Chapter 1

Highlights of top quark production measurements at ATLAS

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Measurements of top-quark production have been performed in various modes with the ATLAS detector at the Large Hadron Collider. Inclusive and differential top-quark pair ($t\bar{t}$) production cross sections are discussed with emphasis on associated QCD activities. The interference of timelike top-quark propagators in $Wt + b$ and $t\bar{t}$ productions is studied in the single top production. Top-quark productions in $Z + t$ and $t\bar{t} + \text{boson}$ have been searched for using a multi-variate analysis method to maximize the sensitivity for their small cross sections and complicated kinematics. The obtained significances indicate the evidence for $Z + t$ production and discovery of $t\bar{t} + H$, top-Yukawa coupling.

1.1 Introduction

The top quark is the Standard-Model (SM) particle with the largest mass, which was discovered in 1995 by CDF and DØ experiments at the TEVATRON $p\bar{p}$ collider ($\sqrt{s} = 1.8$ and 1.92 TeV). The ATLAS experiment using pp collisions at the LHC ($\sqrt{s} = 7, 8$ and 13 TeV) [1] has collected a large amount of data since 2012, which allows high-precision measurements of top-quark properties. Top quark decay kinematics is characteristic by its large mass of ~ 172.5 GeV involving decaying objects with high-momentum b and $W(\rightarrow \ell\nu \text{ or } qq')$. Therefore,

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the top quark production measurements are useful for tests of SM physics (e.g. QCD and Electro-weak vertices are included in $t\bar{t}$ and single-top productions, respectively). These results will constrain Monte-Carlo tuning parameters for precise SM physics simulations, which realizes better predictions of background processes for beyond SM (BSM) searches. The top quark itself may have a special role in mass origin in several BSM theories, and deviations from SM can probe contributions from certain BSM physics. In this paper, highlights of the top quark production measurements are shown.

1.2 Inclusive Production Cross-sections

In the ATLAS experiment, inclusive cross sections have been measured at 7, 8 and 13 TeV for $t\bar{t}$ channels including at least one lepton in the final state objects and for single-top in three production modes (Wt , t -channel, and s -channel). All results are consistent to SM predictions as shown in Figure 1.1 [2]. The most precise $t\bar{t}$ inclusive cross section at 13 TeV is $818 \pm 8(\text{stat.}) \pm 27(\text{syst.}) \pm 19(\text{lumi.})$ pb obtained from the dilepton channel [3].

Figure 1.1: Inclusive cross section measurements at various center of mass energies [2]. All measurements are consistent to SM predictions.

1.3 $t\bar{t}$ Production

The differential cross sections about various kinematic variables have been measured at $\sqrt{s} = 13$ TeV [4]. The kinematics of hadronic top quarks ($t \rightarrow bW \rightarrow bq\bar{q}'$ decay chain) can directly probe the associated QCD activities. The differential cross section with relation to the transverse-momentum (p_T) of the hadronic top quark is shown in Figure 1.2a. This measurement was performed in the ℓ +jets channel, namely requiring other top quark to decay leptonically. Although the $t\bar{t}$ signal modeling in 13 TeV has been improved based on the 8 TeV measurements, discrepancies in the high p_T region are to be noted.

To investigate this result, $t\bar{t}$ differential cross sections for specific number of additional jets were also measured [5]. Figures 1.2b to 1.2d show the differential cross sections in hadronic top p_T , where the number of jets was required to be 4, 5, or ≥ 6 jets corresponding to 0, 1, or ≥ 2 additional jets. The discrepancies were observed mostly in the channel with no additional jets.

Figure 1.2: Differential $t\bar{t}$ cross section as a function of the hadronic top p_T . Inclusive measurement, (a), is subdivided into three categories, (b), (c), and (d), by requiring 0, 1, and ≥ 2 additional jets, respectively.

