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Top Quark Properties Measurements with the ATLAS Experiment

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Abstract.

Results on recent measurements of top quark properties with the ATLAS experiment at the European Laboratory, CERN, are shown. The measurements are performed using the full data set recorded during the LHC Run-I. The full data set consists of a collected integrated luminosities \(\int L\,dt\) of 4.6 fb\(^{-1}\) recorded at a proton-proton collision energy of \(\sqrt{s} = 7\) TeV and 20.3 fb\(^{-1}\) collected at 8 TeV. The mentioned top quark properties include: spin correlation, charge asymmetry, W-boson polarization, color flow, top mass and top width in events with a top and anti-top quark pair (\(t\bar{t}\)). An introduction to the LHC and the ATLAS detector is included and latest main results from this experiment. The contents include the current world benchmark results for the different properties and plans for future measurements during the ongoing LHC Run-II.

1. Performance of LHC and the ATLAS detector during Run-I

The successful operation of the Large Hadron Collider (LHC), and the ATLAS experiment is the product of the hard work of thousands of people involved in their design, construction and careful usage. The studies and results presented in this contribution could not have been possible without the support of this collaboration. The CERN laboratory directs the operation of the LHC which has a 27 km circumference that extends to both sides of the border between France and Switzerland. This massive accelerator runs at unprecedented collisions energies, being able to operate at a design luminosity of \(10^{34}\) cm\(^{-2}\) s\(^{-1}\) \([1]\). ATLAS is the largest detector located around the LHC ring. It produces two independent magnetic fields around the collision point, in the inner section a superconducting Central Solenoid (CS), is used to bend all charged particles in a plane perpendicular to the beam before they reach the electromagnetic and hadronic calorimeters. In the outer section a superconducting air cored toroid surrounding the calorimeters, provides with a set of particle detectors known as Muon Spectrometer (MS), located before, inside and after the toroidal field, an excellent muon identification. The LHC has already run with proton-proton (\(pp\)), collision energies of \(\sqrt{s} = 7\) and 8 TeV during its Run-I, larger by more than a factor of four with respect Fermilab’s Tevatron accelerator beam energies. It delivered an integrated luminosity of 5.46 fb\(^{-1}\) and 22.8 fb\(^{-1}\) at 7 and 8 TeV respectively. From these integrated luminosities, about 4.57 fb\(^{-1}\) and 20.3 fb\(^{-1}\), subsequently, are categorized as good quality Data for physics analysis \([2]\).

2. Predictive power of the standard model, Higgs mass and super-symmetry

Rate of production of several specific processes has been measured with the ATLAS detector at 7 and 8 TeV. The results of these measurements are compared with their corresponding theoretical expectation as given by the standard model of particle physics (SM). All the production measurements performed so far are in agreement with what is predicted by the SM \([3]\). During the first run of the LHC a particle consistent with the so-called Higgs boson (H) was discovered by the CMS and ATLAS collaborations. These two experiments used for this purpose mainly the \(H \rightarrow \gamma\gamma\) channel (two energetic photons are produced in the final state) and the \(H \rightarrow 4\ell\) channel (4 leptons are produced in the final state) to discover this particle and measure its mass value, whose value is not predicted by...
the SM. After combining their individual measurements with the two mentioned channels, the final reported Higgs mass by the ATLAS and CMS collaborations corresponding to the LHC Run-I is \( m_H = 125.09 \pm 0.24 \) (\( \pm 0.21 \pm 0.11 \)) GeV [4].

The ATLAS collaboration has performed a wide range of direct searches for particles consistent with the theory of Super-Symmetry (SUSY), during Run-I. So far no significant excess of events over the SM expectation has been observed. Exclusion limits have been set for the masses of the supersymmetric particles. So far only ‘low mass regions’ in the scale of SM particles have been excluded for the different SUSY particles, indicating that if they exist they should be more massive than any particle we know [5].

