

Precise top quark cross-section results at LHC

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Abstract.

The measurements of the inclusive $t\bar{t}$ cross section is presented for proton-proton collisions recorded at $\sqrt{s}=7$ and 8 TeV by the ATLAS and the CMS experiments using the lepton+jets and the dilepton events. The most precise single measurement at 7 TeV is $\sigma_{t\bar{t}} = 161.9 \pm 2.5(\text{stat.})_{-5.0}^{+5.1}(\text{syst.}) \pm 3.6(\text{lumi.})$ pb, using a luminosity of 2.3 fb^{-1} . The measurements from the two experiments are also combined to reach higher precision. With a luminosity of about 1 fb^{-1} , the combined cross-section is $\sigma_{t\bar{t}} = 173.3 \pm 2.3(\text{stat.}) \pm 9.8(\text{syst.})$ pb. At $\sqrt{s}=8$ TeV, $\sigma_{t\bar{t}}$ is measured in the lepton+jets and dilepton channels with the CMS detector and the corresponding combined measurement is $\sigma_{t\bar{t}} = 227 \pm 3(\text{stat.}) \pm 11(\text{syst.}) \pm 10(\text{lumi.})$ pb.

1. Introduction

With the large $t\bar{t}$ cross sections $\sigma_{t\bar{t}}$ at the LHC and the high integrated luminosity, top physics enters into a new area. Despite the large backgrounds from multi-jets, typical of hadronic colliders, the proton-proton collisions data recorded at the LHC, together with highly performing detectors, such as the ATLAS and the CMS detectors, allows to measure the $t\bar{t}$ cross section to a high level of precision. Precise measurement of $\sigma_{t\bar{t}}$ is a very good test of the perturbative QCD, which leads to an approximate NNLO $t\bar{t}$ cross sections of 167_{-18}^{+17} pb and 252_{-29}^{+27} pb [1] at 8 TeV. Low uncertainty on the $t\bar{t}$ normalization is also important for the search for new physics, as possible deviations from the Standard Model (SM) predictions, or to reach a good control of the $t\bar{t}$ background in the exclusive searches for Beyond Standard Model signatures. The measurement of $\sigma_{t\bar{t}}$ with a very high level of precision at the LHC becomes possible because of large the statistic available, both in signal and control regions. It is used to estimate the various backgrounds first, but also to have a better understanding of systematic effects. One can reach even better precision by combining the different cross-section measurements. Top quarks are decaying into a bottom quark and a W boson in almost 100% of the cases. As the subsequent W can either decay into a lepton (anti-lepton) and its associated anti-neutrino (neutrino), or into a pair of quarks, one can observe three main decay channels for $t\bar{t}$ events : the dilepton channel (in about 10% of the cases), the lepton+jets channel (in about 45% of the cases) and all-hadronic channel (in about 45% of the cases). The most precise measurements are usually perform using $t\bar{t}$ events with at least one W boson decaying leptonically, with the charged lepton being either a muon or an electron, leptons from τ decays are normally included. Those channels are less contaminated by QCD multi-jets backgrounds, and allows to reach good trigger efficiencies. In addition, the missing transverse energy (E_T), can be used to further reject QCD multi-jets and electroweak backgrounds. Leptonic channels are also less sensitive to the description of jets, and thus conduct to lower uncertainties. The lepton+jets channel benefits from a higher statistic of



signal events, but is affected by the QCD multi-jet and the W+jets backgrounds. The dileptonic channels produce less signal events, but it is well compensated by the high luminosity reached at the LHC, and by a lower background contamination.

2. Top pair cross section at $\sqrt{s}=7$ TeV in the lepton+jets channel

In this section, the ATLAS and CMS $t\bar{t}$ cross section measurements in the lepton+jets channel are described. They are performed at $\sqrt{s}=7$ TeV, using different integrated luminosities.

