Measurements on top quark pairs in proton collisions recorded with the ATLAS detector
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The data in the previous chapters shows that we are able to isolate events with top quark pair decay from other physics processes. We have measured the inclusive production cross section with 35 pb$^{-1}$ of data, the initial dataset of 2010. In this chapter we perform a measurement with the 2011 data set described in Chapter 4, with an integrated luminosity of 1.04 fb$^{-1}$, i.e., over 25 times more. We study the rapidity of the reconstructed top quarks and separate positively and negatively charged top quarks. In this way we can measure the asymmetry between production angles of top and antitop quarks, the so-called top quark charge asymmetry, as described in Chapter 1. A similar measurement by the ATLAS collaboration is published in Ref. [70].

This chapter is organized as follows: First, in Section 6.1 we define two observables to quantify the charge asymmetry. In Section 6.2 we present the relevant kinematic variables and identify differences in distributions of events containing only positively or negatively charged leptons. The asymmetry in top quark events and in physics backgrounds after selection is discussed in Section 6.3. The measurement on data and the comparison with expectation are presented in Section 6.4 and 6.5, for both variables. Section 6.6 summarizes the results.

6.1 Top quark charge asymmetry at the parton level

In Chapter 1 we discussed the source of charge-asymmetric $t\bar{t}$ production in the Standard Model. Here, we translate this to observables feasible for ATLAS. The asymmetry can be parametrized in several ways. We discuss two parametrizations, corresponding to an “integrated asymmetry”, $A_{int}$ and a “differential asymmetry”, $A_{diff}(y)$.
6.1.1 Integrated asymmetry

The integrated asymmetry is the most straightforward and establishes the difference in absolute rapidity ($\Delta|y|$) between the top quark and antitop quark,

$$\Delta|y| = |y_t| - |y_{\bar{t}}|,$$

The distribution of $\Delta|y|$ is symmetric around zero when the production process is invariant under charge conjugation. But, if charge conjugation symmetry does not hold, this changes. When positively charged top quarks are produced more often with a smaller angle with respect to the $z$-axis, the distribution will be shifted towards the positive side. This is illustrated in Figure 6.1. On the left side are two situations that can occur. In the top graphs, the production is charge symmetric, and hence the distribution of the rapidities of top and antitop quarks are identical. This results in a symmetric distribution of $\Delta|y|$. The bottom graphs depict the situation where production is no longer symmetric under charge conjugation, and top quarks (which are positively charged) are produced in the forward direction more often. This results in differently shaped distributions in $y$ and therefore a shift in the $\Delta|y|$ distribution.

![Figure 6.1](image-url) – Schematic view of two situations of the rapidity distributions of top quarks and antitop quarks and the effect this has on the absolute rapidity differences.

This shift can be quantified as an asymmetry:

$$A_{int} = A_{\Delta|y|} = \frac{N^+_{\Delta|y|} - N^-_{\Delta|y|}}{N^+_{\Delta|y|} + N^-_{\Delta|y|}}$$

Here, $N^+_{\Delta|y|}$ and $N^-_{\Delta|y|}$ are the integrals of events with $\Delta|y| > 0$ and $\Delta|y| < 0$, respectively.
6.1. Top quark charge asymmetry at the parton level

In simulation, the asymmetry emerges for top quark pair events generated using NLO calculations (MC@NLO). Figure 6.2 shows the distribution of $\Delta|y|$ for events produced with gluon fusion ($gg$) and events produced in quark-antiquark or quark-gluon production processes ($q\bar{q}$ and $qg$), at parton level. The simulation used in this and other plots in this chapter are based on 2 million simulated $t\bar{t}$ events, corresponding to an integrated luminosity of roughly 12 fb$^{-1}$. The distribution is broken down into a symmetric part and an asymmetric part. Collisions where the initial partons were gluons (80.1% of the events) are shown in light gray. This distribution is predicted to be symmetric, we find $A_{int} = 0.001 \pm 0.001$, which is indeed consistent with zero.

The dark-colored distribution, representing events inferred by quark-antiquark annihilation and quark-gluon collisions, is expected to show asymmetric effects. These two contributions form the remaining 20% of the collisions. The quark-antiquark (19.1%) and quark-gluon processes (0.8%) show an overall asymmetry in $\Delta|y|$ of $0.025 \pm 0.002$. The overall asymmetry for the complete sample adds up to $A_{int} = 0.006 \pm 0.001$.