Cross sections for $t\bar{t}$ production associated with additional b -quarks were

also measured in the ℓ +jets and dilepton channels [6]. The measurements can test QCD calculations involving massive b -quarks, and allow significant reduction of systematic uncertainties from background modeling in analyses such as $t\bar{t} + H$ ($H \rightarrow b\bar{b}$) process. Figure 1.3a shows the cross section with relation to the number of b -jets ($N_{b\text{-jets}}$) measured in the dilepton channel. Events in the bin with $N_{b\text{-jets}} = 2$ have no additional b -quarks, events with additional b -quarks are filled into second ($N_{b\text{-jets}} = 3$) and third ($N_{b\text{-jets}} \geq 4$) bins where certain discrepancies were observed between the data and all simulations other than Sherpa 2.2. The inclusive cross sections for $t\bar{t}$ production with additional b -quarks were shown in Figure 1.3b in comparison with Sherpa 2.2 as SM prediction. The observed cross sections are slightly higher than the simulation, but still within 2σ uncertainties. The measurement is dominated by systematic uncertainties in $t\bar{t}$ modeling, jet energy scale, and b -tagging.

Figure 1.3: Cross sections for $t\bar{t}$ production associated with additional b -quarks [6].

As a consequence of the increased center of mass energy at $\sqrt{s} = 13$ TeV, two jets from W decay tend to be merged into a single jet, and study of such boosted topologies are interesting to be carried out [7]. In the all-hadronic channel, the differential cross sections with 36.1 fb $^{-1}$ data were measured with relation to boosted kinematics of hadronic top quarks. Predictions are generally consistent with the data, as shown in Figure 1.4.

Figure 1.4: Cross sections for boosted $t\bar{t}$ production as a function of p_T of the leading top and $t\bar{t}$ system, which were measured in boosted top kinematics in the all hadronic channel. [7].

1.4 Single Top Quark Production

The differential measurements of the Wt production were performed using 36.1 fb^{-1} data, which is sensitive to the V_{tb} coupling [8]. In the event selection, a multi-variate analysis was utilized by using four-momenta of leptons, b -jet, and E_T^{miss} . By constructing a boosted decision tree (BDT) and requiring its score higher than 0.3 (Figure 1.5a), systematic variations of the background process were suppressed. The obtained differential cross section with relation to the mass of a lepton and b -jet is shown in Figure 1.5b. Although the slope was observed in the ratio of the data and predictions, results are consistent within uncertainties. Because uncertainties are still dominated by both statistic and systematic uncertainties, more precise measurement will be performed by using increased data statistics at $\sqrt{s} = 13 \text{ TeV}$.

In the middle plot of Figure 1.5b, results obtained with two different methods of Wt and $t\bar{t}$ interference subtraction schema are shown. In $Wt + b$ and $t\bar{t}$ productions, processes with one and two timelike top-quark propagators interfere due to their identical $WWb\bar{b}$ final states. These Feynman diagrams are shown in Figure 1.6. To make the interference effect noticeable in one variable, $m_{b\ell}^{\text{minimax}}$ was defined as [9]:

$$m_{b\ell}^{\text{minimax}} = \min [\max (m_{b_1 \ell_1}, m_{b_2 \ell_2}), \max (m_{b_1 \ell_2}, m_{b_2 \ell_1})],$$

where $b_{1,2}$ ($\ell_{1,2}$) denote reconstructed b -jets (leptons) and m denotes their invariant mass. Three simulation samples were prepared for this measurement:

- inclusive sample $\ell\ell\nu\nu b\bar{b}$ final state.

(a) BDT score distribution constructed by four-momenta of leptons, b -jet, and E_T^{miss} . The events higher than 0.3 are used for the differential cross section measurement.

(b) Differential cross section with relation to the invariant mass of the lepton and b -jet

Figure 1.5: BDT score used in the event selection and the differential cross section for Wt production [8].

- DR (diagram removal): exclusive samples of Wt and $t\bar{t}$ NLO, where all doubly resonant amplitudes are removed from the Wt sample.
- DS (diagram subtraction): exclusive samples of Wt and $t\bar{t}$ NLO, where resonant contributions are canceled out by gauge-invariant subtraction terms.