First, the ATLAS measurement [2] is performed using 0.70 fb^{-1} of proton-proton collisions recorded by the ATLAS experiment. It is using the electron and muon+jets channels. The event selection asks for the events to pass a single-lepton trigger and to contain exactly one reconstructed, isolated and identified lepton with $E_T > 25 \text{ GeV}$ for electrons ($p_T > 20 \text{ GeV}$ for muons) and $|\eta| < 2.5$. In addition, events are required to contain at least 3 reconstructed jets with $p_T > 25 \text{ GeV}$ and $|\eta| < 2.5$, and to satisfy $\cancel{E}_T > 35 \text{ GeV}$ for the electron+jets channel (25 GeV for the muon+jets), $m_T(W) > 25 \text{ GeV}$ and $\cancel{E}_T + m_T(W) > 60 \text{ GeV}$, with $m_T(W)$ the transverse mass of W boson, determined using the lepton 4-momenta and the \cancel{E}_T . Lepton selection efficiencies in the simulation is corrected by comparing data and simulation for $Z \rightarrow l^+l^-$ events. The contamination of W+jets events is estimated from data using the charge asymmetry of the W events, and the QCD multi-jets contamination is determined using a Matrix Method. Other background events, like DY, single top-quark or dibosons events, are determined using simulations. $\sigma_{t\bar{t}}$ is determined using a maximum likelihood (profile) fit on a discriminating distribution, constructed from the pseudo-rapidity $|\eta|$ of the lepton, the p_T of the leading jet, the aplanarity (related to the "sphericity" of top events) and the $H_{T,3p}$ variable (related to the "transversity" of top events). The Likelihood used in the analysis is written as :

$$\mathcal{L}(\vec{\beta}, \vec{\delta}) = \prod_{k=1}^{120} \mathcal{P}(\mu_k, n_k) \times \prod_j G(\beta_j, \Delta_j) \times \prod_i G(\delta_i, 1),$$

with the first term being a Poisson probability

density to observed n_k events when μ_k is expected, the second term drives the normalization of signal and backgrounds events using Gaussian distributions and the third term introduces systematic uncertainties as nuisance parameters. In some other measurements presented in this note, similar techniques are used. Various systematic sources are considered in the measurement, the dominant ones being related to the uncertainty on the integrated luminosity, to the $t\bar{t}$ modeling and to the selections of jets and leptons. After the fit, the likelihood discriminant distribution can be seen on figure 1.

The measured cross section is found to be $\sigma_{t\bar{t}} = 179.0 \pm 3.9(\text{stat.}) \pm 9.0(\text{syst.}) \pm 6.6(\text{lumi.}) \text{ pb}$. The dependence of the cross section on the top-quark mass is $\sigma_{t\bar{t}} = 411.9 - 1.35 \times m_{\text{top}}(\text{GeV}) \text{ pb}$. Another ATLAS measurement [3] uses a luminosity of 4.66 fb^{-1} and, in addition to the previously described event selection, uses the semi-muonic decay of b-hadrons in order to identified jets originating from b quarks. A detailed study of such soft-muon tagger performances is done in order to have a good control of the related systematic uncertainties. $\sigma_{t\bar{t}}$ is measured from a counting experiment, and found to be $\sigma_{t\bar{t}} = 165 \pm 2(\text{stat.}) \pm 17(\text{syst.}) \pm 3(\text{lumi.}) \text{ pb}$.

Within the CMS experiment, $\sigma_{t\bar{t}}$ in the lepton+jets channel is measured using integrated luminosities of 0.8 to 1.1 fb^{-1} [4], depending on the channel. The events passing single lepton triggers are required to contain exactly one isolated and identified electrons with $p_T > 45 \text{ GeV}$ (35 GeV) and $|\eta| < 2.5$ ($|\eta| < 2.1$) for electrons (respectively for muons), at least one jet with $p_T > 30 \text{ GeV}$ and $|\eta| < 2.4$, possibly identified as a b-jet, and $\cancel{E}_T > 30 \text{ GeV}$ for the electron+jets channel ($\cancel{E}_T > 20 \text{ GeV}$ for the muon+jets). Events with another loosely isolated lepton are rejected. The trigger and lepton selection efficiencies are determined using Z events from data, and used to correct the simulation. The cross section measurement is based on a profile likelihood fit of the multidimensional distribution of the jet multiplicity N_{jet} , the b-tagged jet multiplicity $N_{b\text{-tag}}$ and the possibly reconstructed secondary vertices mass M_{SV} . The secondary vertices reconstructed within jets allow to discriminated light-flavor quarks and

