Searching for the Top: observation of the heaviest elementary particle at the LHC
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On the 30th of March 2010 the LHC collided protons at a center of mass energy ($\sqrt{s}$) of 7 TeV for the first time. Until Monday the 30th of August ATLAS had recorded over 3 pb$^{-1}$ of data at this energy. The era of complex physics analyses at the LHC energy scale and therefore also top-quark analysis had started. In this chapter we will study the data and the distributions of objects important to the top-quark pair production cross section measurement will be shown. Note that not only is the energy less than the $\sqrt{s} = 10$ TeV that was planned for, also the amount of accumulated data is lower than was anticipated. Nonetheless, in the next chapters we will show that data-driven QCD estimates and ultimately the measurement of the top-quark pair production cross section are possible with this small data-set.

After a more detailed account of the available data in Section 6.1 we will start the data analysis by looking at basic distributions to assess whether the data behaves as expected in Section 6.2. The last part of this chapter, Section 6.3 will be dedicated to the test of our methods of the previous chapter. In the next chapter we will perform the QCD estimation in the selected sample of $t\bar{t}$ candidates in detail.

6.1 The full dataset

In the first 5 months of operation the ATLAS detector recorded more than 700 million collision events [128]. Not all of these collisions passed our quality cuts. For a run to be accepted for physics analysis all sub-detectors have to flag the data quality of a run as good [129] according to the status of all their systems. All data quality decisions are then used to create so called ‘good run lists’ (GRL’s) which differ for different physics analyses. For complex analyses all detector subsystems have to be working nominally and the GRL for such an analysis will only contain a sub-sample of the total data. After requiring the runs to pass the GRL for top physics, the total of recorded data added up to 2.89 pb$^{-1}$ [130], which is about 80% of the recorded integrated luminosity.

The runs are divided in different periods, where each period is defined as a time of
Distributions in data

data-taking with consistent detector and trigger settings [131]. A significant change to the configuration defines the start of a new period. In Table 6.1 the periods are listed with their integrated luminosity after the required top GRL.

<table>
<thead>
<tr>
<th>time period</th>
<th>integrated luminosity nb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A+B</td>
<td>Mar 30 - May 17</td>
</tr>
<tr>
<td>C</td>
<td>May 18 - Jun 05</td>
</tr>
<tr>
<td>D</td>
<td>Jun 24 - Jul 19</td>
</tr>
<tr>
<td>E</td>
<td>Jul 29 - Aug 18</td>
</tr>
<tr>
<td>F1+F2</td>
<td>Aug 19 - Aug 30</td>
</tr>
<tr>
<td>total</td>
<td>Mar 30 - Aug 30</td>
</tr>
</tbody>
</table>

Table 6.1: Integrated luminosity as recorded by ATLAS per run period after requiring the top GRL.

Since period A and B were reprocessed together in order to have a consistent set of ATLAS software over the entire data-taking period, they are always grouped together and we quote them as such. We can note that there is almost an exponential growth in integrated luminosity over time due to higher luminosities delivered by the LHC. This increase in instantaneous luminosity is caused by decreasing the size of the interaction region through focusing of the beams (‘squeezing’) and later by increasing the number of colliding bunches and the number of protons per bunch, see Section 2.1. In Figure 6.1 we show the integrated luminosity as it is delivered by LHC and recorded by ATLAS.

6.2 Data validation

Since this is the first time that the data is investigated, some basic distributions will have to be shown to spot possible detector problems and gain better understanding of the objects that are important for our analysis. All sub-detector systems have performed extensive validation of their system and no major problems have been identified. In this section distributions will be shown of a subset of the data that is interesting for the $t\bar{t}(\mu)$ searches. Events are selected with the following cuts to ensure that the topology of the investigated events is already close to the top environment and to avoid non-collision backgrounds (like cosmic muons) and events where we have known problems:

- passed muon trigger with $p_T > 10$ GeV
- at least one muon that passes all the top-muon-cuts except isolation cuts
- at least one jet with $p_T > 20$ GeV
- a primary vertex with at least 4 tracks
- no jets marked as bad in the event,

where bad is a way of marking jets that are most likely to originate from noise or detector problems [116].
6.2 Data validation

Figure 6.1: The integrated luminosity as it is delivered by the LHC machine and recorded by ATLAS in pb$^{-1}$.

