

Recent inclusive $t\bar{t}$ cross section measurements

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Results of the recent measurements for the inclusive $t\bar{t}$ production cross section in the proton-proton collisions at LHC are presented. The analyses use proton-proton collision data recorded by the ATLAS and CMS experiments at center-of-mass energies of 7, 8, and 13 TeV. Measurements of the production cross sections of $t\bar{t}b\bar{b}$, $t\bar{t}W$, $t\bar{t}Z$, and $t\bar{t}\gamma$ processes are also reported.

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1. Introduction

Measurements of the production cross section of the top-quark pair at proton-proton (anti-proton) collisions serve as important tests of the standard model (SM). As these cross sections can be predicted by the quantum chromodynamics (QCD) based calculations their measurements are useful in constraining the essential ingredients of the calculations, such as the parton distribution functions, strong coupling constant, and top quark mass. The $t\bar{t}$ production also constitutes dominant background to many new physics searches at LHC, for example the Higgs boson production in association with a top-quark pair. Thus, precise measurement of the $t\bar{t}$ production cross section will provide a better estimate of the background rates. Furthermore, possible deviation of the measured cross section from the theoretical prediction may provide indirect evidence for physics beyond the SM.

This article presents the results from the recent measurements of inclusive cross sections of $t\bar{t}$ productions ($\sigma_{t\bar{t}}$), including processes with additional particles. The reported measurements are performed by the ATLAS and CMS experiments at LHC [1, 2] using the proton-proton collision data recorded at $\sqrt{s} = 7, 8,$ and 13 TeV.

2. Inclusive $t\bar{t}$ cross section

In the SM, the top quark decays to a b quark and a W boson with a branching fraction $\mathcal{B}(t \rightarrow W^+b) \approx 1$. Thus, the final states of the $t\bar{t}$ production process is categorized according to the decay of the W bosons. The value of $\sigma_{t\bar{t}}$ is measured in the following three final states: 1) where both W bosons decay to leptons, 2) where one W boson decays to leptons while the other decays to quarks, and 3) where both the W bosons decay to quarks. In the following subsections we describe measurements performed in various final states.

2.1 Measurement in $e^\pm\mu^\mp$ +jets final state

Events are selected in this final state when one of the W bosons decays to an electron and a neutrino and the other decays to a muon and a neutrino. This channel has the smallest branching fraction, however, it suffers from minimal background contamination leading to a better precision in the measurement of cross section. Candidate events are identified using exactly one isolated electron and one isolated muon of opposite charge.

The CMS analysis based on the 7 and 8 TeV data requires no additional selection on the number of jets or b-tagged jets [4]. However, events are categorized according to the number of b-tagged jets and extra non-b-tagged jets. The event selection in ATLAS requires one or two b-tagged jets, thus dividing samples into two sub-categories. ATLAS performed a simultaneous measurement of $\sigma_{t\bar{t}}$ and b-tagging efficiency by solving two simultaneous equations defined by the number of events with one or two b-tagged jets [3]. The inclusive cross section measured at 7 and 8 TeV are $\sigma_{t\bar{t}} = 182.9 \pm 3.1$ (stat) ± 4.2 (syst) ± 3.6 (lumi) ± 3.3 (beam) pb and 242.4 ± 1.7 (stat) ± 5.5 (syst) ± 7.5 (lumi) ± 4.2 (beam) pb, respectively [3]. The corresponding b-tagging efficiency are $\epsilon_b = 0.557 \pm 0.009$ and 0.55 ± 0.006 , which agree well with the estimation from Monte Carlo simulations. The cross section is also measured in the fiducial region, defined by

events containing an $e\mu$ pair. The CMS measurement used a binned likelihood fit to the softest non-b-tagged jet p_T distribution in each category, simultaneously to both 7 and 8 TeV data. Results were obtained for $\sigma_{t\bar{t}}$ as well as the cross section in the fiducial region with $p_T > 20$ GeV and $|\eta| < 2.4$. The inclusive cross section measured by CMS at 7 and 8 TeV are 173.6 ± 2.1 (stat) $^{+4.5}_{-4.0}$ (syst) ± 3.8 (lumi) pb and $\sigma_{t\bar{t}} = 244.9 \pm 1.4$ (stat) $^{+6.3}_{-5.5}$ (syst) ± 6.4 (lumi) pb, respectively [4].