![Figure 6.2 – Difference in absolute value of rapidities of the top and antitop quarks, for MC@NLO events at parton level. The distributions are based on ~2 million of $t\bar{t}$ events.](image)

### 6.1.2 Differential asymmetry

The second observable for the top quark charge asymmetry as defined in [42] is:

$$A_{diff}(y) = A(y) = \frac{\frac{dN(t)}{dy} - \frac{dN(\bar{t})}{dy}}{\frac{dN(t)}{dy} + \frac{dN(\bar{t})}{dy}}.$$
Chapter 6. Measurement of the top quark charge asymmetry

The number of top quarks and antitop quarks is determined as a function of rapidity, resulting in an asymmetry that depends on $y$. Figure 6.3 shows a schematic view of this asymmetry. For charge symmetric production, hence for equal rapidity distributions of top and antitop quarks as in the upper graph, the asymmetry follows a straight line at $A_{\text{diff}}(y) = 0$. For charge-asymmetric production, as in the lower graph, this translates into a U-shaped asymmetry, with positive values for high values of the absolute rapidity and negative values around $y = 0$.

![Figure 6.3](image)

Figure 6.3 – Schematic view of two situations of the rapidity distributions of top quarks (light red) and antitop quarks (dark blue) and its effect on the differential asymmetry distribution.

We measure this effect in simulation, as shown in Figure 6.4. Events in the simulation that originate from charge symmetric gluon fusion are separated from the other two contributions, quark-antiquark and quark-gluon production. The combination of the latter two forms a U-shape, confirming the presence of the asymmetry in $t\bar{t}$ production. The weighted sum of the $gg$, $q\bar{q}$ and $qg$ (i.e., the mixture as expected in data) is shown as ‘total’. This demonstrates that the asymmetry is visible in the inclusive sample. To quantify this effect, we fit the distribution with a second order polynomial:

$$f(y) = c_0 + c_1 y^2.$$  

The skewness is compatible with zero and therefore we omitted the linear term. The values of the coefficients of the two-parameter fit are: $c_0 = (-4.1 \pm 0.6) \times 10^{-3}$ and $c_1 = (3.6 \pm 0.3) \times 10^{-3}$. The fit function is drawn in the figure as well, for which the $\chi^2$ per degree of freedom is 0.7.

So far, we determined the two parametrizations of the charge asymmetry in $t\bar{t}$ production at parton level. In the following, we will determine the size of the asymmetry in simulated data after full event generation, reconstruction and application of the selection, for both $t\bar{t}$ events and the expected background. After that we measure the asymmetry in data.
6.2 Properties of the data set

We perform this analysis on the 2011 data set, as introduced in Chapter 4. The event selection we apply in this analysis is presented in Section 4.5. Summarizing, we require a lepton (electron or muon) and at least four jets, of which at least one has to be identified as a $b$-jet. Furthermore, there are thresholds on the missing transverse energy and the transverse $W$ boson mass, their actual values depend on the physics channel. Especially the $b$-tagging requirement leads to a pure sample of $t\bar{t}$ events.

6.2.1 Event yield

The event yields of signal and background are presented in Table 6.1. It shows the expected and observed number of events that pass the selection, after application of all corrections to the simulation. The $W$+jets and multijet background are obtained from data-driven techniques. We assigned uncertainties of 30% and 100% to these estimates, respectively. All other physics processes are taken from simulation.

The total number of expected signal events in the electron channel is 3846, for an integrated luminosity of 1.04 fb$^{-1}$, with a signal to background ratio (S/B) of 3.5. In the muon channel the expected number of $t\bar{t}$ events is 5470, with S/B = 2.7.

Figure 6.4 – The differential asymmetry distribution for MC@NLO events at parton level. The distributions are based on 2 million $t\bar{t}$ events. The dark gray areas correspond to events with gluon-gluon production process. The light gray areas depict the (asymmetric) remainder, quark-antiquark and quark-gluon processes. The black points are the summed distribution.
Table 6.1 – Expected and observed event yields, for an integrated luminosity of 1.04 fb\(^{-1}\), after \(b\)-tagging.