6.2.1 Primary vertex

We know from the previous chapter that the location of the primary vertex plays a role in the computation of the d0 significance of the muon. It is also an interesting starting point for the data distributions since the primary vertex marks the spot of the interaction that we will study. In Figure 6.2 (left) we show the location of the primary vertex in the plane transverse to the beam direction and the uncertainty of the x-coordinate of the primary vertex is shown in Figure 6.2 (right).

We note that the interactions seem to occur mostly almost centered around zero in x and shifted up slightly in y with respect to the (0,0) of the ATLAS detector. This has no consequence for physics analyses since all quantities will be computed with respect to the primary vertex. The less pronounced second accumulation of primary vertices which can be seen in lower left side of the plot are the primary vertices from the early runs with different LHC settings. The spread in the z coordinate, along the beam axis, is much larger: of the order of 100 mm. The uncertainty on the location of the primary vertex is small (the distribution for the y-coordinate looks similar) since we select events on having at least four tracks in the primary vertex [132]. The mean of the uncertainty on x (y) is found to be $<\sigma_x> = 18 \mu m$ ($<\sigma_y> = 18 \mu m$).
### 6.2.2 Trigger efficiency

In trying to isolate $t\bar{t}(\mu)$ candidates from all interactions, the presence of an isolated muon is vital. It is therefore important to study the muon-trigger efficiency since it will enter directly the cross section calculation in Chapter 8. The muon trigger used for the first analysis was the $\text{mu10}$ trigger meaning that it triggers on muons with $p_T$ above 10 GeV. The offline selection of muons with $p_T$ above 20 GeV ensures that efficiency is at the plateau of the turn-on curve of the trigger, see Section 3.1. The efficiency in data is obtained using a tag-and-probe method in a sample of $Z \rightarrow \mu^+\mu^-$ events [106]. The tag is a muon that passes all our selection criteria and is matched to a trigger object and the probe is any muon that satisfies all muon criteria and the requirement that the muons have opposite charge and have an invariant mass within 12 GeV of the $Z$-mass.

The trigger efficiency is then defined as:

$$\epsilon_{\text{trigger}} = \frac{N_{(\text{probe, matched})}}{N_{(\text{probe, all})}}, \quad (6.1)$$

where $N_{(\text{probe, matched})}$ is the number of trigger objects matched to the probe offline lepton. From this efficiency differences between Monte Carlo and data can be identified and treated with scale factors (SF). The SF for the muon trigger is given by:

$$\text{SF}_{\text{trigger}} = \frac{\epsilon_{\text{trigger}}(\text{data})}{\epsilon_{\text{trigger}}(\text{MC})}, \quad (6.2)$$

where the efficiencies are as defined above. If this $\text{SF}_{\text{trigger}}$ is not equal to one, we need to include it in all our data-MC comparison plots by normalizing the MC to $\text{SF}_{\text{trigger}}$. It
turns out that the trigger efficiency of the data taken in the period A-F is not the same as the one for the Monte Carlo. SF$_{\text{trigger}}$ depends on the pseudorapidity of the muon ($\eta$) and is given by \cite{106}:

\[
|\eta_{\text{muon}}| \leq 1.05 : SF_{\text{trigger}} = 0.919 +0.022 \text{ (stat + syst)},
\]
\[
|\eta_{\text{muon}}| > 1.05 : SF_{\text{trigger}} = 0.967 +0.014 -0.018 \text{ (stat + syst)}. \quad (6.3)
\]

We will show all comparisons between data and Monte Carlo with this scale factor applied to the MC distributions from here-on.

### 6.2.3 Muons

Isolated muons play a key role in selecting $t\bar{t}(\mu)$ candidates from background events. In this section the muon distributions will be presented that are important for the top-quark pair production cross section analysis in the muon channel and the data driven background estimation of QCD. All plots shown in the rest of this chapter will contain QCD multi-jet Monte Carlo and signal MC, where signal refers to samples that contain prompt muons. The signal MC is a mix of $t\bar{t}$ simulated events and the prompt backgrounds ($W+\text{jets}$ also containing $W+\text{bb+jets}$, $W+\text{cc+jets}$ and $W+c+jets$, $Z+\text{jets}$, single top and di-boson) as mentioned in Section 1.4.3.

