Top quark pair and single top cross sections and ttX (CMS)

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Abstract

Latest results on inclusive and differential top quark pair and single top quark production cross sections are presented using proton-proton collision data collected by the CMS experiment. The differential cross sections are measured as a function of various kinematic observables of the top quarks and the jets and leptons of the event final state. The results are confronted with precise theory calculations and used to constrain Standard Model parameters. Measurements are performed also with high p_T top quarks, i.e., in boosted regimes.

1 Introduction

The top quark is one of the most interesting particles present in the Standard Model (SM) of particle physics as it is postulated to interact with unknown particles from theories beyond the SM because of its high mass. Precise measurement of the properties of the top quark helps in the improvement of search sensitivity and test of perturbative Quantum Chromodynamics. Differential cross section measurements are used to test fixed-order predictions and extract QCD parameters. The $t\bar{t}$ production is dominant at LHC and serves as the background for many new physics searches.

There have been many earlier measurements at 7, 8, and 13 TeV center-of-mass energy as shown in Figure 1. In this proceeding, we summarise the recent cross section measurements by the CMS experiment at the LHC. For a more detailed description of each of the measurements, the reader is encouraged to look at the corresponding paper. Here we summarise the $t\bar{t}$ measurements in Section 2.3, tW in Section 3.2, and $t\bar{t}$X in Section 5 where X stands for γ, $c\bar{c}$, and $b\bar{b}$.

2 $t\bar{t}$ production

Due to the higher cross section among all t quark production processes, the $t\bar{t}$ production process is extensively studied at the LHC. Depending on the subsequent decays of the two t quarks, the final states consist of either all jets, ℓ + jets, or 2ℓ + jets. All-jet final states have larger size of the selected data set but more multijet background whereas the 2ℓ + jets final states have fewer events but small background. The ℓ + jets final states fall in between the two. However, the measurement of cross sections from all these final states is needed in order to
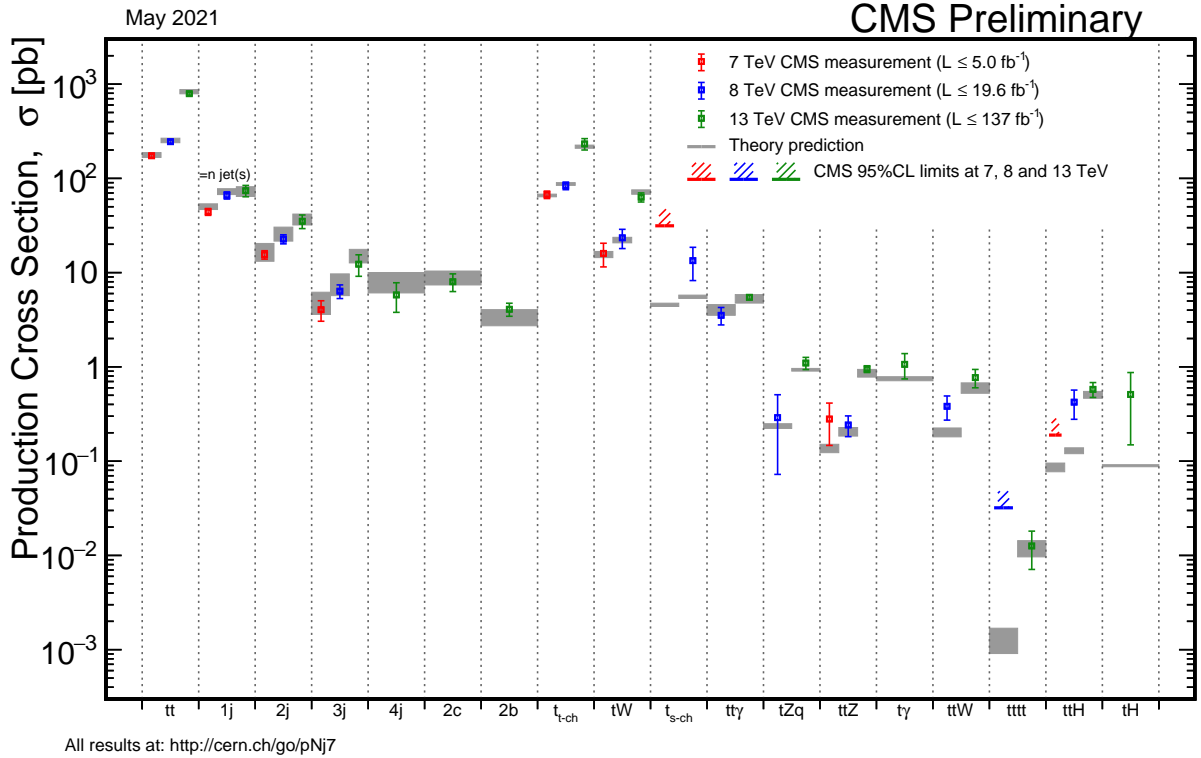
Figure 1: Top quark production cross section at various center-of-mass energies measured by the CMS experiment. The measurements are performed for the production of single t, $t\bar{t}$, $t\bar{t}$ + jets, t + X, $t\bar{t}$ + X, $t\bar{t}t\bar{t}$, etc. Among these, a few of them are new at 13 TeV whereas a few of them are still being studied. There is a good agreement between the predicted and measured values within the uncertainties.

