Top quark pair cross section prospects in ATLAS

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The observation of the top quark will be an important milestone in ATLAS. This talk reviews methods that ATLAS plans to use to observe the top quark pair production process and measure its cross section.

1. Introduction

The motivations to study top quarks are manifold. The top quark can be used as a probe for new physics. Top pair production process presents a dominant background to many New Physics searches. Finally, it will be a valuable tool for detector calibration at the LHC. Establishing a top quark signal will be an important milestone in the ATLAS physics program.

The results in this talk are based upon simulations with 14 TeV center of mass energy. Unless stated otherwise, the studies presented here are documented in [1].

In hadron collisions, the top quark can be produced via either the strong (tt) or electroweak (single top) process. While the pair production was established at the Tevatron in 1995 [2], [3], it took until 2009 to observe the electroweak process [4], [5]. While at the LHC we expect to observe single top in a much shorter time frame, the initial focus will be on the tt process.

The production cross section of top quark pairs increases from about 7 pb at the Tevatron to about 900 pb (√s = 14 TeV) or 400 pb (√s = 10 TeV) at the LHC. For example, with 200 pb$^{-1}$ of integrated luminosity at 10 TeV about 80k tt would be produced. Another important consideration is that the production cross section of the dominant background, W+jets, increases more slowly with energy than the signal cross section. That improves S/B and makes the tt process easier to observe than at the Tevatron.

According to the Standard Model, the top quark decays almost exclusively into a b quark and a W boson. Top quark pair decays are classified according to the decay modes of the two W bosons into all hadronic, lepton+jets, and dilepton channels. In ATLAS the initial focus will be on decays that have either an electron or a muon from W decay in the final state. Such decays will be an important detector validation and calibration tool because they contain energetic jets, leptons, b-jets, and large missing transverse energy, allowing ATLAS subdetectors to be exercised. Jet energy scale and b-jet identification efficiency can be calibrated using tt events.

The lepton+jets channel has a relatively large branching fraction (about 15% per flavor), and full kinematic information for the hadronic top quark is preserved, allowing for a mass peak reconstruction. The background in this channel may be relatively large, but it is dominated by one process, W+jets.

The dilepton channel has a much lower background. An interesting feature of the eµ channel is that one can measure trigger efficiencies directly on tt events. But dilepton channels also have a much smaller branching fractions (about 1% for eµ, ee or 2% for eµ), and more kinematic information is lost because of the two escaping neutrinos.

2. Total cross section measurements

2.1. Lepton+jets analysis

Event preselection

- Lepton $p_T > 20$ GeV, $|\eta| < 2.5$
- $E_T > 20$ GeV
- $\geq 4$ jets $p_T > 20$ GeV, $|\eta| < 2.5$
- Including $\geq 3$ jets $p_T > 40$ GeV

Note that no b-tagging is used. We require either a “medium” electron, or a “combined” muon [1].

![Figure 1: A stack plot of the 3-jet invariant mass for $t\bar{t}$ events in the muon+jets channel that were reconstructed correctly (clear histogram), where a wrong jet combination was chosen (cyan histogram), and non $t\bar{t}$ background (yellow histogram at the bottom). The distributions are normalized to 100 pb$^{-1}$ at 14 TeV.](attachment:figure1.png)

There are different methods to reconstruct the hadronically decaying top quark, that is, to determine which of the jets in the events are produced by decay...
products of that quark, in a $t\bar{t}$ event. The method used here is based on the fact that at the LHC top quarks are not produced at rest but have a non-zero $p_T$. Since QCD has no intrinsic mass scale, the average $p_T$ of an object is proportional to the mass of the object. The top quark is the heaviest Standard Model object, so we select the 3 jets that maximize $\sum_{i=1}^{3} \vec{p}_T, i$ as the daughters of the top, and treat the invariant mass of the three jet combination as the mass of the reconstructed top candidate. Figure 1 shows invariant mass spectra for correctly and incorrectly reconstructed signal events, and also the background contribution (dominated by $W + \text{jets}$).

After a 3-jet combination is assigned to a top quark, we apply an additional cut: at least one of the pairs of jets originating from the top quark should have an invariant mass compatible with that of the $W$:

- $|M_{jj} - M_W| < 10 \text{ GeV}$ for a hadronic-top jet-pairing

The expected numbers of events in 100 pb$^{-1}$ at 14 TeV for the signal and main backgrounds after the selection cuts are summarized in Table I.