#### Isolation

As was stressed before, the muon isolation is probably the single most important variable to distinguish prompt from non-prompt muons. One does not expect the isolation to look exactly the same in data as in MC, since it is a complicated variable to model. The isolation involves understanding the precise energy deposit in cells in the calorimeter, subtracting the expected loss term of the muon itself and correcting for dead material like cables according to the direction of the muon. We do expect to see long tails associated with QCD and a sharp peak at low values that indicates the prompt component. The isolation distribution will also be a clear indicator if data and Monte Carlo are in agreement since it has some separating power to see whether any discrepancy comes from signal samples or from QCD multi-jet events. In Figure 6.3 (left) the $E_{T}^{dR=0.30}$ is presented for events with the cuts given at the beginning of Section 6.2. Also shown are the signal Monte Carlo samples and the QCD Monte Carlo.

Although at low values of the isolation the data and MC distributions are in reasonable agreement, there is a large discrepancy at high $E_{T}$. The shape of the distribution at higher values however seems to be simulated correctly and follows the shape of the QCD distribution. This hints at an underestimation of the QCD background. In Figure 6.3 (right) we show the same distribution, but with the QCD Monte Carlo scaled up by a factor three compared to its nominal predicted yield. The agreement between data and simulation is good after the scaling. Although the scale factor is by no means a

$^{1}$

$E_{T}^{dR=0.30}$ is the transverse energy in a cone of dR = $\sqrt{(\Delta \phi)^2 + (\Delta \eta)^2}$ = 0.30 around the muon.
precise measure, we will use it throughout this chapter to compare data and Monte Carlo shapes. We can conclude already that understanding QCD in more detail will be of great importance for the cross section measurement, since simulation underestimates this background. There are two more variables that characterize the isolation of the muon: the sum of the transverse momentum of all tracks in a cone around the muon track and the distance of the muon to the closest jet \[118\].

In Figure 6.4 the \[p_T^{dR=0.30}\] is shown\footnote{\[p_T^{dR=0.30}\] is the transverse momentum of all tracks in a cone of \(dR = 0.30\) around the muon.} for data and MC in the left plot and the distance of the muon to the closest good jet (\(p_T > 20\) GeV) is presented in the right plot.

Both figures show that data behaves as expected from MC. The distribution of the \(p_T\) of
all tracks around the muon has an empty bin near zero since it uses only tracks with a minimum \( p_T \) of 1 GeV. In Figure 6.5 same distributions are shown after requiring the muon to have an \( E_T^{dR=0.30} \) less than 4 GeV.

\[
\int L \, dt = 2.89 \, \text{pb}^{-1}
\]

The plots show good agreement between data and MC. Since the isolation of the muon behaves as expected from simulation, we will require in the following comparisons the muon to be isolated using the following selection criteria, see Section 3.2.2:

- \( E_T^{dR=0.30} < 4 \) GeV
- \( p_T^{dR=0.30} < 4 \) GeV
- no jet with \( p_T > 20 \) GeV closer than \( dR = 0.40 \) to the muon.

We refer to muons that pass these requirements as ‘analysis muons’. The \( E_T^{dR=0.30} < 4 \) GeV requirement is justified by Figure 6.3 (right) and the second and third requirement are justified by Figure 6.5 where the requirements are indicated by arrows. Note that the isolation cuts above are somewhat different from the ones in the previous chapter as has been mentioned before.

**Pseudo rapidity and transverse momentum**

When requiring at least one selected jet (which is a jet with \( |\eta| > 2.5 \) and \( p_T \) above 20 GeV) and an analysis muon, we are entering the kinematic region of the top-quark. It is informative to show first the pseudo rapidity and the transverse momentum of the analysis muon. In Figure 6.6 \( |\eta| \) and \( p_T \) of the muon are shown after requiring at least one selected jet.

