ttbar (+x) PAIR PRODUCTION AT THE LHC

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The production cross section of top quark pairs was measured by the ATLAS and CMS collaborations at the Large Hadron Collider (LHC) in pp collisions at \( \sqrt{s} = 7, 8, \) and 13 TeV. This report briefly summarizes the most recent results.

1 Introduction

Since the beginning of the LHC operation, about 10 million top quark pairs were produced at each of the ATLAS\(^1\) and CMS\(^2\) experiments. For both detectors the identification efficiencies of leptons, photons, and jets originating from quarks and gluons are known precisely, and their energy scales are well calibrated. This allows for the precise measurement of the production cross section of top quark pairs, either inclusive, or differential as a function of top quark properties or event observables, or in association with a vector boson. The measurements were performed at center-of-mass energies of \( \sqrt{s} = 7, 8, \) and 13 TeV.

2 Inclusive ttbar cross sections

The most precise inclusive ttbar cross section was measured by CMS in the dilepton channel.\(^3\) Events containing exactly one muon and one electron with a transverse momentum \( p_T \) of at least 20 GeV were selected without any requirement on jets. The cross section is extracted by a binned likelihood fit to the trailing jet \( p_T \) (which is not b-tagged) in 12 categories and results in

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\begin{align*}
\sigma_{ttbar}^{7\text{ TeV}} & = 173.6 \pm 2.1 \text{ (stat)} ^{+4.5}_{-4.0} \text{ (syst)} \pm 3.8 \text{ (lumi)} \text{ pb} \left( ^{+3.6\%}_{-3.5\%} \right), \\
\sigma_{ttbar}^{8\text{ TeV}} & = 244.9 \pm 1.4 \text{ (stat)} ^{+6.3}_{-5.5} \text{ (syst)} \pm 6.4 \text{ (lumi)} \text{ pb} \left( ^{+3.7\%}_{-3.5\%} \right),
\end{align*}
\]

where the largest uncertainties stem from trigger/lepton efficiencies, DY background and the luminosity measurement. The cross section is used to extract the top quark pole mass and set constraints on top squark pair production. The result is in good agreement with the one from ATLAS\(^4\): \( \sigma_{ttbar}^{8\text{ TeV}} = 242.4 \pm 1.7 \text{ (stat)} \pm 5.5 \text{ (syst)} \pm 7.5 \text{ (lumi)} \pm 4.2 \text{ (beam)} \text{ pb} \left( ^{+4.3\%} \right) \).

The CMS measurement in the lepton+jets channel\(^5\) requires events with exactly one lepton, missing transverse energy (MET), and 4 jets, of which one has to be tagged as stemming from a b quark. The top quarks are fully reconstructed and the \( M_{fb} \) distribution is fitted to extract the cross section to be

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\begin{align*}
\sigma_{ttbar}^{7\text{ TeV}} & = 161.7 \pm 6.0 \text{ (stat)} \pm 12.0 \text{ (syst)} \pm 3.6 \text{ (lumi)} \text{ pb} \left( ^{+8.6\%} \right), \\
\sigma_{ttbar}^{8\text{ TeV}} & = 228.9 \pm 3.8 \text{ (stat)} \pm 13.7 \text{ (syst)} \pm 6.0 \text{ (lumi)} \text{ pb} \left( ^{+6.7\%} \right),
\end{align*}
\]
with using in-situ determinations of both the jet scale factor from $W \rightarrow jj$ candidates and the b-tag efficiency from a sample without b-tag requirement. Within uncertainties there is agreement with the corresponding ATLAS result \(^6\) of $\sigma_{t\bar{t}}^{8 \text{ TeV}} = 260 \pm 1 \text{ (stat)}^{22}_{23} \text{ (syst)} \pm 8 \text{ (lumi)} \pm 4 \text{ (beam)} \text{ pb (} \pm 9.5\%).

The ATLAS collaboration measured the $t\bar{t}$ cross section at 13 TeV \(^7\) by fitting the number of b-tagged jets in events with exactly one electron and one muon ($p_T > 25 \text{ GeV}$). The result is $\sigma_{t\bar{t}}^{13 \text{ TeV}} = 803 \pm 7 \text{ (stat)} \pm 27 \text{ (syst)} \pm 45 \text{ (lumi)} \pm 12 \text{ (beam)} \text{ pb (} \pm 6.7\%).$ where the largest uncertainties stem from hadronization and the luminosity measurement. The published CMS measurement at 13 TeV \(^8\) is already superseded by a preliminary result \(^9\) using the full dataset collected in 2015 and improved detector calibrations. The result is obtained by counting the number of events containing one electron, one muon (each with $p_T > 20 \text{ GeV}$), and two jets with $p_T > 30 \text{ GeV}$ and at least one b tag: $\sigma_{t\bar{t}}^{13 \text{ TeV}} = 793 \pm 8 \text{ (stat)} \pm 38 \text{ (syst)} \pm 21 \text{ (lumi)} \text{ pb, where}$ the relative uncertainty was improved from 11.6% to 5.6%. An overview of the most precise measurements as a function of $\sqrt{s}$ is shown in Fig. 1 (left).