Both ATLAS and CMS experiments have also performed the measurements in the $e\mu$ +jets channel using 13 TeV data recorded during the year 2015 [5, 6]. ATLAS used a total integrated luminosity of 3.2 fb^{-1} while CMS used 2.2 fb^{-1} of data. The analysis strategy in ATLAS is similar to that of the 7 and 8 TeV analyses. However, CMS measured the cross section by simply counting the number of events with exactly one isolated, oppositely charged $e\mu$ pair and at least two jets one of them is b-tagged. The measured cross section value in CMS is $\sigma_{t\bar{t}} = 792 \pm 8$ (stat) ± 37 (syst) ± 21 (lumi) pb. In case of ATLAS it is $\sigma_{t\bar{t}} = 818 \pm 8$ (stat) ± 27 (syst) ± 19 (lumi) ± 12 (beam) pb and the fiducial cross section is $\sigma_{t\bar{t}}^{\text{fid}} = 11.32 \pm 0.1$ (stat) ± 0.29 (syst) ± 0.26 (lumi) ± 0.17 (beam) pb. The obtained b-tagging efficiency is $\epsilon_b = 0.559 \pm 0.004$ (stat) ± 0.003 (syst), which is consistent with simulation.

The CMS experiment has also measured the cross section at $\sqrt{s} = 5.02$ TeV using data provided by LHC during a very short run in 2015 [6]. The analysis is performed using a similar strategy as for 13 TeV, only excluding the requirement of b-tagged jets. Only 24 events are observed in data while 17.0 ± 0.2 events are expected for signal ($t\bar{t} \rightarrow e^\pm\mu^\mp$) and 3.9 ± 0.8 events for background. The measured cross section is $\sigma_{t\bar{t}} = 82 \pm 20$ (stat) ± 5 (syst) ± 10 (lumi) pb, which agrees with the theoretical prediction within uncertainties though afflicted by a large statistical error.

2.2 Measurement in e^+e^- and $\mu^+\mu^-$ final states

The most recent measurement of $\sigma_{t\bar{t}}$ in the final states $t\bar{t} \rightarrow e^+e^- + \text{jets}$ and $t\bar{t} \rightarrow \mu^+\mu^- + \text{jets}$ is performed by ATLAS using 85 pb^{-1} of data recorded at $\sqrt{s} = 13$ TeV during early 2015 [8]. Events are selected with a pair of isolated, oppositely charged but same flavour leptons (e or μ). To suppress contribution from the Z+jets process, events with a dilepton mass within $M_Z \pm 10$ GeV are rejected. The $\sigma_{t\bar{t}}$ value is obtained with a similar strategy as in the $e\mu$ analysis by counting the number of events with exactly one and two b-tagged jets. A simultaneous estimation of $\sigma_{t\bar{t}}$ and b-tagging efficiency is obtained. The measured cross sections are $\sigma_{t\bar{t}}(e^+e^-) = 824 \pm 88$ (stat) ± 91 (syst) ± 82 (lumi) pb, $\sigma_{t\bar{t}}(\mu^+\mu^-) = 683 \pm 74$ (stat) ± 76 (syst) ± 68 (lumi) pb, and $\sigma_{t\bar{t}}(e^+e^- + \mu^+\mu^-) = 749 \pm 57$ (stat) ± 79 (syst) ± 74 (lumi) pb.

2.3 Measurement in e/μ +jets final states

Candidate events are selected in this final state when one of the W bosons decays to an electron or a muon and a neutrino, while the other decays hadronically. Events are retained if there are with exactly one isolated, high p_T electron/muon, and a number of additional jets. The ATLAS analysis for the data recorded at $\sqrt{s} = 8$ TeV requires the presence of at least 3 jets of which at least one is b-tagged. The number of events in the signal region is determined with a template fit to a likelihood discriminant that is constructed from several kinematic variables. The measured inclusive cross sections are $\sigma_{t\bar{t}}(e + \text{jets}) = 256 \pm 2$ (stat) ± 25 (syst) ± 7 (lumi) ± 4 (beam), $\sigma_{t\bar{t}}(\mu + \text{jets}) = 260 \pm 1$ (stat) $^{+22}_{-23}$ (syst) ± 8 (lumi) ± 4 (beam), and the combination is $\sigma_{t\bar{t}}(\ell + \text{jets}) = 258 \pm 1$ (stat) $^{+22}_{-23}$ (syst) ± 8 (lumi) ± 4 (beam) [9].