The result is shown in Figure 1.7. The inclusive sample describes the data well. DR and DS samples have opposite descriptions in the high mass range dominated by $Wt + b$ production. Their difference is used as an estimate of the systematic uncertainty on the measurement of the Wt cross section.

The $Z + t$ production which is sensitive to the V_{tq} coupling [10], was also measured. Since its cross section is significantly small compared to the Wt production, a multi-variate analysis was utilized in the signal region to extract the $Z + t$ events. A neural network (NN) was constructed by basic four-momenta variables; the resulting NN score ($\mathcal{O}_{\text{NN}}$) is shown in Figure 1.8. The measured cross section is $600 \pm 170(\text{stat.}) \pm 140(\text{syst.})$ fb. Evidence for $Z + t$ production

Figure 1.6: Interfering Feynman diagrams involving one or two timelike top-quark propagators [9].

Figure 1.7: Differential cross section for $\ell \ell \nu \nu b \bar{b}$ with relation to $m_{b\ell}^{\text{minimax}}$. Three predictions of different interference treatments are shown [9].

is obtained with corresponding measured significance of 4.2σ from the no $Z + t$ process assumption to be compared with 5.4σ is expected.

Figure 1.8: The neural-network score in the signal region. Signal and backgrounds are normalized to the expected number of events after the fit [10].

1.5 $t\bar{t} + X$ Production

1.5.1 $t\bar{t} + \gamma$

The $t\bar{t} + \gamma$ production analysis is sensitive to the t - γ electro-magnetic coupling. The analysis focused on the ℓ +jets channel and used 20.2 fb^{-1} data at $\sqrt{s} = 8 \text{ TeV}$ [11]. The fitting was performed using the reconstructed photon p_T distribution. The extracted signal events are consistent to the NLO SM prediction in both inclusive and differential cross section measurements, as shown in Figure 1.9.

1.5.2 $t\bar{t} + W$ and $t\bar{t} + Z$

The cross section for $t\bar{t}$ production in association with a massive vector boson (W or Z) is often expected to be affected by BSM interferences. The $t\bar{t}+Z$ is also sensitive to the t - Z neutral-current coupling. Due to the complex kinematics of the final state, the analysis was performed separately in $t\bar{t} + W$ and $t\bar{t} + Z$. Each analysis was sub-divided to several signal regions and control regions to maximize the sensitivity [12]. Totally nine signal regions to extract $t\bar{t}+W/Z$ and two control regions to handle WZ and ZZ background processes were defined. The number of events in each region is shown in Figure 1.10a. Using them, a binned maximum likelihood fit was performed with four parameters, two cross sections for $t\bar{t} + W$ and $t\bar{t} + Z$ and two correction scale factors for WZ and ZZ . The measured cross sections are:

$$1.50 \pm 0.72(\text{stat.}) \pm 0.33(\text{syst.}) \text{ pb for } t\bar{t} + W$$

$$0.92 \pm 0.29(\text{stat.}) \pm 0.10(\text{syst.}) \text{ pb for } t\bar{t} + Z.$$

Figure 1.9: Inclusive and differential cross section for $t\bar{t} + \gamma$ production [11].

This result corresponds to 2.2σ (3.9σ) deviation from the no $t\bar{t} + W$ ($t\bar{t} + Z$) assumption while 1.0σ (3.4σ) is expected. The correlation among the two cross sections is shown in Figure 1.10b, which is consistent to SM prediction. The obtained WZ and ZZ correction scale factors are also compatible to SM. Results are dominated by the statistic uncertainty, and more data will allow precise measurements of the $t\bar{t} + V$ production.

Figure 1.10: The number of events in each analysis region and the correlation of fitted $t\bar{t} + W$ and $t\bar{t} + Z$ production cross sections [12].

1.5.3 $t\bar{t} + H$

The cross section measurement of $t\bar{t}$ production in association with a Higgs boson is a unique analysis significantly sensitive to the t - H Yukawa coupling. The $t\bar{t} + H$ production has an even smaller cross section and much complicated kinematics than $t\bar{t} + W$ and $t\bar{t} + Z$ productions. The analysis was separately optimized in different Higgs decaying channels, $H \rightarrow b\bar{b}$, $H \rightarrow WW/ZZ/\tau\tau$, and $H \rightarrow \gamma\gamma$. A multi-variate analysis was utilized to maximize the sensitivity in all three analysis channels.