Note that after the analysis muon requirement the MC is underestimating the data even after scaling the QCD up by a factor three. This underestimation might originate...
not only from the QCD contribution, but also signal processes like $W+\text{jets}$ might be underestimated. We will look into this in more detail in the next chapter. The plot of the $|\eta|$ of the muon has a seemingly large discrepancy around $|\eta| = 0.2$. We think that this is caused by low statistics of the QCD sample (scaled up by a factor 3), an upward fluctuation of the data in that region and the overall underestimation mentioned above. No problems with the $\eta$ distribution have been reported by the ATLAS muon performance group.

**Impact parameter significance**

The impact parameter and the impact parameter significance are both useful variables to distinguish prompt from non-prompt muons. In the ABCD method of Section 5.3 we used this separation power. In Figure 6.7 the impact parameter (left) and the impact parameter significance (right) are shown for analysis muons requiring at least one selected jet. Both the impact parameter and the impact parameter significance distributions are not in perfect agreement when comparing data and MC. The peak at very low values seems to agree with the signal MC and the tail at high value seems well simulated by the QCD MC. There is however a discrepancy at intermediate values. It has been suggested that the prompt peak is indeed slightly wider than expected. Fortunately this does not influence the methodology used in our data-driven studies since our cut-value used for the ABCD method in the previous chapter of $d_0$ significance equal to 3 seems to reside inside the QCD tail. $^3$ The mean of the uncertainty on the $d_0$ of the muon is $<\sigma_{d_0}(\mu)> = 16 \, \mu m$ which is of the same order of magnitude as the uncertainty on the transverse coordinates of the primary vertex, see Figure 6.2 (right). From Equation 5.1 it can be seen that both uncertainties are taken into account when calculating the $d_0$ significance.

$^3$In Chapter 8 we will even change to 5 for the ‘matrix method’. 

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Figure 6.6: Muon distribution after requiring an analysis muon and at least one selected jet. The QCD is scaled up by a factor 3. Left: muon-$|\eta|$. Right: muon-$p_T$. 

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Figure 6.7: Left: the impact parameter of analysis muons. Right: the impact parameter significance of analysis muons. Events have at least one selected jet and the QCD is scaled with a factor 3.

Due to the $\phi$ terms needed to correct the uncertainty on the primary vertex coordinates however, the dominant uncertainty for the calculation of the $d_0$ significance is $\sigma_{d_0}(\mu)$.

### 6.2.4 Missing transverse energy

The missing transverse energy ($\cancel {E_T}$) is an important variable to distinguish top signal from QCD background due to the undetectable neutrino in $t\bar{t}(\mu)$ decays. In principle QCD events are expected to have low $\cancel {E_T}$, so any measured $\cancel {E_T}$ is due to reconstruction issues like noise and missed jets (or neutrinos from heavy quark decays). In Figure 6.8 the $\cancel {E_T}$ distribution is shown for events with at least one selected jet and an analysis muon.

Figure 6.8: The $\cancel {E_T}$ distribution after requiring an analysis muon and at least one selected jet. The QCD is scaled with a factor 3.
After scaling-up the QCD Monte Carlo, we note that the shape of the data distribution is well simulated by MC. This is non trivial since the $E_T$ is a difficult variable to simulate due to the interplay of all aspects of the detector like muon energy loss terms and the jet reconstruction. The small difference in the signal tail hints towards a possible underestimation of the signal component. Note that the uncertainty on the $t\bar{t}$ and $W+$jets production cross section is not negligible. The plot however does give us confidence that the $E_T$ cut we obtained from MC studies is indeed behaving as expected. Note also that we will cut quite hard on QCD when we require $E_T$ above 20 GeV (the QCD efficiency for this cut is $\sim 10\%$ see Section 1.4.3).

6.2.5 Jets

Jets are essential for understanding the top-quark pair decay since the semi-leptonic decay channel of $t\bar{t}$ involves in principle four jets, see Figure 1.7. Since we select events on the number of high-$p_T$ jets they contain, it is important to see if data looks similar to what we expect in the distribution of the number of jets. We show in Figure 6.9 (left) the jet multiplicity (i.e. the number of selected jets with $p_T > 20$ GeV) after the cuts described at the beginning of Section 6.2 with the additional isolation requirement on the muon as in Section 6.2.3 (i.e. requiring an analysis muon).