The CMS analysis for the data recorded at $\sqrt{s} = 7$ and 8 TeV requires the presence of at least 4 jets of which at least one is b-tagged. The number of events in the signal region are extracted by fitting to the distribution of M_{lb} (invariant mass of lepton plus b-tagged jet system). A cross check analysis is performed with a fit to the M_3 (invariant mass of the system of 3 highest p_T jets) distribution. The shape of the QCD background is obtained from data. Two different event generators, MADGRAPH and POWHEG, are used to model signal template. The measured cross sections at 8 TeV are $\sigma_{\bar{t}t}(\ell + \text{jets}) = 228.5 \pm 3.8 \pm 13.7 \pm 6.0$ pb (using MADGRAPH) and $\sigma_{\bar{t}t}(\ell + \text{jets}) = 237.1 \pm 3.9 \pm 14.2 \pm 6.2$ pb (using POWHEG), obtained using the fit to M_{lb} [10]. The corresponding results obtained with the cross check analysis are $\sigma_{\bar{t}t}(\ell + \text{jets}) = 227.1 \pm 2.5 \pm 19.1 \pm 6.0$ pb (using MADGRAPH) and $\sigma_{\bar{t}t}(\ell + \text{jets}) = 238.4 \pm 2.8 \pm 20.0 \pm 6.2$ pb (using POWHEG). The uncertainties are due to statistical, systematic, and luminosity, respectively. The cross section measured at 7 TeV (using MADGRAPH) is $\sigma_{\bar{t}t}(\ell + \text{jets}) = 161.7 \pm 6.0 \pm 12.0 \pm 3.6$ pb. The measured ratio of the cross sections for 7 to 8 TeV is $1.43 \pm 0.04(\text{stat}) \pm 0.07(\text{syst}) \pm 0.05(\text{lumi})$ [10].

ATLAS has also performed measurements in this channel with the data recorded in 2015 during early 13 TeV runs, which correspond to an integrated luminosity of 85 pb^{-1} [11]. The cross section is measured with a simple counting of number of selected events. The obtained cross section is $\sigma_{\bar{t}t}(\ell + \text{jets}) = 817 \pm 13(\text{stat}) \pm 103(\text{syst}) \pm 88(\text{lumi})$ pb. CMS repeated the analysis with the full 2015 data at 13 TeV corresponding to a luminosity of 2.3 pb^{-1} [12]. Candidate events are categorized on the basis of number of jets and number of b-tagged jets. The cross section is measured by using a simultaneous binned likelihood fit to M_{lb} or $\min(M_{lb})$ distributions in all categories. The measured cross section is $\sigma_{\bar{t}t}(\ell + \text{jets}) = 834.6 \pm 2.5(\text{stat}) \pm 22.8(\text{syst}) \pm 22.5(\text{lumi})$ pb.

2.4 Measurement in fully hadronic final states

CMS has also performed the measurement of $\sigma_{\bar{t}t}$ in a fully hadronic final state where both W bosons decay to hadrons. Though, this final state has the largest branching fraction ($\approx 46\%$) it suffers from very large QCD multijet backgrounds. Events are triggered using a multijet trigger and selected in offline requiring at least six jets of which two or more are b-tagged. To discriminate signal from multijet background, the full $\bar{t}t$ system have been reconstructed using a kinematic fit. The kinematic fit restores the reconstructed top-quark mass (m_t) to its nominal value and improves the mass resolution significantly that helps in separating it from the QCD background. An unbinned maximum likelihood fit to the m_t distribution is performed to extract the signal and background normalizations. The analysis is carried out using the data recorded in 2012 at $\sqrt{s} = 8$ TeV as well as the data collected during 2015 at $\sqrt{s} = 13$ TeV [13, 14]. The measured cross section using the 8 TeV data, corresponding to a luminosity of 18.4 fb^{-1} , is $\sigma_{\bar{t}t}(\text{all jets}) = 275.6 \pm 6.1(\text{stat}) \pm 37.8(\text{syst}) \pm 7.2(\text{lumi})$ pb. The measured value with 2.53 fb^{-1} of 13 TeV data is $\sigma_{\bar{t}t}(\text{all jets}) = 834 \pm 25(\text{stat}) \pm_{-104}^{+118}(\text{syst}) \pm 23(\text{lumi})$ pb. The measurement is also performed in a scenario where the top quark is boosted and is reconstructed as a single jet with a large distance parameter $R = 0.8$ using the anti- k_T algorithm. The measured cross section in the boosted scenario using 2.53 fb^{-1} of 13 TeV data is $\sigma_{\bar{t}t}(\text{all jets}) = 727 \pm 46(\text{stat}) \pm_{-112}^{+115}(\text{syst}) \pm 20(\text{lumi})$ pb.

