Top quark pair production cross-section in proton-proton collisions at √s = 7 TeV

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Summary

The Standard Model is the cornerstone theory for Particle Physics that describes matter particles and the interactions between them. As a result of its robust mathematical formulation it allows for detailed and precise quantitative predictions to be made. However, although it has been a very successful theory until this day, many questions remain unanswered. The Large Hadron Collider was built with the goal to address many of these questions. Being the world's most energetic particle collider by smashing protons together at an outstanding center-of-mass energy of 7 TeV (8 TeV in 2012; 13 TeV expected in 2014), the LHC gives the possibility to explore regions of the phase-space that were previously uncharted. In other words, it enables physicists to test the Standard Model even further but also pave the way to new discoveries.

Motivation

In this thesis, we presented a first measurement of the top quark pair production cross-section using data delivered by LHC and recorded with the ATLAS detector. The motivation behind this cross-section analysis is summarized on the following:

i. To test Quantum Chromodynamics and establish the validity of the Standard Model at the collision energy of the LHC.
ii. To challenge the experiment with identifying a complex signature under an enormous background of processes, gaining in parallel a better understanding of the detector.
iii. To provide a footing for analyses that explore models Beyond the Standard Model and which consider the top quark pair production as a background to their signal.

Triggering on events

One of the most important aspects of the analysis process was to select the appropriate sample of events. This selection is typically separated into the online and the offline selection stages.

The online selection, also known as *triggering*, is performed at quasi-realtime by specialized algorithms (triggers) which run once the collision products are recorded by the different sub-detectors. Events that get rejected by all algorithms are deleted immediately, while events that are accepted by at least one algorithm are stored to mass-storage for further processing in the offline analysis. The triggering of events has the disadvantage that it imposes a selection efficiency to the final measurement which must be measured accurately. On the other hand, it is absolutely necessary in order to protect the detector's data-taking process from the immense rate of incoming events, most of which are of no interest. In the cross-section measurement, for each of the channels, $t\bar{t}(\mu)$ or $t\bar{t}(e)$, we chose a single-lepton trigger, muon or electron respectively, with a requirement on the minimum transverse momentum (p_{T}) of the lepton.

With the first data collected, starting from April 2010 and until July 2010, we assessed the performance of the *muon* trigger hardware and software by examining a subset of the single-lepton triggers. These performance checks were made based on an inclusive sample where only the presence of a muon was required and no other kinematic cuts were applied. This was possible because of the low luminosity of the LHC during the first stages of the experiment.

We measured the turn-on curves, namely the efficiency of the trigger with respect to the p_{T} of the muons, where the efficiency is defined as the ratio of the number of selected and triggered muons over the total number of selected muons. Also we measured the resolution of the algorithms by fitting the residual distribution for different p_{T} regions. The residual is measured by comparing the relative difference between the offline estimate for the muon's p_{T} with the estimate from the respective trigger algorithm. The resulting plots showed a good performance of the trigger and in most cases a reasonable agreement between data and Monte Carlo. For those cases that discrepancies were observed, all of which indicated a worse performance than expected, the issues were identified and solutions were provided with the priority towards maximum efficiency.

In addition to the performance measurements, we also presented a methodology for estimating the trigger efficiency directly from data, for when the data are kinematically biased. The study focused on the most commonly used method, the tag-and-probe, which was also utilized for the cross-section measurement. We showed that it is possible to measure the efficiency in an unbiased way by identifying $Z \to \mu\mu$ candidates based on a single muon trigger (tag) and counting the number of times the second muon was actually triggered by the system (probe).

Analyzing the sample

After events are selected by the trigger, the sample was refined even further using specific kinematic cuts. These cuts were motivated by the expected final state signature of the single-lepton $t\bar{t}$ events and their goal was to increase the signal-to-background ratio.

With the top quark almost exclusively decaying into a W boson and a bottom quark (b-quark), the $t\bar{t}(\mu)$ and $t\bar{t}(e)$ topologies, which were considered the signal for this analysis, are characterized by one W boson decaying leptonically ($W \to \ell\nu_\ell$) and one decaying hadronically ($W \to q\bar{q}$). Therefore, the signal events contain an energetic charged lepton (electron or muon) and its neutrino partner, two jets from light quark hadronization, and two jets induced from b-quark hadronization; extra jets maybe produced as the result of initial and final state radiation, namely emissions of gluons or photons radiating immediately before and after the collision. The hadronization process, is a consequence of the properties of the strong force which does not allow quarks or gluons to be free. Therefore, the resulting quarks in the $t\bar{t}$ topology, form hadrons which further decay resulting in a narrow cone of particles, the *jet*. The b-jets are a powerful selection tool because b-quarks form exclusively B-hadrons. The B-hadrons in turn have a relatively long lifetime (approximately 1.6 pico-seconds) which allows the observation of a secondary interaction vertex, and therefore the *tagging* of the jet.