![Figure 6.9](image)

**Figure 6.9:** Left: the number of selected jets with $p_T > 20$ GeV after requiring an analysis muon. Right: with additional $E_T > 20$ GeV cut. The QCD is scaled with a factor 3.

We can conclude that with the QCD scaled up, the MC simulates the data well in shape. The normalization seems also here (see the previous sections) not perfect: the first four jet bins are slightly underestimated. One reason for this effect could be a difference in the jet energy scale between data and Monte Carlo, causing more jets to be selected in data. Since the shape of the jet multiplicity distribution is the same however, this does not change the selection efficiency and inspires confidence that we can use the jet selection as was discussed in Chapter 3. The same distribution but with additional $E_T$ cut, shown in Figure 6.9 (right), exhibits the same behaviour with ten times less QCD and suggests
that it is the signal MC that is slightly underestimated. As a last check before moving on to the actual estimation of QCD background, we show the $p_T$ distribution of the selected jet with highest $p_T$, the leading jet, (left) and of the selected jet with the 4th highest $p_T$ (right) in Figure 6.10 after requiring an analysis muon.

![Figure 6.10: Distribution of the jet $p_T$ after requiring an analysis muon and at least one selected jet. Left: the leading jet. Right: the fourth jet. QCD is scaled with factor 3.](image)

It can be seen that for the leading jet $p_T$ the agreement between data and MC is not perfect. In the low $p_T$ region the discrepancy is large. It is not a priori clear whether this comes from an underestimation of the signal MC or the QCD simulation. Since the uncertainties of the production rates of both are large (dominated by the $W$+jets uncertainty for the signal MC), data-driven techniques will be used to estimate the background contributions to the top-quark pair production cross section measurement.

### 6.3 First test of methods to estimate QCD

In the previous section we established that the data behaves as expected in most basic variables used in selecting $t\bar{t}$ candidates. This section will focus on checks of the QCD estimation methods discussed in the previous chapter. Note that the center of mass energy that was anticipated in Chapter 5 was unfortunately not reached. Data at an energy of 7 TeV was delivered, where an energy of 10 TeV was used to develop the methods. This lowers the cross section of top-quark pair production substantially, but also the QCD production rate [73,81]. The consequence of the low integrated luminosity is that statistics will be the limiting factor for the data-driven methods. Since we also tightened the good muon cuts to deal with the higher-than-expected QCD rates, this might render the methods not feasible.
### 6.3.1 ABCD method

The first method to estimate the QCD background, discussed in Section 5.3, is the ABCD method. The ABCD method uses two uncorrelated variables: the d0 significance and the relative isolation. By dividing a two-dimensional plot into four regions, the QCD content in the signal region was computed by using the simple Equation 5.2: \[ C = \frac{A}{B}. \]

To check whether the method can be used to obtain a solid estimate of the QCD background in the small data-set, we will test the method in the signal region as was defined in the previous chapter. In Figure 6.11 (left) the d0 significance versus the relative isolation after all other muon cuts in events with at least 4 selected jets after E_T cut is presented. The table in Figure 6.11 (right) shows the number of selected events per region.

<table>
<thead>
<tr>
<th>number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>A 1825</td>
</tr>
<tr>
<td>B 4</td>
</tr>
<tr>
<td>C 73</td>
</tr>
<tr>
<td>D 0</td>
</tr>
</tbody>
</table>

**Figure 6.11:** Left: the d0 significance versus the relative isolation after all other muon cuts for events with at least 4 selected jets after E_T cut. Right: number of events in each region of the ABCD plot for events with at least four selected jets and after E_T cut.

Due to the empty region D and the low statistics in B, there is unfortunately only one possible conclusion: the ABCD method is not suitable with only 2.89 pb^{-1} of data at \( \sqrt{s} = 7 \) TeV. Possible fixes include choosing the regions differently or using an extension of the ABCD method. These fixes are implemented in the so-called matrix method. The matrix method allows for signal events to enter the control region by assigning an efficiency to events to enter different regions. In the limit of no signal events outside of the signal region the ABCD method is mathematically equivalent to the matrix method. We will explore this method in the next chapter.