3. Introduction to top quark physics

![Figure 1. Diagram representing a \( t\bar{t} \) pair semi-leptonic decay. From [6].](image)

The top quark\(^1\) is the heaviest known fundamental particle with a measured mass value equal to \( \sim 172.5 \) GeV. The heavier particles following the top quark are the recently discovered Higgs boson with mass \( \sim 125 \) GeV, the \( Z^0 \) boson with a mass \( \sim 90 \) GeV and the \( W^\pm \) boson with a mass \( \sim 80 \) GeV. These particles, due to their large mass, compared with the rest of the fundamental particles, are the source of a huge variety of decays under study at the LHC.

The SM states that the top quark decays via the electroweak interaction to an on-shell W-boson plus one of the down-type quarks, decaying with a rate over 99 % in the form \( t \rightarrow W\text{-boson} + b\text{-quark} \) [7]. A deviation from these predicted rate could indicate beyond the SM processes involving contributions from unobserved heavier quarks. Some extensions of the SM allow the mentioned rate to be smaller allowing the production of charged Higgs particles via top decays like \( t \rightarrow b + H^+ \). However recent searches for charged Higgs bosons show no deviations from the SM predictions [8]. At the LHC, top quarks are produced mainly as top and anti-top quark pairs (\( t\bar{t} \)) via the strong interaction. The nature of the event relies on the decays of the two produced W-bosons. In the selected events for the measurements discussed in this article, one of the W-bosons decays to a couple of leptons while the other to a couple of quarks, which is known as semi-leptonic channel. Also events where the two W-bosons decay to a couple of leptons, known as dilepton channel, are considered. As indicated in Figure 1, several properties associated with the top quark can be measured from these events. Study of the properties of the top quark is an ideal strategy to test the SM, as the latter delivers well defined predictions for their values.

4. Measurement of top quark properties

Brief description and results over the most relevant top quark properties measured by the ATLAS detector are shown in this section.

\(^1\) Unless explicitly stated, top quark refers to both the top and the anti-top quark
4.1. Spin correlation in $t\bar{t}$ events

The top quark decay products give us direct access to its spin, as it decays before hadronisation ($<10^{-24}$ s), before QCD interactions can affect this quantity. The top quark spin determines the angular distribution of its daughters when it decays. For this analysis a spin correlation coefficient $A_{helicity}$ is defined as:

$$A_{helicity} = \frac{N_{like} - N_{unlike}}{N_{like} + N_{unlike}}$$

where $N_{like}$ are the number of selected events where the top and antitop quarks have their spins pointing in the same direction and $N_{unlike}$ stands for events where the pair have their spins pointing in opposite directions. For this study only dileptonic events are selected, where the two W-bosons decay leptonically. Additional events allowing the production of super-symmetric neutralino ($\tilde{\chi}_0^1$), and stop ($\tilde{t}_1$), particles are also searched. Monte Carlo (MC) samples with different underlying values of $A_{helicity}$ are produced. These templates are compared with actual Data using the distribution of the variable $\Delta\phi$ as in Figure 2. This variable stands for the azimuthal angle between the two charged leptons in the event. In this figure it is indicated the MC template that fits better with the observed data, yielding a measured value of spin correlation ($A_{helicity}^{meas}$), divided over the SM expected value of $f_{SM} = \frac{A_{helicity}^{meas}}{A_{helicity}^{SM}} = 1.20 \pm 0.05$ (stat.) $\pm 0.13$ (syst.) [9]. The errors correspond to 68% confidence level (1-$\sigma$ errors), so the result is in agreement with the SM prediction, and is compatible with previous measurements by DØ, CDF and CMS collaborations, but more precise. The Plot in Figure 3 is constructed to set limits over the mass of the stop quark, for this purpose the rate of production of $pp \to \tilde{t}_1\tilde{t}_1$ events is measured assuming various masses for the the stop quark. The black line corresponding to observed values goes below the red line of predicted values by SUSY at the point where $m_{\tilde{t}_1} \sim 191$ GeV. It is then possible to exclude stop masses below this value.