study various physics beyond the SM. In these proceedings, we present the measurement from the ℓ + jets and 2ℓ + jets final states for $t\bar{t}$ production.

2.1 Inclusive and differential cross section measurements in the ℓ + jets final states

The measurement of the $t\bar{t}$ cross section is performed using 137 fb^{-1} integrated luminosity in the e + jets and μ + jets final states [1]. In order to increase the sensitivity, the events are further divided into boosted and resolved categories based on the kinematics of the decay products of the $t\bar{t}$ pair. The final cross section is extracted by a simultaneous fit combining events from both final states and all categories. Various distributions such as the transverse momentum of the t quark, invariant mass of $t\bar{t}$, etc are used to measure the differential and double differential cross-sections at parton and particle levels. A neural network is exploited in the reconstruction of variables from boosted t quarks. A χ^2 test is performed to compare the measurements with several predictions. The dominant source of systematic uncertainty comes from jet energy correction.

The measured value of the inclusive cross section, 791 $\pm$ 25 pb, is in agreement with the corresponding predicted value of 832 $\pm$ 46 pb. One of the most striking features of this measurement is that the measured cross section is more precise (3.2% uncertainty) as compared to the predicted value (5.5% uncertainty). The measured and predicted differential and double differential cross sections as functions of various variables are in agreement within the uncertainties for most of the variables. However, there is a slight discrepancy in the double differential measure-

ment for higher p_T of the hadronically decaying t quark in the range $0 < p_\mathrm{T}(t\bar{t}) < 120\,\mathrm{GeV}$. A similar over-prediction is also observed from the ATLAS experiment [2] and signals a possible mismodeling of the Monte Carlo event generator used for the simulation of predicted events.

2.2 Inclusive cross section measurement in the $2\ell+$ jets final states at 5.02 TeV center-of-mass energy

As shown in Figure 1, all measurements are performed at 7, 8, and 13 TeV center-of-mass energies. This is the first measurement at 5.02 TeV, which provides another test for the SM at lower energy [3]. The measurement is performed using $0.304\,\mathrm{fb}^{-1}$ integrated luminosity in the e + jets and μ + jets final states. The cross section is extracted by performing the fit on the total number of events after applying all selections. The dominant source of systematic uncertainty comes from the jet energy correction. The predicted cross section at the next-to-leading order (NLO) in QCD and observed value are $66.8^{+1.9}_{-2.3}(\mathrm{scale}) \pm 1.7(\mathrm{PDF})^{+1.4}_{-1.3}(\alpha_S)$ pb and $60.3 \pm 5.0(\mathrm{stat}) \pm 2.8(\mathrm{syst}) \pm 0.9(\mathrm{lumi})$ pb, respectively. They agree within the uncertainties.

2.3 Inclusive cross section measurement in the $2\ell+$ jets final states including τ lepton

This is the first measurement involving tau leptons [4] and provides another way of checking lepton flavor universality. With the third generation of lepton and quarks, it is sensitive to beyond SM contributions such as the production of charged Higgs boson. In this analysis, one of the leptons from $2\ell+$ jets final states is required to be a hadronically decaying τ and the other one is either an electron or muon. The measurement is performed at 13 TeV using $35.9\,\mathrm{fb}^{-1}$ integrated luminosity. The cross section is extracted using the profile likelihood method based on the transverse mass of the lepton and missing transverse energy. The QCD multijet background is estimated from data. The main sources of systematic uncertainty are from τ_h identification and misidentification. The measured cross section combining both channels is $\sigma_{t\bar{t}}(\ell\tau_h) = 781 \pm 7(\mathrm{stat}) \pm 62(\mathrm{syst}) \pm 20(\mathrm{lumi})$ pb, which is in agreement with the corresponding predicted value. The ratio of this with the same flavor cross section $R_{\ell\tau_h/\ell\ell} = 0.973 \pm 0.009(\mathrm{stat}) \pm 0.066(\mathrm{syst})$ is close to 1 within the uncertainties. Hence the lepton flavor universality violation is not observed.