<table>
<thead>
<tr>
<th>Components</th>
<th>(e^{+})jets</th>
<th>(\mu^{+})jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>(t\bar{t})</td>
<td>3846 ± 32</td>
<td>5470 ± 38</td>
</tr>
<tr>
<td>(W^{+}) + jets</td>
<td>567 ± 170</td>
<td>1164 ± 349</td>
</tr>
<tr>
<td>(Z^{+}) + jets</td>
<td>41 ± 3</td>
<td>90 ± 5</td>
</tr>
<tr>
<td>(WW/ZZ/WZ)</td>
<td>11 ± 1</td>
<td>15 ± 1</td>
</tr>
<tr>
<td>Single top</td>
<td>260 ± 5</td>
<td>347 ± 6</td>
</tr>
<tr>
<td>Multijet (data-driven)</td>
<td>147 ± 147</td>
<td>408 ± 408</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>1027 ± 225</td>
<td>2027 ± 537</td>
</tr>
<tr>
<td>Sum Backgrounds</td>
<td>4872 ± 227</td>
<td>7496 ± 538</td>
</tr>
<tr>
<td><strong>Total Expected</strong></td>
<td>5078 ± 71</td>
<td>7846 ± 89</td>
</tr>
<tr>
<td><strong>Observed</strong></td>
<td>5078 ± 71</td>
<td>7846 ± 89</td>
</tr>
</tbody>
</table>

6.2.2 Control plots on background-subtracted data

We already concluded in Chapter 4 that the shapes and normalization of the background and signal match the data. The following section identifies charge-asymmetric effects in data. We identify possible asymmetries or irregularities within the kinematic properties, since this could propagate into the top quark reconstruction, faking an asymmetry. We do this by subtracting the simulated (single top and diboson) and data-driven (multijet and \(W^{+}\) + jets) background from data. Subsequently we divide the background-subtracted data according to the charge of the lepton. We compare the events containing positively charged leptons to events with negatively charged leptons.

Fake asymmetry in electrons

One of the issues for electrons that needs attention is the hardware problem in the calorimeter readout, as mentioned in Section 4.1.2. Due to this problem, a sector of the calorimeter was inactive, meaning that most of the data are recorded with a gap in the calorimeter between \(0 < \eta < 1.4\) and \(-1 < \phi < 0.5\). The gap affects electrons and jets and automatically leads to an asymmetric distribution in terms of \(\eta\) and \(\phi\). Figure 6.5(a) shows the density of electrons in data, as a function of \(\eta\) and \(\phi\). The acceptance gap due to the calorimeter problem is visible, as well as the crack region between barrel and endcap on both sides of the detector (\(|\eta| \sim 1.4\)). The gap is in principle not expected to bias \(A_{\text{int}}\) or \(A_{\text{diff}}(y)\), because there is no reason to assume that the acceptance depends on the charge of the lepton, but we nevertheless study the differential distribution of the
6.2. Properties of the data set

electrons.

Figure 6.5(b) shows the distribution of $\eta$ of selected electrons. In this figure, we compare the events with a positively charged lepton, with the negatively charged events, as a function of $\eta$. The category of positive leptons is depicted with histograms, and the negatively charged leptons with dotted markers. For visibility reasons, the error bars of the negatively charged events reflect the sum of the uncertainty of both the positive and negative charged events. This includes the statistical uncertainties of simulated events, as well as the systematic uncertainty on the data-driven background estimates. Since the charge-asymmetric contributions of $W + \text{jets}$ and single top events are subtracted, the total yield of the events are expected to be equal. Due to the calorimeter gap, we observe a larger number of events with $\eta < 0$. We express this difference in the ‘fake’ asymmetry $A_f$:

$$A_f = \frac{N_{\eta>0} - N_{\eta<0}}{N_{\eta>0} + N_{\eta<0}},$$

(6.1)

where $N$ is the number of events with the subscript indicating the range in $\eta$. $A_f$ is $-0.048 \pm 0.027$ for events with negatively charged leptons and $-0.050 \pm 0.029$ for events with positively charged leptons. This is a direct consequence of the calorimeter gap, but the fake asymmetry is of equal size and sign for both charges. Therefore, we do not expect that this specific asymmetry influences the top quark charge asymmetry, as the latter is measured by rapidity differences rather than rapidity itself. The ratio of negative to positive events is shown in the bottom plot. The distributions match, but show a few statistical fluctuations in the (badly populated) forward areas.

![Figure 6.5](image)

**Figure 6.5** – (a) Electron density in data as a function of $\eta$ and $\phi$. (b) Electron $\eta$ for events with leptons of positive and negative charge.

Figures 6.6(a) and 6.6(b) display the electron charge comparison with respect to the azimuthal angle $\phi$. In addition to the lepton charges, the data are divided by splitting up events based on the sign of the pseudorapidity. In (a), showing events with $\eta < 0$, 

the histograms match apart from minor differences in a few bins. In (b), representing the other side of the detector, at $\phi = -1$ the calorimeter inactive area emerges, but appears to be reasonably insensitive to lepton charge, as expected.

![Figure 6.6](image)

**Figure 6.6** – Electron $\phi$ for events with leptons of positive and negative charge, in the region $\eta < 0$ (a) and $\eta > 0$ (b).