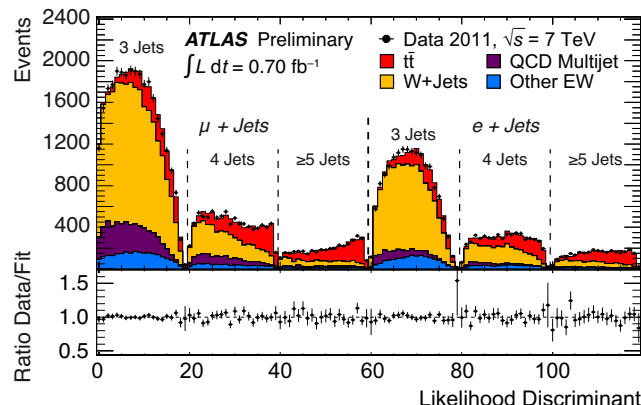


Figure 1. Result of combined fit to data in the exclusive three-jet bin, the exclusive four-jet bin and the inclusive five-jet bin of the electron+jets and muon+jets channels. The lower plot shows the ratio of data to the sum of fitted signal and background contributions.

gluon jets against b-quark jets. The likelihood fit treat the main systematic sources as nuisance parameters, and the normalization of almost all the background processes are free parameters. The QCD multi-jets is however determined using a control sample enriched in multi-jets events. The main sources of systematic uncertainties are the luminosity, the jet energy scale and resolution (JES/JER), the lepton selection and the description of Parton Density Functions (PDF). After combining the electron+jets and muon+jets channel, the $t\bar{t}$ cross section is found to be $\sigma_{t\bar{t}} = 164.4 \pm 2.8(\text{stat.}) \pm 11.9(\text{syst.}) \pm 7.4(\text{lumi.})$ pb.

3. Top pair cross section at $\sqrt{s}=7$ TeV in the dilepton channel

In this section, the ATLAS and CMS $t\bar{t}$ cross-section measurements in the dilepton channel are described. They are performed at $\sqrt{s}=7$ TeV using different integrated luminosities.

For the ATLAS measurement [5], the integrated luminosity used is 0.7 fb^{-1} . After selecting a dataset based on single lepton trigger, the event selection asks for 2 reconstructed, isolated and identified electrons ($p_T > 25 \text{ GeV}$, $|\eta| < 2.5$) and muons ($p_T > 20 \text{ GeV}$, $|\eta| < 2.5$) with opposite charges. Another selection requires the presence of a selected lepton and an isolated tracks with opposite charges. In addition, the selected events are required to contain at least 2 jets with $p_T > 25 \text{ GeV}$ and $|\eta| < 2.5$, possibly b-tagged. For the di-electron and the di-muon channels, the dilepton invariant mass m_{ll} is required to be $> 15 \text{ GeV}$, and $\cancel{E}_T > 60 \text{ GeV}$ (40 GeV in case of b-tagged jets). To further remove events containing a Z boson a cut on the dilepton invariant mass is also applied, such as $|m_{ll} - m_Z| > 10 \text{ GeV}$, with m_Z the mass of the Z boson. For the electron-muon channel, the sum of p_T of the selected jets is require to be above 130 GeV. The trigger and lepton selections efficiencies are determined using Z events from data. The DY background is estimated using a control sample enriched in Z mass. The $t\bar{t}$ (lepton+jets) and W+jets events are estimated from data using an extended Matrix Method. The contamination of the other sub-dominant backgrounds, such as single top-quark, $Z \rightarrow \tau\tau$ and dibosons events, are determined from simulations. The main systematics sources are coming from the luminosity, the jet and \cancel{E}_T selections and the modeling of signal events. After combining the dilepton channels, the $t\bar{t}$ cross section is measured to be $\sigma_{t\bar{t}} = 176 \pm 5(\text{stat.})_{-11}^{+14}(\text{syst.}) \pm 8(\text{lumi.})$ pb.