3 tW production

The tW production process is one of the sub-dominants in terms of the total cross section as shown in Figure 1. It is also sensitive to the relevant CKM matrix element. Any deviation from the predicted value may be indicative of physics beyond the SM. Similar to the $t\bar{t}$ measurement, we present the recent studies from the ℓ + jets and 2ℓ + jets final states.

3.1 Inclusive cross section measurement in the $\ell+$ jets final states

The measurement is performed in the e + jets and μ + jets final states with $35.9\,\mathrm{fb}^{-1}$ integrated luminosity [5]. An event-level discriminant based on Boosted Decision Trees is used to extract the cross section. The events are divided into different signal and control regions based on the number of jets and b-tagged jets. A simultaneous fit is performed on the discriminant combining 3 categories and 2 final states. The dominant source of systematic uncertainty comes from the jet energy correction. The predicted (at NLO) and measured cross sections are $79.5^{+1.9+2.0}_{-1.8-1.4}$ pb and $89 \pm 4(\mathrm{stat}) \pm 12(\mathrm{syst})$ pb, respectively. They are in agreement within the uncertainties.

3.2 Differential cross section measurement in the $2\ell + $ jets final states

The differential cross section is measured with $35.9\,\text{fb}^{-1}$ integrated luminosity in the $2\ell + $ jets final states with different lepton flavors (electron or muon) as a function of the six variables [6]: p_T of the leading lepton, p_T of the jet, angular difference $\Delta\varphi(\text{e}^\pm, \mu^\mp)$, longitudinal momentum $p_\text{Z}(\text{e}^\pm, \mu^\mp, j)$, invariant mass $m(\text{e}^\pm, \mu^\mp, j)$, and transverse mass $m_\text{T}(\text{e}^\pm, \mu^\mp, j, p_\text{T}^\text{miss})$. Signal extraction is performed by subtracting backgrounds from data. The jet energy correction uncertainties are the dominant ones. Predicted and measured cross sections are in agreement within the uncertainties across different bins of all variables.

4 $t\bar{t}\gamma$, $t\bar{t}c\bar{c}$, $t\bar{t}b\bar{b}$ productions

Although the cross sections of these processes are smaller as shown in Figure 1, they are useful in studying rare phenomena within the SM and new physics beyond it, for example, the $t\bar{t}\gamma$ measurement allows in constraining the $t\gamma$ electroweak coupling and $t\bar{t}c\bar{c}$ or $t\bar{t}b\bar{b}$ provide a useful test of NLO QCD calculations.

4.1 Inclusive and differential $t\bar{t}\gamma$ cross section measurements in $\ell + $ jets final states

This is the first $t\bar{t}\gamma$ cross section measurement at 13 TeV by the CMS experiment using $137\,\text{fb}^{-1}$ integrated luminosity [7]. The measurement is performed in the $\text{e} + $ jets and $\mu + $ jets final states with one photon. Photons are classified based on matched generator parton in the genuine, nonprompt, misidentified, and multijet photon categories. Different phase spaces based on object selections and kinematic cuts are exploited to improve the precision. QCD multijet and electroweak backgrounds are measured from data. A simultaneous fit combining all event categories is performed to extract the cross section. The dominant uncertainties in the cross section comes from $\text{W}\gamma$ normalization and misidentified γ estimation. The measured value of the inclusive cross section in the fiducial phase space is $800 \pm 46(\text{syst}) \pm 7(\text{stat})$ fb. The ratio of the measured and predicted (at NLO) cross section is $1.034^{+0.060}_{-0.058}$, that is, they agree within the uncertainties. There is also good agreement for the differential cross section in most bins of p_T and η of the photon. Though there is a slight over-prediction in the bins where statistical precision is low.