3 Differential $t\bar{t}$ cross sections: global properties of $t\bar{t}$ events

Global properties of $t\bar{t}$ events are measured at particle level (i.e., corrected for detector effects) so that the results can be confronted with state-of-the-art QCD simulation including parton shower and hadronization. CMS measured $t\bar{t}$ production with additional jet activity in dilepton events at 8 TeV \(^{11}\) as a function of multiplicity, $p_T$, and $\eta$ of additional light and b jets, as well as their summed $p_T$ (HT), di-jet angles and invariant masses, and gap fractions in different $\eta$ regions. A measurement of the fiducial $t\bar{t}$ production cross section with one or two additional b jets was done by ATLAS at 8 TeV, disfavoring extreme $g \rightarrow bb$ splitting scenarios. \(^{12}\) The differential $t\bar{t}$ cross section as a function of the additional jet multiplicity in dilepton events at 13 TeV was measured by ATLAS for four different jet thresholds of 25, 40, 60, and 80 GeV, and compared to the predictions of different MC generator setups and tunes.\(^{13}\) In lepton+jets events at 13 TeV different event observables are measured by CMS\(^{14}\), including the missing transverse energy (MET), HT, jet multiplicity ($p_T > 25 \text{ GeV}$) and lepton $p_T / \eta$.

4 Differential $t\bar{t}$ cross sections: top quark observables

Differential $t\bar{t}$ cross sections as function of top quark observables are measured both at particle and parton level. The "pseudo" top at particle level is defined by a reconstruction prescription and has no or minimal dependence on internal matters of the event simulation. Therefore, it
can be compared to any complete $t\bar{t}$ simulation. On the contrary, measurements at parton level rely on simulation for unfolding to stable top quarks in order to compare with fixed-order QCD calculations.

ATLAS measured properties of top quarks and the $t\bar{t}$ system (e.g., $p_T$, rapidity $y$) at 8 TeV in both fiducial (particle level) and full (parton level) phase space. Parton level results are also available from CMS in lepton+jets and dilepton channels. The $p_T$ of highly boosted top quarks is measured by ATLAS in events with 1 lepton, 1 small-radius ($R$) jet and one trimmed large-$R$ jet, where one of the jets is b-tagged. The the large-$R$ jet is considered as hadronic top candidate and its $p_T$ is measured at particle level but also unfolded to the parton-level top quark. A similar measurement of boosted top quarks was performed by CMS. The richness of results at 7 and 8 TeV was used by both collaborations to validate the new generator setups for 13 TeV simulation and motivate the parameter choices.

Differential $t\bar{t}$ cross sections at 13 TeV are available by CMS in both the lepton+jets and dilepton channel. In the lepton+jets channel, an analytic solution for the neutrino momentum is used and the best top candidates are found by mass constraints. Top and $t\bar{t}$ observables are then measured at parton and particle level, e.g. the $p_T$ of the $t\bar{t}$ system shown in Fig. 1 (right). The dilepton analysis uses a kinematic reconstruction algorithm and measures top and $t\bar{t}$ observables at parton level. In addition, both analyses report the measured the jet multiplicity.

5 $t\bar{t}+V$ production cross sections

For the measurement of the $t\bar{t}+W$ and $t\bar{t}+Z$ production cross sections at 8 TeV ATLAS and CMS select events with jets and multiple leptons. The event yields or discriminator distributions from multivariate analysis are fitted in up to 20 event categories, where the non-prompt lepton background is estimated from $t\bar{t}$ and $Z+jet$ control regions. While both measurements of the $t\bar{t}+Z$ cross section are in agreement with theory calculations, the measured $t\bar{t}+W$ cross sections are larger by a factor $\sim 2$, although with large uncertainties. The CMS analysis additionally constrains axial and vector components of the $tZ$ coupling and dimension-six operators.

The ATLAS analysis at 13 TeV selects events with (b) jets and 2 or 3 leptons (one pair with same charge) as $t\bar{t}+W$ candidates, and events with (b) jets and 3 or 4 leptons (one $Z\rightarrow \ell^+\ell^-$ candidate) as $t\bar{t}+Z$ candidates. Diboson backgrounds are extracted from control regions. The measured cross sections are in agreement with the standard model, although there is again a factor $\sim 2$ in the $t\bar{t}+W$ cross section with a significance of about one standard deviation. The post-fit event yields are shown in Fig. 2 (left). At CMS the $t\bar{t}+Z$ 13 TeV cross section is measured in events with 3 or 4 leptons and at least 2 jets, using data-driven estimates for non-prompt lepton and diboson backgrounds and a binned likelihood fit to multiple categories shown in Fig. 2 (right). Systematic uncertainties are treated as nuisance parameters in the fit and the result is in agreement with the expectation.

Both experiments also measured the $t\bar{t}+\gamma$ production cross sections at 7 or 8 TeV, respectively, showing no significant deviation from the standard model.

6 Summary

ATLAS and CMS performed measurements of the inclusive $t\bar{t}$ cross section at 7, 8, and 13 TeV. The measurements reach a precision below 4% that is similar to latest calculations, and show excellent agreement with the standard model predictions. Both experiments measure a higher production rate of $t\bar{t}+W$, with respect to the standard model expectation, but the limited precision does not allow for a conclusion. Differential cross sections are measured as a function of various observables. Results using final-state objects at particle level are used for validation and tuning of latest MC simulation setups. Parton level distributions of top quark quantities allow for comparison to higher-order theory calculations.
Figure 2 – Number of events selected in different control and signal regions for measuring the production cross section of the $ttW$ process at ATLAS\textsuperscript{25} (left) and of $ttZ$ at CMS\textsuperscript{26} (right) at 13 TeV.

References