Within CMS, $\sigma_{t\bar{t}}$ is measured using an integrated luminosity of 2.3 fb^{-1} [6]. The dataset used is based on dilepton triggers. The event selection requires the presence of 2 reconstructed, isolated and identified leptons with opposite charges, with $p_T > 20 \text{ GeV}$ and $|\eta| < 2.5$ for electrons

($|\eta| < 2.1$ for muons). The following requirements are applied in order to remove DY events : $m_{ll} > 20$ GeV, $|m_{ll} - m_Z| > 15$ GeV and $\cancel{E}_T > 40$ GeV. The last two cuts are applied only on the dielectron and dimuon channels. In addition, only events with at least 2 jets (possibly b-tagged), with $p_T > 30$ GeV and $|\eta| < 2.5$, are used to performed the measurement. Dilepton trigger efficiencies are estimated using an independent sample triggered by the \cancel{E}_T . The lepton selection efficiencies are estimated from $Z \rightarrow ll$ events and the \cancel{E}_T selection efficiency is estimated from $t\bar{t}$ signal events in the electron-muon channel. $\sigma_{t\bar{t}}$ is measured using a profile likelihood ratio fit on the 2-dimensional distribution of the jet and b-tagged jet multiplicities, with the systematic sources treated as nuisance parameters. A counting analysis is also performed as a cross-check. The $Z \rightarrow ll$ background contamination in the dielectron and dimuon channels is estimated using the expected ratio of events outside and inside the Z mass cut. The $Z \rightarrow \tau\tau \rightarrow e\mu$ background contamination in the electron-muon channel is estimated from a template fit of the m_{ll} distribution. The number of events with at least one non-prompt lepton (not coming from γ^*/Z and W decays) is estimated using an extended Matrix Method. The contamination of other backgrounds is estimated from simulations. Data-to-simulation comparisons of the b-tagged jet multiplicities are shown in figure 2.

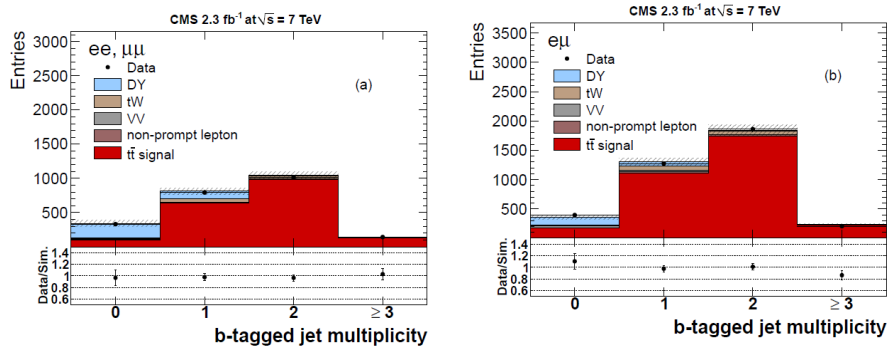


Figure 2. The multiplicity of b-tagged jets in events passing full event selections for (a) the summed ee and $\mu - \mu$ channels, and (b) the $e\mu$ channels.

The main systematic sources are coming from the uncertainty on JES and on the leptonic branching ratio of W bosons. After combining the dileptonic channels, the $t\bar{t}$ cross section is measured to be $\sigma_{t\bar{t}} = 161.9 \pm 2.5(\text{stat.})^{+5.1}_{-5.0}(\text{syst.}) \pm 3.6(\text{lumi.})$ pb. This corresponds to the most precise $t\bar{t}$ cross section measurement at the LHC. The dependence of $\sigma_{t\bar{t}}$ on the mass of the top-quark is found to be $\sigma_{t\bar{t}}/\sigma_{t\bar{t}}(m_t = 172.5) = 1.00 - 0.005 \times (m_t - 172.5) - 0.000137 \times (m_t - 172.5)^2$. This precise measurement of the $t\bar{t}$ cross sections allows to estimate other quantities, like the strong coupling constant α_S [7].