3. Measurement of $t\bar{t} + b\bar{b}$ production cross section

Measurements are performed by the ATLAS and CMS experiments on the production cross section of $t\bar{t}$ in association with two b quarks ($\sigma_{t\bar{t}+b\bar{b}}$) [15, 16, 17]. This process is an irreducible background to the production of the Higgs boson in association with a top-quark pair, $t\bar{t}H$, where the Higgs boson decays to a $b\bar{b}$ pair. ATLAS has carried out analysis using 20.3 fb^{-1} of the 8 TeV data in both dilepton and lepton-plus-jets final states. The number of signal events are extracted by fitting the distribution of the b-tagging multivariate discriminant. Measurements are performed for fiducial cross section of $t\bar{t}$ with one or two b-tagged jets. A cut-based analysis employing very tight selection criteria is used to cross check the fit-based results. Both are found to be compatible within their measured uncertainties. The measured ratio $R_{t\bar{t}+b\bar{b}} = \sigma_{t\bar{t}+b\bar{b}}/\sigma_{t\bar{t}}$ is 1.30 ± 0.33 (stat) ± 0.28 (syst)%.

The CMS experiment has also performed a similar analysis using the 8 TeV data corresponding to an integrated luminosity of 19.6 fb^{-1} in the dilepton final state with four or more jets, including two b-tagged jets. The ratio $R_{t\bar{t}+b\bar{b}}$ is determined for a minimum jet p_T of 20 and 40 GeV. The measured ratio is 0.022 ± 0.003 (stat) ± 0.005 (syst) for $p_T > 20$ GeV. CMS has also carried out this measurement, employing a similar analysis strategy, using 2.3 fb^{-1} of the 13 TeV data recorded during 2015. The measured ratio is 0.022 ± 0.003 (stat) ± 0.006 (syst), compatible with the previous result.

4. Measurement of $t\bar{t}W$, $t\bar{t}Z$, and $t\bar{t}\gamma$ production cross sections

ATLAS and CMS have performed measurements for the production cross section of $t\bar{t}W$ and $t\bar{t}Z$ processes using data recorded at $\sqrt{s} = 8$ and 13 TeV [18, 19, 20, 21]. Events with two same-charge leptons or three leptons are used to measure $\sigma_{t\bar{t}W}$, while events with three or four leptons are used to measure $\sigma_{t\bar{t}Z}$. The results are dominated by uncertainties due to low statistics of selected samples. Both experiments have also measured the $t\bar{t}\gamma$ production cross section using data recorded at $\sqrt{s} = 7$ and 8 TeV [22, 23]. Events are selected with an isolated lepton, an isolated photon, and additional jets. The obtained cross section agrees with the theoretical prediction within uncertainties.

5. Summary

The ATLAS and CMS experiments have measured the inclusive cross section of $t\bar{t}$ production at $\sqrt{s} = 7, 8,$ and 13 TeV using proton-proton collision data delivered by the LHC. A review of recent results from measurements are presented in this article. The measured cross sections are in good agreement with theoretical predictions as shown in Fig. 1. Results on the production cross section of $t\bar{t} + b\bar{b}$, $t\bar{t}W$, $t\bar{t}Z$, and $t\bar{t}\gamma$ processes are also reported, which again agree with the theory within uncertainties.

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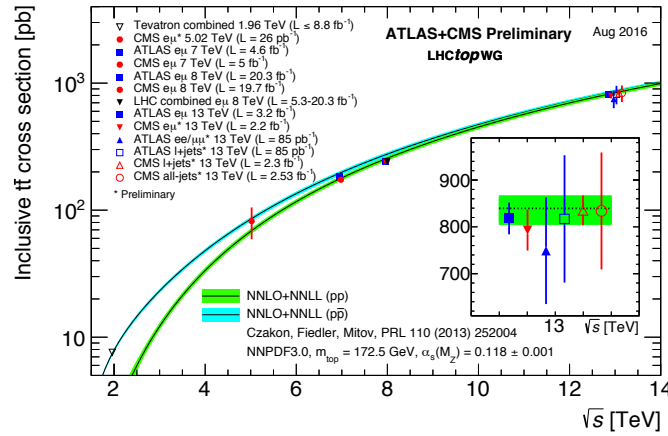


Figure 1: Measured inclusive $t\bar{t}$ production cross section as function of the centre-of-mass energy in proton-(anti)proton collisions at Tevatron and LHC. The measurements are in good agreement with the theoretical predictions based on NNLO+NNLL calculations.

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