1], which includes a comprehensive set of normalized and absolute cross sections using full Run 2 data at 13 TeV. The measurements are performed at parton and/or particle level as functions of kinematic observables of the $\mathrm{t\bar{t}}$ system, the top quark and antiquark and their decay products, and the number of additional jets in the event not originating from the $\mathrm{t\bar{t}}$ decay. Several new observables have been measured for the first time ever and the total uncertainty has been reduced by a factor of ≈ 2 with respect to the previous analysis in the dilepton channel using 2016 data [29].

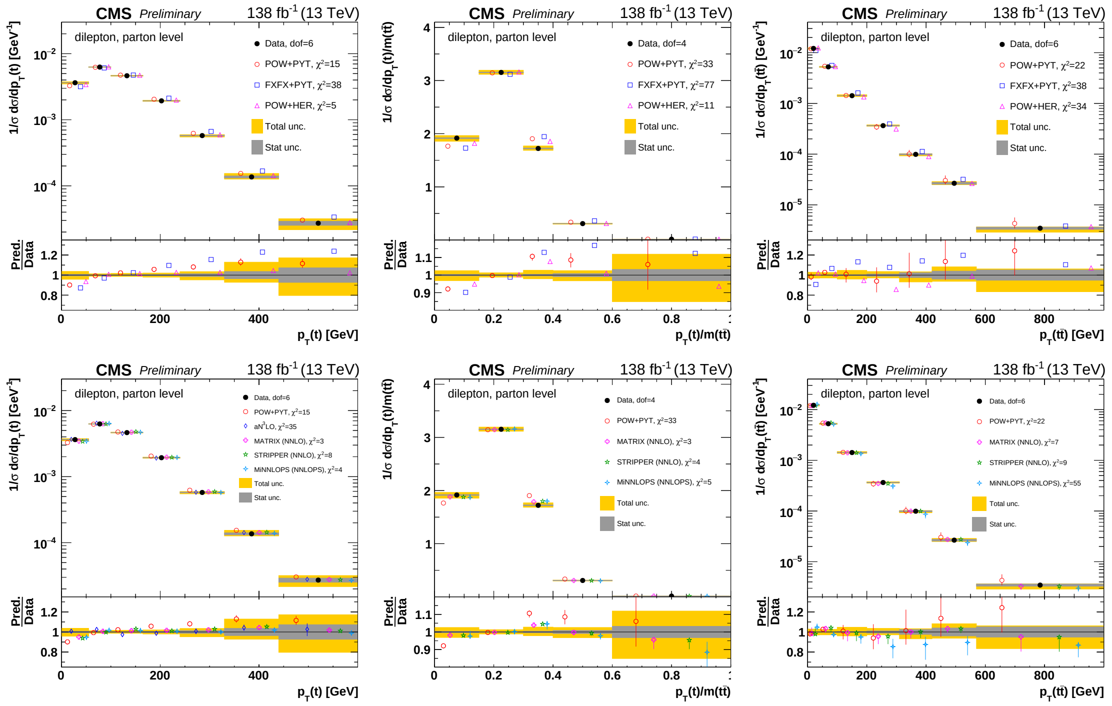

Figure 2: Normalized differential cross sections of $\mathrm{t\bar{t}}$ production are shown for $p_{\mathrm{T}}(\mathrm{t})$ (left), $p_{\mathrm{T}}(\mathrm{t})/m(\mathrm{t\bar{t}})$ (middle) and $p_{\mathrm{T}}(\mathrm{t\bar{t}})$ (right). The measurements are performed at parton level in the full phase space and comparisons are done to NLO MC models in the upper row and to beyond-NLO models in the bottom row.

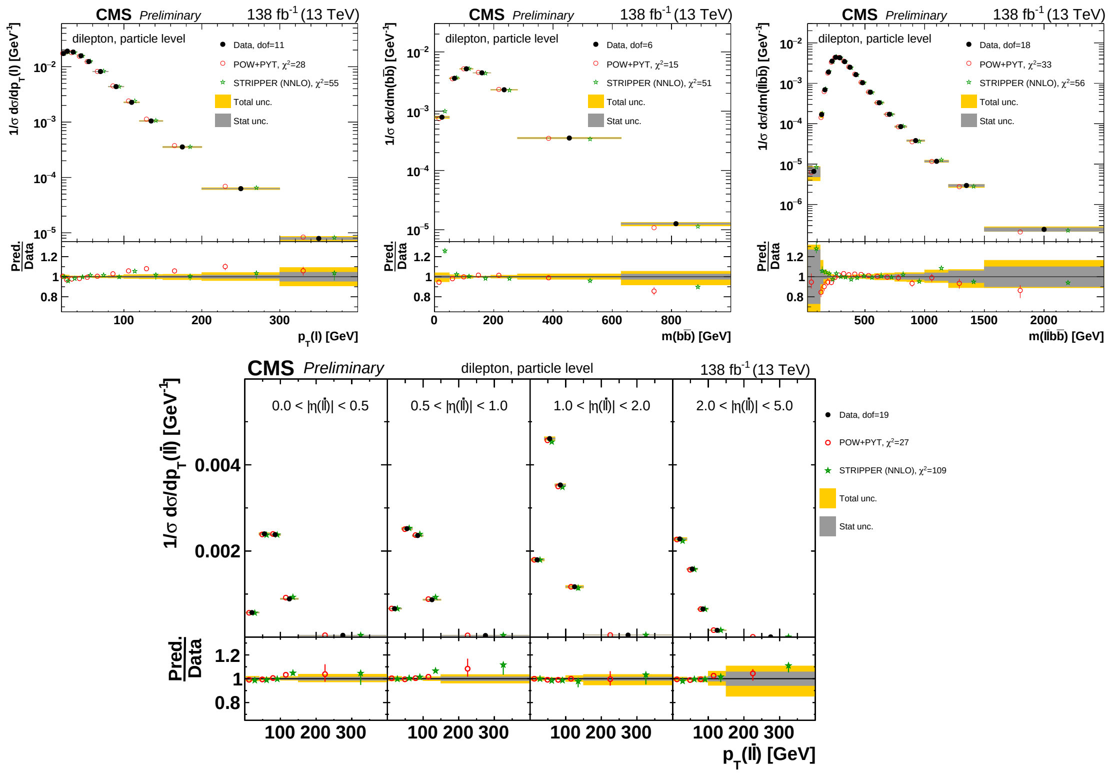

Figure 3: Normalized differential cross sections of $\mathrm{t\bar{t}}$ production are shown for $p_{\mathrm{T}}(\mathrm{l})$ (left), $m(\mathrm{l\bar{l}})$ (middle) and $m(\mathrm{l\bar{l}b\bar{b}})$ (right) in the upper row, while $||\eta(\mathrm{l\bar{l}})|, p_{\mathrm{T}}(\mathrm{l\bar{l}})|$ is shown in the bottom row. The measurements are performed at particle level in the fiducial phase space and comparisons are done to beyond-NLO models.

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