4.2 Inclusive $t\bar{t}c\bar{c}$ cross section measurement in $2\ell + $ jets final states

Due to the availability of c-jet taggers at 13 TeV, there has been an improvement in the sensitivity in the measurement involving c jet in the final state. For the first time, a $t\bar{t}c\bar{c}$ cross section measurement is performed by the CMS Collaboration [8]. The analysis is performed in the $2\ell + $ jets final states with the same flavor lepton (e, μ, or τ) with $41.5\,\text{fb}^{-1}$ integrated luminosity at the center-of-mass energy of 13 TeV. A neural network is trained to distinguish between top quark pair events with additional jets. Event level neural network predicts output probabilities for five output classes $P(t\bar{t}c\bar{c})$, $P(t\bar{t}cL)$, $P(t\bar{t}b\bar{b})$, $P(t\bar{t}bL)$, and $P(t\bar{t}LL)$. Two variables are derived based on these

$$\Delta_\text{b}^\text{c} = \frac{P(t\bar{t}c\bar{c})}{P(t\bar{t}c\bar{c}) + P(t\bar{t}b\bar{b})},$$

$$\Delta_\text{L}^\text{c} = \frac{P(t\bar{t}c\bar{c})}{P(t\bar{t}c\bar{c}) + P(t\bar{t}LL)}. \tag{1}$$

A 1-d histogram is constructed from the 16 bins of the 2-d plane of these two variables

$$\Delta_\text{L}^\text{c} \otimes \Delta_\text{b}^\text{c} : [0, 0.55, 0.65, 0.85, 1.0] \otimes [0, 0.35, 0.5, 0.6, 1.0]. \tag{2}$$

The $t\bar{t}c\bar{c}$, $t\bar{t}b\bar{b}$, $t\bar{t}LL$ cross sections are simultaneously extracted by fitting the neural network outputs from simulation and observation. The dominant source of systematic uncertainty comes from the jet energy correction and c-tagging calibration. The $t\bar{t}c\bar{c}$ cross section in the full phase space is measured to be $7.43 \pm 1.07(\text{stat}) \pm 0.95(\text{syst})$ pb. An overall agreement is observed between the measured and predicted value at the level of one to two standard deviations for the $t\bar{t}c\bar{c}$, $t\bar{t}b\bar{b}$, and $t\bar{t}LL$ processes.

4.3 Inclusive $t\bar{t}b\bar{b}$ cross section measurements in $\ell + $ jets and $2\ell + $ jets final states

The measurement is performed at 13 TeV with $35.6\,\text{fb}^{-1}$ integrated luminosity [9]. The cross section is separately extracted for both final states for $t\bar{t}$ and $t\bar{t}jj$ and their ratio in the visible and full phase space. The fit is performed on the b-tagging discriminant value of the two jets. A 1-d histogram is constructed from the 10x10(20x20) bins of the 2-d plane of these two variables for $\ell + $ jets ($2\ell + $ jets) final states. Theoretical uncertainties from the final state radiation and madevent parton-shower matching are dominant. The corresponding measured cross section for $t\bar{t}b\bar{b}$ in the full phase space is $4.7 \pm 0.2(\text{stat}) \pm 0.6(\text{syst})$ pb and $2.9 \pm 0.1(\text{stat}) \pm 0.5(\text{syst})$ pb for $\ell + $ jets and $2\ell + $ jets final states, respectively. These are consistent within the uncertainties, with the SM prediction obtained using a matrix element calculation at NLO order in QCD matched to a parton shower.

5 Conclusion

In these proceedings, a summary of the inclusive, differential, and double differential cross section measured by the CMS experiment is presented for different final states. The measured value of $t\bar{t}$ cross section is more precise as compared to the predicted one. A slight over-prediction is seen in the differential $t\bar{t}\gamma$ due to low statistics and double differential $t\bar{t}$ cross section due to mismodeling of the p_{T} spectrum of the $t\bar{t}$ system. The $t\bar{t}$ measurement at 5.02 TeV provides another way of testing the consistency of SM prediction with the observation at lower energy. For the first time, the final states involving τ lepton are analyzed for the $t\bar{t}$ process. Other measured cross sections for the tW, $t\bar{t}\gamma$, $t\bar{t}c\bar{c}$ and $t\bar{t}b\bar{b}$ production processes are in agreement with SM prediction within the systematic and statistical uncertainties.

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