### 6.3.2 Fit method

For the fit method, discussed in detail in Section 5.4, the tail of the isolation distribution was used to fit for the QCD distribution and then extrapolate this fit into the signal
6.3 First test of methods to estimate QCD

region. As was done for the ABCD method in the previous section, we will check the fit method here before going into the data-driven QCD estimation in detail in Chapter 7. In Chapter 5 the relative isolation was used to perform the fit. In Figure 6.12 (left) the relative isolation for muons after all other muon cuts and $E_T$ requirement for events with 4 or more jets is shown.

![Relative isolation for muons](image)

**Figure 6.12:** The relative isolation for the muon after all other muon cuts and $E_T$ requirement for events with at least 4 selected jets. Left: without overlap removal. Right: with overlap removal

The fit that was used is a combination of a Landau with a third order polynomial (same as in Section 5.4). The prediction of the number of QCD events below relative isolation of 0.1 given by extrapolating the fit in Figure 6.12 (left) is:

$$ I = 68.6 \pm 11.8 \text{ (stat)} \quad (6.4) $$

events in the signal region where the error is the statistical error as explained and computed in Section 5.4. Note that the relative isolation cut was optimized for 10 TeV collisions and Figure 6.12 (left) seems to suggest that the cut value would need to be re-optimized. A shift from 0.1 to 0.05 seems reasonable and would yield an estimate for the number of QCD events under the new cut value (using the same fit) of $I_{0.05} = 17 \pm 3$. However in the previous section it was already shown that the QCD contribution is larger than expected and this lead us to the use of even tighter muon cuts, i.e. additional muon cuts. Especially the overlap removal of muons to jets removes a large amount of QCD background. In Figure 6.12 (right) the relative isolation for the muon after all other muon cuts and $E_T$ requirement events with 4 or more selected jets is presented after overlap removal. Unfortunately the conclusion also for this method is simple: the fit method does not work with the proposed cuts with only $2.89 \text{ pb}^{-1}$ of data at $\sqrt{s} = 7$ TeV since there is no statistics left above the cut value (even with a re-optimized value) to perform the fit.

Solutions to this could be loosening the cuts, especially the overlap removal. From both the relative isolation in Figure 6.12 (left) and the absolute isolation in Figure 6.3 (right)
one might conclude that the isolation cuts could be tightened, deeming the overlap removal unnecessary. There is however a strong argument to use the overlap removal: one knows that the muons close to a jet are non-prompt muons from heavy flavour decay and hence should not be taken for top-quark analysis. It has been decided by the ATLAS collaboration to use the overlap removal cut as a default muon cut in the top-quark analysis. This decision has lead us to investigate the matrix method to estimate the QCD background. This method will be discussed and used on data in the next chapter.

6.4 Summary

In this chapter input distributions for the estimation of the QCD background and eventually for the top-quark pair production cross section determination have been presented. A first comparison between data and Monte Carlo suggests that the QCD background is roughly a factor three higher than expected. By scaling the QCD Monte Carlo with this factor the combined simulated signal samples ($t\bar{t}$, $W+$jets, $Z+$jets, single top and di-boson) and the QCD Monte Carlo describe the data well. The small discrepancy in normalization can be explained by the crude scaling of the QCD Monte Carlo but also by the large uncertainties of production cross section of the $W+$jets samples. Therefore a data-driven QCD estimation is needed, which will be presented in the next chapter. In Chapter 8 also a data-driven technique for the $W+$jets estimation will be shown. The QCD estimation methods of Chapter 5 have been tested. The small data-set at lower than anticipated energy caused the ABCD method to become unsuited for a solid estimation of the QCD background due to lack of statistics. The second method presented in the previous chapter, the fit method, performs well with the cuts it was optimized for. Due to a decision of the ATLAS collaboration to adopt the overlap removal requirement of muons to jets, the distribution needed to perform the fit at high values of the relative isolation lacks statistics. The overlap removal cut made also this method not suitable for the small data-set available. In Chapter 7 we will present an alternative method to estimate the QCD background for the $t\bar{t}$ cross section measurement. The method will utilize many of the key aspects of prompt and non-prompt muons that have been discussed in this chapter.