4. Combinations of top pair cross sections at $\sqrt{s}=7$ TeV

A way to further increase the precision on $\sigma_{t\bar{t}}$ is to combined statistically uncorrelated measurements. The combination of the different $\sigma_{t\bar{t}}$ measurements within the same experiment are already performed within the ATLAS [8] and the CMS [9] collaborations. A first combination of the LHC results [10],[11] is provided by the TOP-LHC working group with 0.7 to 1.1 fb^{-1} , thus without including the last ATLAS and CMS measurements. For sake of simplicity, the individual ATLAS and CMS combinations are used as input to a Best Linear Unbiased Estimator (BLUE [12]) method. The BLUE method was found to give similar results than more complex methods based on likelihood fits. To be able to perform the combination, the different systematic

sources and their correlations are compared among the two experiments. The systematic sources coming from the detector modeling, Jet Energy Scale and background determination from data are assumed to be uncorrelated. Those coming from the signal and backgrounds modeling, taken from simulations, are assumed to be fully correlated. Special care is ported on the systematics from the luminosity, as the uncertainty from the bunch charges is considered as fully correlated, while the uncertainty related the detectors (which are different) is taken as uncorrelated. The combination of ATLAS and CMS cross-section measurements is found to be $\sigma_{t\bar{t}} = 173.3 \pm 2.3(\text{stat.}) \pm 9.8(\text{syst.})$ pb. After combination, the uncertainty on $\sigma_{t\bar{t}}$ becomes 5.8%, with an observed gain of 7% with respect to the most precise individual measurement.

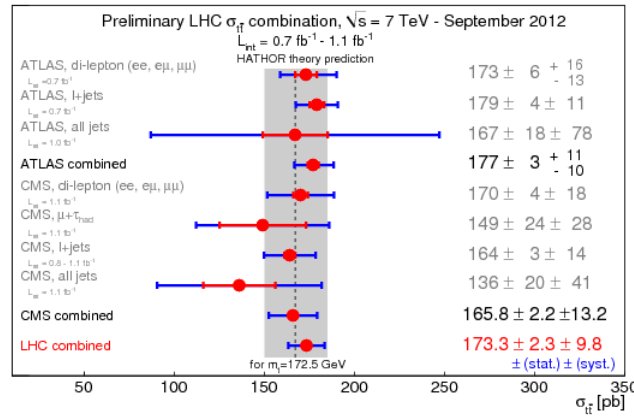


Figure 3. Input $\sigma_{t\bar{t}}$ measurements by the ATLAS and CMS collaborations and the result of the LHC combination. The band corresponds to the approximate NNLO in QCD calculation.

5. Top pair cross sections and their combinations at $\sqrt{s}=8$ TeV with the CMS detector

The $t\bar{t}$ cross section is also measured at $\sqrt{s} = 8$ TeV with the CMS detector in the dilepton [13] and the lepton+jets [14] channels, using luminosities between 2.4 to 2.8 fb^{-1} . The ratio of $\sigma_{t\bar{t}}$ at 7 and at 8 TeV is also calculated in the dilepton channel. $\sigma_{t\bar{t}}$ in the lepton+jets channel is measured after an event selection similar to the one presented in section 2. Instead of performing a profile likelihood fit of the multidimensional distribution of the N_{jet} , N_{b-tag} and M_{SV} , the $t\bar{t}$ cross section is determined by requiring the selected events to contain at least one b-tagged jet and by performing a binned likelihood fit of the invariant mass of the lepton and the closest b-tagged jet M_{lb} . A cross-check analysis is performed using the M3 variable (invariant mass of the combination of 3 jets which has the highest sum p_T). The measured cross section is found to be $\sigma_{t\bar{t}} = 228.4 \pm 9.0(\text{stat.})^{+29.0}_{-26.0}(\text{syst.}) \pm 10.0(\text{lumi.})$ pb. In the dilepton channel, $\sigma_{t\bar{t}}$ is measured with a similar event selection than the one presented in section 3. The measurement is based on a counting experiment using the number of observed event after requiring at least one b-tagged jet in the events. The measured cross section is found to be $\sigma_{t\bar{t}} = 227 \pm 3(\text{stat.}) \pm 11(\text{syst.}) \pm 10(\text{lumi.})$ pb. The combination of these cross sections using a BLUE method is found to be highly dominated by the dilepton channel, which has a very good precision, and leads to the same cross-section value. The ratio of the 8 TeV (combination) and the 7 TeV cross sections is measured to be 1.41 ± 0.10 .