Table I Expected event counts in the lepton+jets channel for 100 pb$^{-1}$ at 14 TeV.

| Source                | $e$  | $\mu$ |
|-----------------------|------|-------|
| signal $t\bar{t}$    | 1262 | 1606  |
| $W + \text{jets}$     | 241  | 319   |
| single top            | 67   | 99    |
| $Z + \text{jets}$     | 35   | 23    |
| other non-QCD         | 31   | 54    |
| Total background      | 374  | 495   |
| S/B                   | 3.4  | 3.2   |

The simplest (“counting”) method to extract the cross section will use the number of data events in the signal region and subtract background estimated from simulations. Another possibility is to fit the 3-jet invariant mass distribution to estimate the number of signal events while normalizing background to data. An example of a fit is shown in Figure 2.

A summary of statistical and dominant systematic uncertainties for these two methods is shown in Table II. One can see that the two methods are complementary because their leading systematics are different: the counting method is more sensitive to the $W + \text{jets}$ background uncertainty and the jet energy scale, but the fitting method has a large systematic associated with the shape of the fitting function. The expected final uncertainties of a $t\bar{t}$ cross section measurement using 100 pb$^{-1}$ of data at 14 TeV, using a combination of the electron+jets and muon+jets channels, are the following. Counting method:

$$\Delta \sigma / \sigma = (\pm 3(\text{stat}) \pm 16(\text{sys}) \pm 3(\text{pdf}) \pm 5(\text{lumi}))\%$$

Fitting method:

$$\Delta \sigma / \sigma = (\pm 7(\text{stat}) \pm 15(\text{sys}) \pm 3(\text{pdf}) \pm 5(\text{lumi}))\%$$

### 2.2. Dilepton channel

ATLAS has developed several methods to measure the $t\bar{t}$ production cross section in the dilepton (lepton=$e, \mu$) channel. The method utilizing a template fit is presented here.

**Event selection**

- 2 opposite sign leptons ($ee, e\mu, \mu\mu$) with $p_T > 20 \text{ GeV}, |y| < 2.5$.
- For the $\mu\mu$ channel: require that the $E_T$ vector is not parallel or anti-parallel to a muon $p_T$ vector.
- For same flavor channels: veto $Z$ mass region, and require $E_T > 35 \text{ GeV}$. There is no $E_T$ cut for the $e\mu$ channel.
Figure 3: Example of $E_T$ vs number of jets distributions used in by the template fit method for $t\bar{t}$ (left), $WW$ (middle), and $Z \rightarrow \tau\tau$ (right) processes. This illustration uses the $e\mu$ channel.

Here we use “tight” electrons, and require, $dR(\mu, \text{jet}) > 0.2$. Event passing those cuts are filled into 2-dimensional histograms of $E_T$ vs the number of jets, such as shown in Figure 3. The distributions of the $t\bar{t}$ signal and different backgrounds in these two variables have different shape, thus allowing a data distribution to be fit with a linear combination of simulated templates to extract the number of signal events. A combination of the templates according to their Standard Model cross sections, projected on the jet multiplicity axis, is shown in Figure 4. The expected uncertainty of the measurement assuming 100 pb$^{-1}$ of data at 14 TeV is

$$\Delta \sigma/\sigma = (4 \text{(stat)} \pm 4 \text{(sys)} \pm 2 \text{(pdf)} \pm 5 \text{(lumi)})\%.$$  

Figure 4: Total composition of the inclusive di-lepton selection versus number of jets. Normalized to 100 pb$^{-1}$ at 14 TeV.

3. Differential cross section

Measuring $\sigma_{t\bar{t}}$ vs kinematic variables of the $t\bar{t}$ system allows one to:

- test QCD predictions
- validate our understanding of detector acceptance
- provide a way to search for New Physics

One of manifestations of physics beyond the Standard Model may be a heavy resonance decaying into a $t\bar{t}$ pair. It could be observed in a $d\sigma_{t\bar{t}}/dm_{t\bar{t}}$ measurement, which we will discuss in this section.

