\textbf{\textit{t\bar{t}} pair production cross section measurement at the LHC}

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\textbf{Abstract.} Measurement of \textit{t\bar{t}} pair production cross sections with an integrated luminosity of around 1 fb\textsuperscript{-1} at \(\sqrt{s} = 7\) TeV obtained with the ATLAS and CMS detectors are reported. The inclusive cross sections in dilepton (ee, \(e\mu, \mu\mu\) and \(e\tau\)) and lepton+jets (e, \(\mu\)) modes are measured. In addition to inclusive cross section, the study of jet multiplicity with additional jets are also presented, which is important to constrain the initial state radiation. Measurement of the charge asymmetry at the LHC is also presented. All measurements are compatible with Standard Model predictions.

1 Introduction

The Large Hadron Collider (LHC) accumulated the data corresponding to an integrated luminosity of almost 1 fb\textsuperscript{-1} in both experiments ATLAS [1] and CMS [2] by the summer in 2011 for HCP2011. At the LHC, the \textit{t\bar{t}} production cross section at \(\sqrt{s} = 7\) TeV is predicted to be 164.6 pb by approximate next-to-next-leading-order (NNLO) calculation and 157.5 pb by next-leading-order (NLO) calculation. The cross section measurement of \textit{t\bar{t}} is important for testing the perturbative QCD which is successful so far and searching for new physics. Any deviation would indicate possible new physics. It is crucial to measure the cross section in all decay modes since new physics can appear in any different decay modes. Top quark decays almost exclusively to W boson ans b quark. Therefore, the decay mode entirely depending on W boson branching ratio. In dilepton decay mode (ee, \(e\mu, \mu\mu\)), tau leptonic decay is included. Considering \(Br(\tau \rightarrow l\nu_\tau\nu_\tau) = 0.35\), the branching ratio would be 6.8\%, 3.8\%, 30\% and 44\% for dilepton, lepton+tau, lepton+jets and all hadronic decay modes, respectively. In addition to inclusive cross section, the jet multiplicity distribution of \textit{t\bar{t}} with additional jets in lepton+jets decay mode is shown, which is important measurement to constrain the initial state radiation (ISR). As the deviation has been observed by Tevatron, the charge asymmetry measurement at the LHC are also performed using the fact that the width of top quark is slightly broader than anti-top quark in rapidity distribution at the LHC.

2 Samples & Objects

At ATLAS, MC@NLO is interfaced with HERWIG (Parton Showering) and JIMMY (Underlying Events). Approximate NNLO of 164.6 pb is used for normalization. At CMS, the signal sample of \textit{t\bar{t}} is modeled by MADGRAPH with PYTHIA matching up to three additional partons. NLO cross section of 157.5 pb is used for normalization. In both experiments, the \(\tau\) decay is handled by TAUOLA and top quark mass is assumed to be 172.5 GeV/c\textsuperscript{2}.

In top quark analysis, almost all physics objects are used. At ATLAS, the absolute pseudo-rapidity (\(|\eta|\)) of electrons and muons are required to be within 2.5. Taus are reconstructed using Boosted Decision Tree. Calo-jets are reconstructed using anti-k\(T\) algorithm with R=0.4. Missing transverse energy (\(E_T^{\text{miss}}\)) is calculated using the opposite direction of vector sum of jets, electrons, muons and unclustered calorimeter energy. At CMS, physics objects are reconstructed through particle-flow reconstruction algorithm which combines all information from all subdetectors and reconstruct all particles. The \(|\eta|\) of electrons and muons are required to be within 2.5 and 2.4, respectively. Taus are reconstructed using Hadron plus strips algorithm. Particle-flow jets are reconstructed using anti-k\(T\) algorithm with R=0.5. \(E_T^{\text{miss}}\) is the opposite direction of vector sum of reconstructed particles.

3 Cross section measurements

3.1 Dilepton (ee, \(e\mu, \mu\mu\))

The dilepton decay mode (ee, \(e\mu, \mu\mu\)) provides clean signals by requiring two isolated leptons with two jets and \(E_T^{\text{miss}}\) even though the branching ratio is small. ATLAS performed the analysis with the integrated luminosity of 0.7 fb\textsuperscript{-1} with and without b-tagging separately [3]. The invariant mass of dilepton must be above 15 GeV to remove multi-jet event sample which does not describe well low mass region. Z boson veto requiring \(|M_{ll} - M_Z| > 10\) GeV and \(E_T^{\text{miss}} > 60\) GeV (or 40 GeV with b-tagging) to remove multi-jet events are applied for \(ee\) and \(\mu\mu\) decay modes. Additionally \(H_T > 130\) GeV (or 140 GeV with b-tagging) is applied. Lepton efficiencies are obtained with Z boson candidates in a data-driven way. The Drell-Yan and multi-jet backgrounds are estimated using Z mass window and Matrix method, respectively. The cross section is obtained from the profile likelihood fitting. The measured cross section without b-tagging is found to be