4.2. Measurement of charge asymmetry in $t\bar{t}$ decays

The rapidity quantity $y$ is defined as:

$$y = \frac{1}{2} \ln \left( \frac{E + p_z}{E - p_z} \right)$$

Figure 2. Distribution of the observable $\Delta\phi$ between two event leptons. Plot is drawn with the predicted distribution from the SM and the actual Data. From [9].

Figure 3. Measured lower limits for the production of a couple of stop quarks $\tilde{t}_1\tilde{t}_1$ compared with the SUSY prediction. From [9].
the largest the value of this variable the closest the particle is traveling to the beam line. For this analysis the rapidities of the top and anti-top quarks are quantified in each of the events to obtain the observable \( \Delta|y| = |y_t| - |y_{\bar{t}}| \), which is the difference between absolute value of top quark rapidity and the absolute value of the anti-top quark rapidity. The measured parameter \( A_C \), regarded as charge asymmetry between top and anti-top quarks, is defined as:

\[
A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}
\]  

(3)

where \( N(\Delta|y| > 0) \) stands for the number of selected events satisfying \( \Delta|y| > 0 \), and \( N(\Delta|y| < 0) \) for events where \( \Delta|y| < 0 \). For this analysis the semi-leptonic channel is used, and as for the case of the spin correlation study, several MC templates are produced with different underlying values of \( A_C \). A statistical fit is done in this case to compare the Data and the different MC models using the distribution of the \( \Delta|y| \) observable. The result of the measurement is \( A_C = 0.009 \pm 0.005 \), where the error includes statistical and systematic uncertainties. Independently the CMS collaboration measured the value \( A_C = 0.0010 \pm 0.0068 \pm 0.0037 \) [10], being then the result from ATLAS more precise. The predicted value for this parameter by the SM is \( A_C = 0.0101 \pm 0.0005 \) [11], both results from ATLAS and CMS are in agreement with the SM. Previously the D∅ and the CDF collaborations measured another asymmetry regarded as forward/backward asymmetry (\( A_{FB} \)) [12], Figure 4 shows in a 2-dimensional plot the region allowed for the SM for the two asymmetries \( A_C \) and \( A_{FB} \) (small rectangle in purple). The figure shows that the current measurements of these two asymmetries are in agreement with the SM prediction [11].

Figure 4. Allowed values from the SM for the two asymmetries \( A_C \) and \( A_{FB} \). Other allowed regions for beyond the SM models are indicated. From [11].

### 4.3. Measurement of color flow in t\( \bar{t} \) decays

The SM establishes that the b-quark decaying directly from the top quark via the emission of a W-boson (as shown in Figure 1) is color connected with its mother particle. This implies that when a couple of quarks are produced from the emerging W-boson, these are color connected as well. These two quarks originate a couple of jets, where a jet is a group of particles product of a quark hadronisation that are identified by the detector. In this context being color connected means that these two jets are not completely free from each other, as it is predicted by the SM. The MC simulation representing the SM keeps certain degree of connection between these two jets, which makes certain special observables get smaller values than what they would get if the jets are set to be free from each other. The degree of connection defines the different models for color connection or color flow. Similarly as with the
previous analyses, two MC samples have been produced for this study: one keeping the predicted degree of connection between the produced jets by the SM and another one decreasing to zero the attraction or connection between the two jets from the W-boson, which is known as the flipped model [13]. To perform this study the quantity \( \vec{r}_i = (\Delta y_i, \Delta \phi_i) \) is defined as the difference between the jet components coordinates \((y_i, \phi_i)\) and the jet coordinates \((y_J, \phi_J)\). This makes possible to define the pull vector of one of the jets emerging from the W-boson as:

\[
\vec{v}_p^j = \sum_{i \in J} \frac{p_T^i |\vec{r}_i|}{p_T^i} \vec{r}_i
\]

This vector allows the definition of the pull angle \( \theta_p(J_1, J_2) \) as the angle between the pull vector associated to one of the produced jets and the remaining jet number 2. The pull angle is sensitive to changes in the color connection between the two jets. If the color flow is flipped as mentioned before, its value gets smaller. Distributions of the pull angle \( \theta_p \) from the SM and the flipped model are compared with the Data collected at \( \sqrt{s} = 8 \) TeV. After a statistical test is performed [13] it is concluded that the flipped model differs from the Data by 2.3 standard deviations, and no significant difference is found between the SM and the Data [13].

