

Measurements of the inclusive $t\bar{t}$ production cross section
at the ATLAS and CMS experimentsMATTEO M. DEFRANCHIS
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The results of the most recent measurements of the inclusive $t\bar{t}$ cross section performed by the ATLAS and CMS experiments at the CERN LHC are summarized. These include results obtained in proton-proton collisions at different centre-of-mass energies, and the first observation of $t\bar{t}$ production in proton-lead collisions. A new result at $\sqrt{s} = 13$ TeV by the CMS Collaboration is presented for the first time at this conference. In this analysis, the total cross section is determined both for a fixed top quark mass value in the simulation of $m_t^{\text{MC}} = 172.5$ GeV, and simultaneously with m_t^{MC} .

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1 Introduction

Measurements of the top quark-antiquark ($t\bar{t}$) production cross section ($\sigma_{t\bar{t}}$) have been performed with increasing precision at the ATLAS [1] and CMS [2] experiments at several centre-of-mass energies (\sqrt{s}) in different decay channels. Theoretical predictions for $\sigma_{t\bar{t}}$ can be derived in quantum chromodynamics (QCD) at next-to-next-to-leading order (NNLO) in perturbation theory. The precision of the calculation is further improved by including next-to-next-to-leading logarithmic (NNLL) corrections [11]. The uncertainty in the predicted $\sigma_{t\bar{t}}$ ranges from 6 to 7%, depending on the centre-of-mass energy, while experimental measurements can reach a precision of 3 to 4%.

The $t\bar{t}$ production cross section depends on fundamental parameters of the standard model (SM), in particular the strong coupling constant (α_S) and the top quark mass (m_t), and on the parton distribution functions (PDF) of the proton. Measurements of $\sigma_{t\bar{t}}$ can therefore be used to constrain SM parameters, but also to probe models of physics beyond the SM.

Typically, the procedure to measure $\sigma_{t\bar{t}}$ consists of two separate steps. First, a visible cross section ($\sigma_{t\bar{t}}^{\text{vis}}$) is measured in the fiducial phase space, where systematic uncertainties can be constrained. The visible cross section is then extrapolated to the full phase space by correcting for the acceptance of the event selection, which is estimated using simulation.

2 Recent ATLAS and CMS measurements

The measurements of $\sigma_{t\bar{t}}$ performed at the ATLAS and CMS experiments using proton-proton collisions at centre-of-mass energies of 7, 8, and 13 TeV are summarized in Fig. 1. The most precise measurements are obtained using final states having one electron and one muon of opposite charge ($e^\pm\mu^\mp$) or a charged lepton and additional jets (lepton+jets), which have the advantage of a high signal purity.

A recent result at $\sqrt{s} = 8$ TeV by the ATLAS Collaboration is obtained using events in the lepton+jets channel, with an integrated luminosity of 20.2 fb^{-1} [3]. In this analysis, the $t\bar{t}$ cross section is determined simultaneously with the b tagging efficiencies and a global jet energy scale factor. Selected events are split into three different signal regions based on the jet and b-tagged jet multiplicities. In categories with higher background contamination, a neural network is trained to separate the signal from the backgrounds, while in the category with the highest signal purity (that corresponding to four selected jets, two of which are b-tagged), the invariant mass of the two non-b-tagged jets is used to constrain the jet energy scale factor, ex-

