Measurements on top quark pairs in proton collisions recorded with the ATLAS detector

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Summary

In the Large Hadron Collider (LHC) protons collide with a center-of-mass energy of 7 TeV and higher. With the vast amount of proton collisions that are being produced, we are able to study the elementary particles and interactions with a very high precision. In this thesis we explained why top quark physics is relevant and forms a keystone of the research in ATLAS. We presented the measurements on two relevant observables of top quark pairs. In the following, we summarize the motivation for the measurements, the analysis features and the final results.

The top quark and the Standard Model

The current knowledge of elementary particles is described in a theory known as 'the Standard Model'. The top quark is one of the six quarks in the Standard Model, but it is about 35 times heavier than the next-to-heaviest quark and has a lifetime of only 10^{-25} seconds. This provides a unique role for the top quark in the Standard Model. The consequences of its high mass are for instance that the production of top quarks in collisions is relatively rare, its decay modes include real W bosons, contrary to the other quarks, and its coupling to the Higgs field is strong. But, in addition, top quark production is sensitive to certain so-called 'new physics' models—extensions of, or alternatives to the Standard Model which predict new heavy bosons. Some of these bosons are likely to decay into a pair of top quarks and hence enhance the production rate of top quarks.

The first analysis in this thesis is a measurement of the production rate of top-antitop quark pairs, 'the top quark production cross section'. Secondly, in the following part the difference between the angular direction of the top and antitop quark, 'the top quark charge asymmetry', is measured. Both the cross section and the charge asymmetry are observables that can potentially reveal physics beyond the Standard Model.

Producing and detecting top quarks

Protons are collided head-on with a center-of-mass energy of 7 TeV at the LHC. Enough energy is contained in the protons to create top quark pairs and hundreds of thousands of top quarks events are expected to have been produced already in these collisions.

The ATLAS detector (25 m × 44 m) aims to identify all remnants of the proton collisions. The detector is manufactured from different types of sensitive material built in concentric layers around the collision point. The subdetectors are foremost dedicated to the tracking of charged particles, energy reconstruction and the reconstruction of muons. A feature of the top quark is that its decay products can consist of a variety of different particles—electrons, muons, taus, hadronic jets, neutrinos—and therefore all subdetectors of ATLAS are required to measure the properties of the complete set of particles that results from this type of collisions. Neutrinos can only be detected indirectly, and therefore we make use of conservation of energy in the transverse plane to obtain an estimate of the direction and momentum for this particle.

Decay modes and selection

The top quark decays almost exclusively to a W boson and a b-quark; the W boson subsequently decays to a pair of light quarks or into a lepton-neutrino pair. The categorization of top quark pair events is determined by the W boson decays. Our analyses focused on the single-lepton decay channel of top quark pairs, in which one W boson decays leptonically, and the other hadronically. In this channel we only select electron or muon events and ignore decays involving tau leptons. This amounts to about 30% of all top quark pair events.

The analyses make use of two distinct data sets, collected in 2010 and 2011. The criteria to select a pure sample of top quark pairs overlap between these years. Events with an energetic electron or muon, at least four hadronic jets (resulting from two b-quarks and two light quarks) and sufficient missing transverse energy (neutrino) are selected. In addition, we make use of a b-tagging algorithm that is able to distinguish b-quarks from the other quarks with an efficiency of approximately 50%.

Measurement of the cross section

The production cross section of top quark pairs is measured using a data set with an integrated luminosity of 35 pb^{-1}. The analysis is based on discriminating signal and background events in the invariant mass distribution of the top quark. The invariant mass of the top quark is obtained from a minimization procedure that for every event evaluates the most likely association of the measured particles and jets to the lepton and partons in top quark decay. The mass distribution of the top quark shows an excess around 170 GeV in signal events. In background events or signal events where the association failed, the mass distribution looks different.

A template fit is simultaneously applied to the invariant mass distribution in six different subsets of the data. These subsets are distinguished by the amount of jets that originate from either light quarks or b-quarks in the event, assuring different ratios of signal-to-background in each subset. The simultaneous fitting of templates to the data in these subsets results in an estimate of the number of signal events in the overall sample. From the number of signal events, we extracted a top quark production cross section in the electron and muon channel, and in a combination of the channels:

$$\sigma_{t\bar{t}}\ (\text{e+jets}) = 216 \pm 23\ (\text{stat})\ ^{+27}_{-24}\ (\text{syst}) \pm 7\ (\text{lumi})\ \text{pb},$$
$$\sigma_{t\bar{t}}\ (\mu\text{+jets}) = 161 \pm 19\ (\text{stat})\ ^{+18}_{-15}\ (\text{syst}) \pm 5\ (\text{lumi})\ \text{pb},$$

$$\sigma_{t\bar{t}}\ (\text{comb}) = 183 \pm 14\ (\text{stat})\ ^{+20}_{-18}\ (\text{syst}) \pm 6\ (\text{lumi})\ \text{pb}.$$

The theoretical value at this center-of-mass energy is $158.7^{+12.2}_{-13.5}$ (scale) $^{+4.3}_{-4.4}$ (PDF) pb. The measurement agrees with the Standard Model prediction, within the experimental precision.

Measurement of the charge asymmetry

The top quark charge asymmetry is measured in a data set with an integrated luminosity of 1.04 fb^{-1}. In the selected events, we utilize the reconstructed event topology that was already introduced in the cross section measurement. The asymmetry is parametrized as the difference between the absolute values of the rapidity of the top and antitop quark in the event, $A_{int} = |y_t| - |y_{\bar{t}}|$. The Standard Model expectation for this observable is A_{int} = 0.001 ± 0.006, but certain new physics models predict much larger values.

After subtracting the background estimations from the data sample, we unfolded the event generation and detector response. The unfolded asymmetry for the two channels and the combined measurement are:

$$A_{int}\ (\text{e+jets}) = 0.074 \pm 0.058\ (\text{stat}) \pm 0.023\ (\text{syst}),$$
$$A_{int}\ (\mu\text{+jets}) = -0.024 \pm 0.050\ (\text{stat}) \pm 0.026\ (\text{syst}),$$

$$A_{int}\ (\text{comb}) = 0.014 \pm 0.038\ (\text{stat}) \pm 0.024\ (\text{syst}).$$

The measurement is therefore in agreement with the Standard Model prediction. Although extreme values of the asymmetry are excluded by this result, we showed that in a similar measurement with a ten times larger dataset definitive constraints on most scenarios can be expected.

Conclusion

We conclude that both measurements agree with the predictions of the Standard Model, within the obtained experimental precision. This result is a strong confirmation of our present theoretical predictions on top quark production. With the increasing amount of data that currently becomes available, the precision of the top quark charge asymmetry can be improved significantly in order to reveal or reject new physics scenarios in the very near future.