A straightforward way to measure the differential cross section is to extend the lepton+jets analysis presented above, and perform on selected events a kinematic fit of the 4 leading jets, lepton, and $E_T$, using $m_{\text{top}}$ and $m_W$ constraints to reconstruct the invariant mass of the $t\bar{t}$ system. The expected shape of the $tt$ invariant mass distribution is shown in Figure 5. However conventional methods of top reconstruction that require the decay products of each top quark to be identified in the detector as distinct jets or isolated leptons become inefficient for highly boosted top quarks, as illustrated in Figure 6. Therefore such methods are not well suited for heavy resonance searches. A new method for top pair reconstruction targeted for heavy resonance searches in the lepton+jets channel, based on [6], [7], is suggested in [8]. The ATLAS note uses a generic narrow $Z'$ decaying to $t\bar{t}$ as a benchmark.

Figure 5: Invariant mass distribution of the $t\bar{t}$ system using conventional event reconstruction in the lepton+jets channel. Normalized to 100 pb$^{-1}$ at 14 TeV.
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with respect to the jet. The cut, assumed to come from the neutrino. A requirement of press QCD background are applied.

electron energy, and additional cuts on the jet to suppress wrong &jet combinations, a cut on the µ is imposed to reject misreconstructed neutrinos, as the decay products are expected to be collinear. Finally, the four momentum of the leptonic top is computed as

$$p_{\text{top},e} = p_\ell + p_{\text{jet}} + p_\nu.$$  

Hadronic top reconstruction

After a leptonic top is reconstructed, the hardest of the remaining jets (which are $k_\perp$ jets with $D = 0.6$) is considered a hadronic top candidate. It must satisfy

$$p_T > 300 \text{ GeV}.$$  

The fine granularity of the ATLAS calorimeter allows jet substructure to be resolved and used to suppress backgrounds. A likelihood variable is build from jet mass and jet substructure variables ($k_\perp$ splitting scales), and a cut on this variable is applied to separate top jets from those coming from other sources.

After applying an out of cone energy correction to the reconstructed tops, the $Z'$ invariant mass is computed as

$$m^2_{Z',\text{rec}} = (p_{\text{top},e} + p_{\text{top},\text{had}})^2.$$  

The resulting distribution for a 2 TeV $Z'$ is shown in Figure [3].

A signal region of $\pm 1\sigma_{\text{reco}}$ around the $Z'$ peak is defined. The signal reconstruction efficiency is 0.094 ± 0.002, and estimated background counts in that region are summarized in Table III. The systematic uncertainty on Standard Model $t\bar{t}$ background includes 10% from the total cross section, and 15% due to extrapolation from a restricted region of the phase space. (Standard Model $t\bar{t}$ samples for this study were generated only at high $t\bar{t}$ invariant masses to get sufficient statistics.)

|                | 21.9 ± 1.0 ± 3.9(sys) | 1.9 ± 0.5 |
|----------------|----------------------|-----------|
| SM $t\bar{t}$  | 21.9 ± 1.0 ± 3.9(sys) | 1.9 ± 0.5 |
| QCD multijet   |                      |           |
| Total          | 23.8 ± 4.1           |           |

A Bayesian technique was used to include uncertainties on the background, signal acceptance and luminosity in an estimate of the sensitivity to a narrow resonance decaying to $t\bar{t}$. The expected 95% CL on $\sigma \times Br(t\bar{t})$ with 1fb$^{-1}$ at 14TeV are

- 550 fb for $M_{Z'} = 2$ TeV
- 160 fb for $M_{Z'} = 3$ TeV

**Table III. Estimated background counts in the signal region for a 2 TeV $Z'$ with 1fb$^{-1}$ at 14TeV.**
Figure 7: 2D distributions of \( x_\ell, y_\mu \) for correct (left), and wrong (right) combinations of a muon and a jet in muon+jets \( Z' \to t\bar{t} \) decays. Events are required to lie above the line to pass selection cuts.

Figure 8: Generated minus reconstructed mass of a 2 TeV \( Z' \).

4. Summary

ATLAS will have a rich top physics program. In addition, top pair events will provide valuable tool for detector validation and calibration. Before exploring and exploiting properties of the top quark we need to observe it. A cross section measurement at a new center of mass energy is also an important physics result.

This talk presented some of the methods that ATLAS will use to measure \( t\bar{t} \) cross section in the lepton+jets and dilepton channels. It also outlined a new method of reconstructing \( t\bar{t} \) events in the lepton+jets channel that is targeted to high mass resonances decaying into \( t\bar{t} \), and showed the expected sensitivity of the new method.

Establishing top signal is an important milestone in the ATLAS physics program, and ATLAS is prepared to achieve this over a wide range of LHC \( \sqrt{s} \), integrated luminosity of usable data, and detector performance.

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