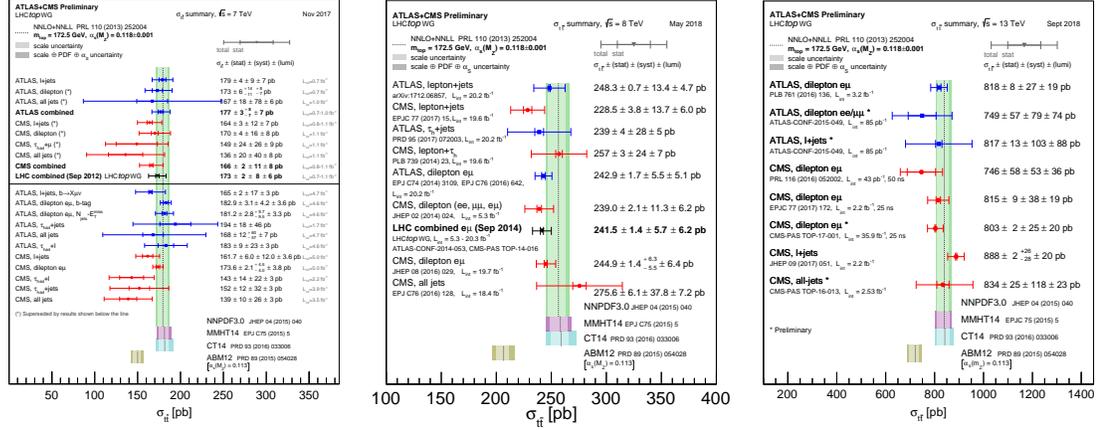


Figure 1: Measurements of the inclusive $t\bar{t}$ cross section by the ATLAS and CMS Collaborations at 7 (left), 8 (middle), and 13 TeV (right) [12].

exploiting the constraint from the mass of the reconstructed W boson. In addition, the event categorization is exploited to constrain the b tagging efficiency. The resulting value of the cross section is $\sigma_{t\bar{t}} = 248.3 \pm 0.7 (\text{stat}) \pm 13.4 (\text{syst}) \pm 4.7 (\text{lum}) \text{ pb}$. The uncertainties denote the statistical uncertainty, the systematic uncertainty, and that coming from the uncertainty in the integrated luminosity. The relative uncertainty of 5.7% is dominated by the uncertainty in the gluon PDF at high momentum fraction.

A precise measurement at $\sqrt{s} = 13 \text{ TeV}$ was performed by the CMS Collaboration in the lepton+jets channel, with an integrated luminosity of 2.2 fb^{-1} [4]. The cross section is determined by means of a likelihood fit where the systematic uncertainties are treated as nuisance parameters and constrained using the data. Selected events are classified in 44 orthogonal categories of jet and b-tagged jet multiplicities, lepton charge and lepton flavour. The $m_{\ell b}^{\min}$ distribution, i.e. the minimum invariant mass between the lepton and a reconstructed b jet, is used to discriminate the signal from the backgrounds. The total cross section is measured to be $\sigma_{t\bar{t}} = 888 \pm 2 (\text{stat}) \pm_{28}^{26} (\text{syst}) \pm 20 (\text{lum}) \text{ pb}$. The relative uncertainty of 3.7% is dominated by the uncertainty in the b tagging efficiency and in the normalization of the W+jets background. The resulting cross section is also used to determine the pole mass of the top quark, which is found to be $170.6 \pm 2.7 \text{ GeV}$.

A precise measurement at $\sqrt{s} = 13 \text{ TeV}$ was also performed by the ATLAS Collaboration, using events in the $e^{\pm}\mu^{\mp}$ final state corresponding to an integrated luminosity of 3.2 fb^{-1} [5]. In this analysis, the cross section is determined simultaneously with the b tagging efficiency. Events with exactly one and two b-tagged jets are selected and split into categories of b-tagged jet multiplicity. The total cross section is mea-

sured to be $\sigma_{t\bar{t}} = 818 \pm 8 \text{ (stat)} \pm 27 \text{ (syst)} \pm 19 \text{ (lum)} \pm 12 \text{ (beam)} \text{ pb}$, with a relative uncertainty of 4.2%. The result is used to perform a precise determination of the ratio of $\sigma_{t\bar{t}}$ to the Z boson production cross section [6], which benefits from the cancellation of several relevant systematic uncertainties. This quantity is sensitive to the ratio of the gluon to the quarks PDF in the proton, and it was demonstrated that the result can be used to improve the precision in PDF determinations [6].