4.4. Measurement of W-boson polarization in \( t\bar{t} \) decays

For this analysis the dilepton and semi-leptonic channels are used. The observable that is recorded at each event is \( \cos \theta^* \), where the angle \( \theta^* \) is defined as the angle between the direction of the momentum of the charged lepton (in the W-boson rest frame) and the W boson momentum in the top quark rest frame. The shape of the distribution of \( \cos \theta^* \) is given by:

\[
\frac{1}{N} \frac{dN}{d\cos \theta^*} = \frac{3}{4} \sin^2 \theta^* F_0 + \frac{3}{8} (1 - \cos \theta^*)^2 F_L + \frac{3}{8} (1 + \cos \theta^*)^2 F_R
\]

where \( F_0, F_L \) and \( F_R \) are known as helicity fractions and have a predicted value within the SM. As with the previous measurements here different MC samples are produced with all the possible values for the helicity fractions. The analysed Data corresponds to an integrated luminosity of \( \int L dt = 1.04 \) fb\(^{-1}\) at 7 TeV. Figure 5 shows all the individual measurements of the helicity fractions performed by ATLAS using two different approaches and channels. After combining all the measurements in the figure, the final result is: \( F_0 = 0.67 \pm 0.07, F_L = 0.32 \pm 0.04 \) and \( F_R = 0.01 \pm 0.05 \), which are consistent with the SM and are in agreement with previous measurements as well [14].

4.5. Measurement of the top quark mass and width in \( t\bar{t} \) decays

![Figure 6. Reconstructed top mass distribution. From [15]](image1)

![Figure 7. Recent measurements over \( m_{top} \). From [15]](image2)
Finally, ATLAS has also measured the mass ($m_{top}$) and width ($\Gamma_{top}$) of the top-quark using a template fit in the same way as all the analyses previously mentioned in this contribution, producing MC samples with various values of the $m_{top}$ and $\Gamma_{top}$ parameters respectively. The most precise measurement of $m_{top}$ was performed with a $pp$ collision energy of 7 TeV using 4.6 fb$^{-1}$ of Data. Figure 6 shows the distribution of the reconstructed top mass, here are included the histogram from the Data and the MC template that best fitted with it. The $m_{top}$ measurement was performed using the semi-leptonic and dilepton channels separately, after the combination of both results the most precise measurement obtained by ATLAS is $m_{top} = 172.99 \pm 0.91$ GeV [15]. Figure 7 shows this result along with other less precise results from ATLAS and the current world combination for $m_{top}$. A similar analysis is in progress to measure the $\Gamma_{top}$ parameter, in this analysis a direct approach is followed as in the recent measurement from the CDF collaboration that sets a upper limit of $\Gamma_{top} < 6.38$ GeV at 95 % confidence level [16].

5. Conclusions and top physics measurements during LHC Run-II

All the measurements of properties of the top quark discussed in this contribution are in agreement with the SM predictions. The $m_{top}$ and $\Gamma_{top}$ measurements are very difficult, because even when having more than two orders of magnitude more Data than the Tevatron experiments, the LHC experiments deal with larger systematic uncertainties, situation that is expected to change during Run-II at $\sqrt{s} = 13$ TeV, as all the detectors will be understood better. ATLAS went through important upgrades before the start of Run-II last December. Also in this second campaign the production of $tt$ pairs is expected to increase by a factor of $\sim 3.3$ with respect to the production at 8 TeV. So higher precision for all the measurements discussed here is expected during Run-II.

References

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