\[\sigma_{ll} = 177 \pm 6\text{(stat.)} \pm 14\text{(syst.)} \pm 8\text{(lumi.)} \text{ pb}\]

and with b-tagging

\[\sigma_{ll} = 183 \pm 6\text{(stat.)} \pm 10\text{(syst.)} \pm 5\text{(lumi.)} \text{ pb}\]
CMS performed the analysis with the integrated luminosity of 1.1 fb$^{-1}$ [3]. The invariant mass of dilepton must be above 12 GeV and $|M_{ll} - M_Z| > 15$ GeV. $E_T^{miss}$ > 30 GeV is required for $ee$ and $\mu\mu$ decay modes. At least one b-tagging is applied. Lepton efficiencies, Drell-Yan and multi-jet backgrounds are obtained in a data-driven way similar to ATLAS. Distributions of b-tagged jet multiplicity at CMS and ATLAS are shown in Fig. 1. The cross section for each decay mode is obtained using counting method. The combined result of the three decay modes is found to be

$$\sigma_T = 169.9 \pm 3.9 \text{(stat.)} \pm 16.3 \text{(syst.)} \pm 7.6 \text{(lumi.)} \text{ pb}$$

using the Best Linear Unbiased Estimator (BLUE) method. The measured cross sections are consistency with NNLO prediction. The systematic uncertainty is now dominant compared to the result based on previous data at ATLAS [5-6] and CMS [7-8].

### 3.2 Dilepton ($\mu\tau$)

The $\mu + \tau$ decay mode is interesting since the charged higgs can decay with the same topology when the higgs mass is larger than top mass. Any deviation on cross section would indicate the new physics. Therefore, reducing the systematic uncertainty is crucial in this decay mode. ATLAS performed the analysis with an integrated luminosity of 1.08 fb$^{-1}$ [9]. This analysis follows lepton+jet analysis event selection since hadronic tau decay is considered. Two tau candidates $\tau$ with 1 track and $\tau$ with more than 1 track are identified using Boosted Decision Tree (BDT). The multi-jet events are removed by subtracting same sign events. Distributions of jet multiplicity with BDT < 0.7 and BDT > 0.7 are shown in Fig. 2. Measured cross section at ATLAS is

$$\sigma_T = 142.2 \pm 21 \text{(stat.)} \pm 20 \text{(syst.)} \pm 5 \text{(lumi.)} \text{ pb}$$

CMS performed the analysis with an integrated luminosity of 1.1 fb$^{-1}$ data [10]. Tau is identified with Hadrons plus strips (HPS) algorithm combining charged hadrons and calorimeter information in strips to take into account $\pi^0$. The fake rate from jets is estimated from multi-jet (gluon jet) and W+jets (quark jet) data sample. Measured cross section is

$$\sigma_T = 148.7 \pm 23.6 \text{(stat.)} \pm 26.0 \text{(syst.)} \pm 8.9 \text{(lumi.)} \text{ pb}$$

Main systematic uncertainties are from tau fake background estimation, identification and b-tagging efficiency.

### 3.3 Lepton+jets

In lepton+jet decay mode ($e, \mu$), the signature of a final state is one exclusive lepton, 4 jets and $E_T^{miss}$. ATLAS performed the analysis with the integrated luminosity of 0.7 fb$^{-1}$ [11]. Exclusively one isolated muon or electron must have $p_T > 20$ or 25 GeV, respectively. $E_T^{miss}$ is required to be larger than 35 and 25 GeV for $e$ and $\mu$, respectively. $M_T^\tau$ (Transverse mass of W boson) must be larger than 25 GeV for electron channel and the sum of $M_{b\bar{b}}$ and $E_T^{miss}$ should be larger than 60 GeV for muon channel to remove further multi-jet contribution. The multi-jet shapes are obtained from data directly using Matrix method. The binned profile likelihood fitting is applied to likelihood discriminant which is as a function of lepton $\eta$, highest jet $p_T$, event aplanarity and $H_T$. The result of the fit is shown in Fig. 3. Main systematic uncertainties are from signal MC generator, jet energy scale (JES), and ISR/FSR. Measured cross section is found to be

$$\sigma_T = 179.0 \pm 3.9 \text{(stat.)} \pm 9.0 \text{(syst.)} \pm 6.6 \text{(lumi.)} \text{ pb}$$

CMS performed the analysis with the integrated luminosity of 1.1 fb$^{-1}$ ($\mu$) and 0.8 fb$^{-1}$ ($e$) [12]. Exclusively one isolated muon or electron must have $p_T > 35$ or 45 GeV, respectively. $E_T^{miss}$ is required to be larger than 20 and 30 GeV for $e$ and $\mu$, respectively. b-tagging with secondary vertex algorithm is applied at CMS. The multi-jet shapes are obtained from data directly using non-isolated data. Binned profile likelihood fitting is applied to secondary vertex mass distribution in 1 b-tag and 2 b-tag jet bins. Measured cross section is found to be

$$\sigma_T = 164.4 \pm 2.8 \text{(stat.)} \pm 11.9 \text{(syst.)} \pm 7.4 \text{(lumi.)} \text{ pb}$$

Main systematic uncertainties are from W+jets Q$^2$ scale, b-tagging efficiency and JES. Comparing the result with 36 pb$^{-1}$ in 2010 [13],[14], the statistical uncertainty is by far reduced and the systematic uncertainty is dominant.