The first measurement of the $t\bar{t}$ cross section at $\sqrt{s} = 5.02 \text{ TeV}$ was recently performed by the CMS Collaboration using data collected in a dedicated LHC run in 2015, corresponding to an integrated luminosity of 27.4 pb^{-1} [7]. Events in the $e^{\pm}\mu^{\mp}$, $\mu^+\mu^-$ and lepton+jets final states are considered. A cut-and-count method is used for events in the dilepton channels, whereas a fit to categories of b-tagged jet multiplicity is used for the lepton+jets channel. The cross section is measured to be $\sigma_{t\bar{t}} = 69.5 \pm 6.1 \text{ (stat)} \pm 5.6 \text{ (syst)} \pm 1.6 \text{ (lum)} \text{ pb}$, in good agreement with the NNLO theoretical prediction $\sigma_{t\bar{t}}^{\text{NNLO}} = 68.9 \pm_{2.3}^{1.9} \text{ (scale)} \pm 2.3 \text{ (PDF)} \pm_{1.0}^{1.4} (\alpha_S) \text{ pb}$. Despite the fact that the measurement is limited by the statistical uncertainty, it was demonstrated that the result can be used to constrain the gluon PDF uncertainty at high momentum fraction [7].

An important result by CMS is the observation of $t\bar{t}$ production in proton-lead collisions [8]. The analysis is performed with 174 nb^{-1} of data at a nucleon-nucleon centre-of-mass energy of 8.16 TeV. Lepton+jets events are selected and classified in categories of b-tagged jet multiplicity. The cross section is determined from a likelihood fit to the invariant mass of jets originated from the decay of W bosons, simultaneously with the b tagging efficiency and a global jet energy scale factor. The significance of the $t\bar{t}$ signal is found to be above five standard deviations.

3 CMS results at 13 TeV with 35.9 fb^{-1}

A new measurement at $\sqrt{s} = 13 \text{ TeV}$ is presented for the first time at this conference by the CMS Collaboration [9]. This is the first result obtained using data collected during the 2016 LHC run, corresponding to an integrated luminosity of 35.9 fb^{-1} . The measurement is performed using two different approaches: in the first, the cross section is determined at the fixed top quark mass in the simulation of $m_t^{\text{MC}} = 172.5 \text{ GeV}$, using events in all the dilepton channels ($e^{\pm}\mu^{\mp}$, $\mu^+\mu^-$, e^+e^-). In the second approach, the cross section is measured simultaneously with m_t^{MC} , and is therefore determined at the optimal mass point. For simplicity, only the $e^{\pm}\mu^{\mp}$ final state is considered in this case.

The method consist of a likelihood fit to distributions of final state observables,

in bins of jet and b-tagged jet multiplicities. Systematic uncertainties are treated as nuisance parameters and are constrained in the fiducial phase space. Spectra of jet transverse momenta (p_T) are used to constrain the jet energy scale uncertainties, while the $m_{\ell b}^{\min}$ distribution is used to determine m_t^{MC} in the simultaneous fit of $\sigma_{t\bar{t}}$ and m_t^{MC} (Fig. 2).