6. Summary

The high luminosities provided by the LHC allows to perform high precision measurement of the $t\bar{t}$ cross section. All measurements are agreeing and are dominated by systematics uncertainties. For the same luminosity (about 1 fb^{-1}) ATLAS and CMS measurements have similar precisions, with total uncertainties of 11.4 pb (6.4%) for ATLAS and 14.4 pb (8.7%) for CMS. The combination of these measurements allows to be to an uncertainty as low as 10 pb. With higher luminosity, very high precision can be reached : 7 pb ($< 5\%$) in the dilepton channel measured with the CMS detector. Similar precisions can be reached with the 8 TeV data, despite the higher multiplicities of pileup events. Finally, the measurements of the $t\bar{t}$ cross section start to be more accurate than the approximate NNLO calculations.

References

- [1] M. Aliev et al., "HATHOR: HAdronic Top and Heavy quarks cross section calculatoR.", Comput. Phys. Commun. **182** (2011) 1034, doi:10.1016/j.cpc.2010.12.040, arXiv:1007.1327.
- [2] ATLAS Collaboration, "Measurement of the $t\bar{t}$ production cross-section in pp collisions at $\sqrt{s}=7$ TeV using kinematic information of lepton+jets events.", ATLAS-CONF-2011-121.
- [3] ATLAS Collaboration, "Measurement of the top quark pair production cross section with ATLAS in pp collisions at $\sqrt{s}=7$ TeV in the single-lepton channel using semi-leptonic b decays", ATLAS-CONF-2012-131.
- [4] The CMS Collaboration, "Measurement of the $t\bar{t}$ production cross section in pp collisions at $\sqrt{s}=7$ TeV with lepton + jets final states", arXiv:1212.6682.
- [5] The ATLAS Collaboration, "Measurement of the cross section for top-quark pair production in pp collisions at $\sqrt{s}=7$ TeV with the ATLAS detector using final states with two high-pT leptons", *JHEP* **07** (2011) 059.
- [6] S. Chatrchyan et al. "Measurement of the $t\bar{t}$ production cross section in the dilepton channel in pp collisions at $\sqrt{s}=7$ TeV, *JHEP* **11** (2012) 067.
- [7] The CMS Collaboration, "First Determination of the Strong Coupling Constant from the $t\bar{t}$ Cross Section", CMS PAS TOP-12-022.
- [8] The ATLAS Collaboration, "Statistical combination of top quark pair production cross-section measurements using dilepton, single-lepton, and all-hadronic final states at $\sqrt{s}=7$ TeV with the ATLAS detector", ATLAS-CONF-2012-024.
- [9] The CMS Collaboration, "Combination of top pair production cross section measurements", CMS PAS TOP-11-024.
- [10] The ATLAS Collaboration, "Combination of ATLAS and CMS top-quark pair cross section measurements using up to 1.1 fb^{-1} of data at 7 TeV", ATLAS-CONF-2012-134.
- [11] The CMS Collaboration, "Combination of ATLAS and CMS top-quark pair cross section measurements using proton-proton collisions at $\sqrt{s}=7$ TeV", CMS PAS TOP-12-003.
- [12] L. Lyons, D. Gibaut, and P. Clifford, "How to combine correlated estimates of a single physical quantity", *Nucl. Instrum. Meth. A* **270** (1988) 110, doi:10.1016/0168-9002(88)90018-6.
- [13] The CMS Collaboration, "Top pair cross section in e/mu+jets at 8 TeV", CMS PAS TOP-12-006.
- [14] The CMS Collaboration, "Measurement of the $t\bar{t}$ production cross section in the dilepton channel in pp collisions at $\sqrt{s}=8$ TeV", CMS PAS TOP-12-007.