### 3.4 Hadronic decay

In hadronic decay mode, The branching ratio of hadronic decay mode is as large as around 45%. However, it suffers from large multi-jet background. In this analysis, 6 jets and at least two b-tagged jets are required. ATLAS performed the analysis with the integrated luminosity of 1.08 fb$^{-1}$ [15]. Additionally $E_T^{miss}$ significance of $E_T^{miss}/\sqrt{H_T} < 3$ is applied. $\Delta R(b, \bar{b}) > 1.2$ is also applied to remove gluon...
splitting. The event mixing technique is used modeling higher jet multiplicity using lower jet multiplicity multi-jet sample. The number of signal is extracted from fitting to mass $\chi^2$. Measured cross section is found to be

$$\sigma_{tt} = (167 \pm 18 \text{(stat.)} \pm 78 \text{(syst.)} \pm 6 \text{(lumi.)}) \text{ pb.}$$

CMS performed the analysis with the integrated luminosity of 1.1 fb$^{-1}$ [16]. The multi-jet shape is obtained from data extrapolating from non b-tagged jet sample (more than 6 jets) to b-tagged jets. In order to take into account the kinematic phase space difference, the scale factor is applied to non b-tagged jet sample as a function of $p_T$ and $\eta$. Unbinned maximum likelihood fitting is applied to top mass distribution to extract the number of signal. Result of the fit to the reconstructed top mass is shown in Fig. 4. Measured cross section is found to be

$$\sigma_{tt} = (136 \pm 20 \text{(stat.)} \pm 40 \text{(syst.)} \pm 8 \text{(lumi.)}) \text{ pb.}$$

The uncertainties are mainly from b-tagging, JES, multi-jet background estimation.

### 3.5 Combined result

ATLAS has shown the combined result from the dilepton analysis performed with 0.7 fb$^{-1}$ and lepton+jets analysis performed with 35 pb$^{-1}$ [17]. The combined result is found to be

$$\sigma_{tt} = (176 \pm 5 \text{(stat.)} \pm 13 \text{(syst.)} \pm 7 \text{(lumi.)}) \text{ pb.}$$

At the time of HCP2011, CMS combined the dilepton (ee, e$\mu$, $\mu\mu$, $\mu\tau$), lepton+jets (e, $\mu$) and all hadronic decay analysis performed with around 1 fb$^{-1}$ [18]. The binned maximum likelihood fitter from lepton+jet analysis is used for combination adding other decay modes as a single bin. Combined cross section result at CMS comparing to the approximate NNLO calculations are shown in Fig. 5. The combined result is found to be

$$\sigma_{tt} = (165.8 \pm 2.2 \text{(stat.)} \pm 10.6 \text{(syst.)} \pm 7.8 \text{(lumi.)}) \text{ pb.}$$

The total uncertainty in combined analysis at CMS only is obtained to be 8%, which is the most precise measurement at the LHC.

### 4 Jet multiplicity

Jet multiplicity distribution of $tt$ with additional jets with different jet transverse momentum is very useful to constrain ISR. ATLAS performed the analysis in lepton+jets channel with a luminosity of 0.7 fb$^{-1}$ [19]. Event selection follows lepton+jet analysis with requiring at least 4 jets and one b-tagging. The background-subtracted reconstructed jet multiplicity as a function of jet $p_T$ threshold (25, 40 and 60 GeV) is compared with ISR variations as shown in Figs 6. The ISR variations were generated by varying the settings of the PYTHIA generator. There is no deviation found from MC@NLO SM prediction. We need more statistics to constrain ISR.

### 5 Charge asymmetry measurement

Tevatron has observed deviation in charge asymmetry measurement. CDF has observed 3.4 $\sigma$ deviation with respect to SM above 450 GeV. The deviation could be explained
PIDITY is used as charged asymmetry variables for the analysis of top quark (valence quark) width. At ATLAS, absolute rapidity distributions of top and anti-top quarks are broader than those at CMS [200 300 400 500 600 700 800 900 1000 1100 1200 √(s) = 7 TeV], Phys. Lett. B (2011) 157.

6 Conclusion

We have produced precise measurement dilepton and lepton+jets decay modes both at ATLAS and at CMS. These measurements are already systematically limited and starting to constrain theory. Improve pileup modeling and b-tagging is required to reduce the systematic uncertainty. The first measurements in fully hadronic decays and decays tau are presented. All measured results are compatible with SM prediction so far.

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