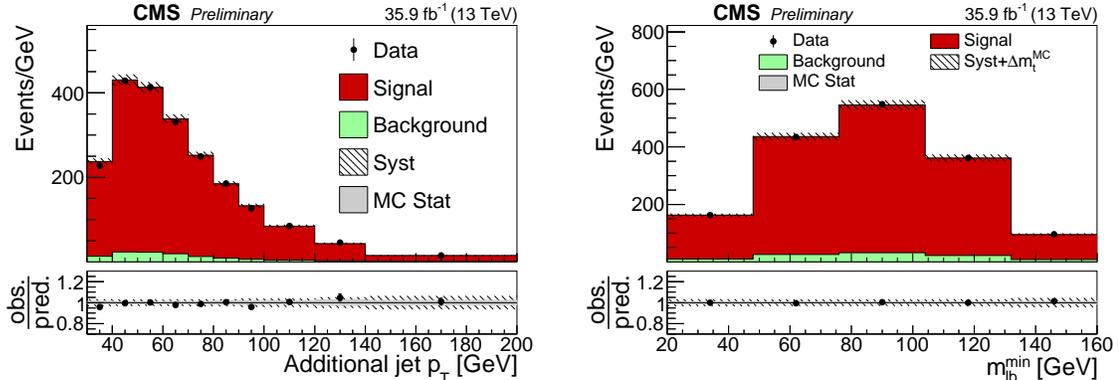


Figure 2: Example of post-fit distributions for the fit of $\sigma_{t\bar{t}}$ at the fixed m_t^{MC} of 172.5 GeV (left) and for the simultaneous fit of $\sigma_{t\bar{t}}$ and m_t^{MC} (right). The jet p_T spectrum corresponds to events with one b-tagged jets and two additional (non-b-tagged) jets, whereas the $m_{\ell b}^{\min}$ distribution corresponds to events with one b-tagged jets and one additional jet [9].

At the fixed value of $m_t^{\text{MC}} = 172.5$ GeV, the visible cross section is measured to be $\sigma_{t\bar{t}}^{\text{vis}} = 25.61 \pm 0.05$ (stat) ± 0.75 (syst) ± 0.64 (lum) pb. The visible phase space is defined as the events having two leptons of opposite charge with $p_T > 20$ GeV, at least one of which with $p_T > 25$ GeV. The extrapolated cross section is found to be $\sigma_{t\bar{t}} = 803 \pm 2$ (stat) ± 25 (syst) ± 20 (lum) pb. The total uncertainty of 4.0% is dominated by the uncertainties in the integrated luminosity (2.5%) and the lepton identification efficiencies (2.0%). The measured cross section is in good agreement with the theoretical prediction at NNLO+NNLL accuracy $\sigma_{t\bar{t}}^{\text{theo}} = 832 \pm_{29}^{20}$ (scale) ± 35 (PDF + α_S) pb [11].

In the simultaneous fit of $\sigma_{t\bar{t}}$ and m_t^{MC} , a total cross section of $\sigma_{t\bar{t}} = 815 \pm 2$ (stat) ± 29 (syst) ± 20 (lum) pb is obtained, in good agreement with the result at the fixed m_t^{MC} . The top quark mass in the simulation is measured to be $m_t^{\text{MC}} = 172.33 \pm 0.14$ (stat) $\pm_{0.72}^{0.66}$ (syst) GeV, in good agreement with previous measurements by ATLAS and CMS [12]. The uncertainty in m_t^{MC} is dominated by jet energy scale uncertainties (0.57 GeV) and the statistical uncertainty of the simulation (0.36 GeV). The latter is estimated by using pseudo-templates, where each bin is varied within its statistical uncertainty. The correlation between different templates is properly

taken into account. The fit to the data is repeated several thousand times, and the spread in the best-fit values of m_t^{MC} and $\sigma_{t\bar{t}}$ is taken as an additional uncertainty. The measured $\sigma_{t\bar{t}}$ is then used to extract α_S and m_t using different PDF sets. Updated results can be found in Ref. [10].

4 Conclusions

The most recent measurements of the inclusive $t\bar{t}$ production cross section by the ATLAS and CMS experiments have been summarized. These include measurements at centre-of-mass energies of 5.02, 8, and 13 TeV in different final states. The first observation of $t\bar{t}$ production in p-Pb collisions at a nucleon-nucleon centre-of-mass energy of 8.16 TeV has also been illustrated. A new result at $\sqrt{s} = 13$ TeV by the CMS Collaboration, obtained using 35.9 fb^{-1} of pp collisions data, is presented for the first time at this conference. In this analysis, the $t\bar{t}$ cross section is determined both for a fixed top quark mass in the simulation of $m_t^{\text{MC}} = 172.5$ GeV, and simultaneously with m_t^{MC} . The cross section is measured with a relative uncertainty of 4.0%, and good precision in the top quark mass is also achieved.

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