Considering these characteristics, it is also evident that identifying the complex $t\bar{t}$ topology is a test for the detector's performance since almost all of the detection technologies are used. Electrons use tracking and calorimetry, muons tracking and muon spectrometry, jets depend on calorimetry while b-jets also utilize tracking techniques, and the neutrino's energy component is extracted by measuring the energy offset, required to balance the total observed transverse energy, using all detector's components.

The template fit method

For the cross-section analysis, the final sample was separated into four exclusive kinematic regions. These regions were distinguished by their high-p_{T} jet multiplicities in the exactly-three jets and the at-least-four jets regions, and according to the number of identified b-jets in the exactly-zero b-jets (no-tag) and the at-least-one b-jets (tagged) region.

The method that was implemented for the cross-section measurement depended on two elements: the *b-tagging rates* at each jet multiplicity region, and the *shape-templates* of the *hadronic top mass* observable in each of the four kinematic regions. These parameters were estimated for both signal and background but with the latter ones being derived by using, primarily, data-driven techniques. In the end, we fitted for the relative normalization of signal and background in each region and from the number of signal events we obtained the final cross-section measurement.

The hadronic top mass observable was derived by identifying the top quark with the hadronic final state, namely the one with its W boson decaying hadronically. This eventually forms a three-jet signature. Due to the large number of jets that are typically found, the best candidate was considered as the three-jet combination with the vector sum of the jet's p_{T} maximized. From the three jets the invariant mass (M_{jjj}) was estimated.

In order to minimize simulation dependance, and therefore systematic effects, the templates for the background were extracted in a data-driven way. The method followed was based on increasing the QCD multi-jet content by simply reverting the lepton requirements. With all other selection cuts left the same, we showed that the M_{jjj} shape is unbiased by this change and equivalent to the shape when obtained by the usual cuts. Subsequently, we showed that the normalization of the sample was greatly increased in favor of the background processes and with minimal contamination from the signal.

Results and outlook

The final results of the fit showed that the experimental measurement for proton-proton collisions at $\sqrt{s} = 7$ TeV is in good agreement with the theoretical expectations. This is evident from figure 1 where the results from the measurement on both channels, as well as their combination, are shown.

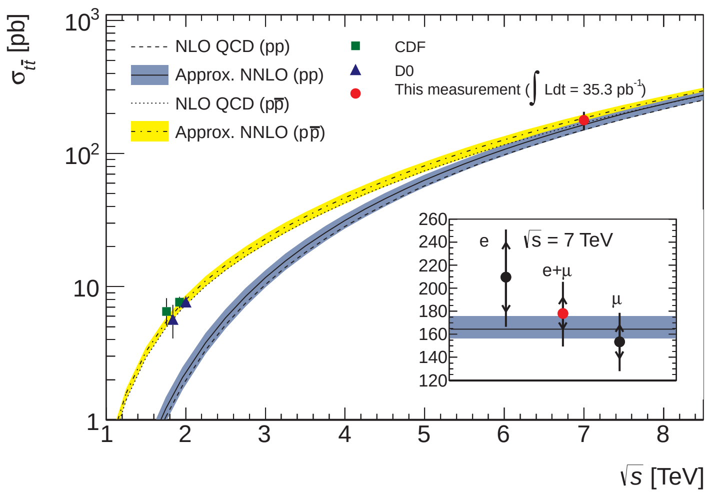

Figure 1: *The $t\bar{t}$ production cross-section as estimated by theory (assuming $M_{top} =$ 172.5 GeV) with respect to the center-of-mass energy of $p-p$ and $p-\bar{p}$ collisions (lines), the measurements made from CDF, DØ of the Tevatron collider (square and triangle points) and the measurement performed in this thesis (circle points) with $\int \mathcal{L}dt = 35.3$ pb^{-1} of $p-p$ collisions delivered by the LHC to the ATLAS detector. The error-bar region in between the arrows indicates the contribution of the statistical uncertainty only.*

The total uncertainty achieved is regarded as competitive, considering the limited amount of statistics, indicating the spectacular capabilities of the detector. With respect to possible improvements on the method, more data accumulated by the detector will definitely reduce the statistical uncertainty but will also allow for better calibration and more efficient data-driven techniques to be applied. In addition, the simulation can be optimized with respect to new findings, allowing for better treatment of the systematic uncertainties.

Naturally, the exciting discovery by ATLAS and CMS of a boson that is consistent with the Higgs boson, draws the attention of the scientific community and of the public as well. However, discoveries such as these can only be made once a good understanding of the detector is achieved and once the known Standard Model processes have been tested. From this point of view, the cross-section measurement of the $t\bar{t}$ is an important milestone as it serves a purpose for both of the above reasons.