In the $H \rightarrow b\bar{b}$ channel [13], there are large amount of irreducible $t\bar{t} + b\bar{b}$ background events. To enhance the signal significance, multiple-staged BDT was built in all nine signal regions. The BDT distribution in the most sensitive signal region is shown in Figure 1.11a.

In the $H \rightarrow WW/ZZ/\tau\tau$ channel [14], BDTs were used in the lepton selection to reduce fake and charge misidentified leptons, and also in the final discriminant for several signal regions with large statistics. The most sensitive signal region focuses on $H \rightarrow WW$, and the BDT distribution for the final discriminant in this region is shown in Figure 1.11b.

Even in the $H \rightarrow \gamma\gamma$ clean channel [15], a BDT was built in the region definition to separate the signal from a large amount of γ +jets process, as shown in Figure 1.11c.

They were combined for the inclusive $t\bar{t} + H$ production measurement after the binned maximum likelihood fit was performed in each analysis channel [15]. The individual and combined results using 36.1-79.8 fb⁻¹ data at $\sqrt{s} = 13$ TeV are summarized in Figure 1.12. The measured cross section is

$$670 \pm 90(\text{stat.})^{+110}_{-100}(\text{syst.}) \text{ fb},$$

which corresponds to 5.8σ deviation from the no $t\bar{t} + H$ assumption while 4.9σ is expected [15]. Figure 1.13 shows all histogram bins sorted by sensitivities, which can validate the fitted signal values.

When combining all data at $\sqrt{s} = 7, 8,$ and 13 TeV, $t\bar{t} + H$ production is observed with a significance of 6.3σ from the no $t\bar{t} + H$ assumption while 5.1σ is expected [15]. This constitutes a direct observation of the Yukawa coupling between the Higgs boson and the top quark.

1.6 Conclusion

Increased $\sqrt{s} = 13$ TeV of LHC allowed extended and precise measurements of top quark production with the ATLAS detector. Generally, good consistencies with SM prediction were obtained in both inclusive and differential cross section measurements in $t\bar{t}$ and single-top productions. However, there is a room to tune MC simulation parameters by using these results (e.g. in high-momentum regions). Measurements with more data and in more channels are expected in the near future.

Figure 1.11: Several BDT distributions in $t\bar{t} + H$ analysis channels.

Rare and complicated processes have also been investigated such as $Z + t$ and $t\bar{t} + X$ productions. The $Z + t$ production measurement showed the evidence by using 36.1 fb^{-1} data at $\sqrt{s} = 13 \text{ TeV}$. Although $t\bar{t} + \gamma$ and $t\bar{t} + V$ productions are now compatible with SM prediction, increased data statistics will allow significantly precise measurements. The $t\bar{t} + H$ production has been established by the ATLAS for the first time by combining all data from $\sqrt{s} =$

Figure 1.12: Combined $t\bar{t} + H$ production cross section, as well as cross sections measured in individual channels using 13 TeV data, which are divided by SM prediction [15]. The black lines (yellow and blue bands) show the total (individual) uncertainties. The red vertical line indicates SM prediction with uncertainties shown as the grey band.

7, 8, and 13 TeV. Precise and direct top Yukawa coupling measurement will be performed by using all data collected up to 2018.

Figure 1.13: Observed number of events in all analysis channels of 13 TeV data after the fit (signal yields correspond to $\mu = \sigma_{t\bar{t}H}/\sigma_{t\bar{t}H}^{SM} = 1.32$) [15]. Signal yields of SM prediction are also shown as $\mu = 1$. The bins are sorted by S/B values, where $S(B)$ denotes signal (background) yields. The second panel shows the fraction of analysis channels in each bin. The lowest panel shows the pulls of the data with respect to the background-only prediction.

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