Figure 6.7(a) shows the transverse momentum of the electron. Events with a momentum larger than 140 GeV are summed and drawn as the overflow bin. In terms of momentum the shape differences are minor. There are neither notable outliers, nor a trend in any direction that indicates anomalous behavior. This demonstrates that the momentum of electrons in our selected sample does not depend on the charge.

**Fake asymmetry in muons**

Considering the muon properties, we follow a similar procedure as for electrons and present $p_T$ (Figure 6.7(b)), $\eta$ and $\phi$ (Figure 6.8). The number of events with muons of positive and negative signs agrees well. Furthermore, the agreement in terms of the shape of transverse momentum is good, no unexpected trends emerge. The shape of the pseudorapidity appears to depend on the sign of the muon, as the multiplicity of muons with charge +1 is somewhat higher than of muons with a charge of −1, if we integrate over the range $\eta < 0$, while for $\eta > 0$ it is the other way around. This is most apparent in the bins surrounding 0. To quantify this observation, we calculate the asymmetry we defined in equation 6.2.2 and obtain $A_f = 0.016 \pm 0.028$ for muons with negative charge. For muons with positive charge, $A_f = -0.045 \pm 0.033$. These numbers are compatible within one standard deviation and hence no asymmetry is obtained. The $\phi$ distribution in 6.8(b) is compatible with a uniform ratio of 1.
6.2. Properties of the data set

Figure 6.7 – Transverse momentum of the electron (a) and muon (b), for data with background subtracted, and for events with positively and negatively charged leptons. Events with momentum larger than 140 GeV in the electron channel are summed and displayed together in the last bin.

Figure 6.8 – Pseudorapidity $\eta$ (b) and azimuthal angle $\phi$ of the muon, for data with background subtracted.
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Jets

Thirdly, we consider hadronic jets. In principle, charge conjugation does not induce asymmetries in the kinematic properties of jets, as they are not directly related to the measurement of the lepton. Misinterpretations in terms of under- or overestimations in background could occur, however. In Figure 6.9 the transverse momenta of jets in the electron channel are presented. In (a) the momentum of all jets are compared for events with opposite-signed leptons. In (b-d) the transverse momenta of the first, second and third jets (ranked in terms of momentum) are compared. The normalization and shape of the two distributions in each of the four plots agree within uncertainties. At low momenta ($p_T < 40$ GeV), negative events contribute more in the three jets with the highest transverse momenta, but only for the hardest jet this is significant. In the cumulative plot (a), this effect disappears. We conclude that this difference will not bias the measurement.

The equivalent distributions for the muon channel are shown in Figure 6.10. In (a) the momentum of all jets are compared for events with opposite-signed lepton, and (b-d) shows the momentum of the three most energetic jets. Again, there is no significant difference that displays a tendency towards any direction in either of the distributions.

The pseudorapidity of jets is an input to the reconstruction of the top quark on the hadronic side of the decay. Figure 6.11 shows the $\eta$ distribution for all jets, in the $e+$-jets (a) and $\mu+$-jets channel (b), for $\eta$ between -4.5 and 4.5. Overall, the jet pseudorapidities do not depend on the lepton charge. The multiplicity of jets with $\eta < 0$ is higher than for the $\eta > 0$, in both data and simulation 5-6% more jets are selected. This is a direct result of the calorimeter gap, and is independent of the lepton charge.

Fake asymmetry in $E_T$ and $m_W^T$

The transverse energy imbalance, $E_T$, is computed from all measured objects, including the lepton, and is therefore directly influenced by potential dependencies. Subsequently, the transverse $W$ boson mass ($m_W^T$) is constructed from the lepton four-momentum and the missing energy. Figure 6.12 checks the agreement between the data of both lepton signs, because both quantities are used in background reducing cuts. The missing transverse energy is displayed in the top plot. It shows no anomalous behavior of this observable. Likewise, the positive and negative events in the transverse $W$ boson mass distributions are compatible with each other, in both channels (c, d).

6.3 Standard Model asymmetries after selection

In Section 6.1, we showed the integrated and differential asymmetry in $t\bar{t}$ at ‘parton level’, where the four-vectors of the top quark follow straight from the theoretical prediction of the Standard Model. All observables, hence also the top quark charge asymmetry, are distorted after the detector simulation, subsequent reconstruction of the physics objects and the final event selection. Besides the top quark pair, also some of the physics backgrounds
experience asymmetric production mechanisms. In this section, we analyze the $t\bar{t}$ asymmetry after full event generation, reconstruction and selection, as well as the contribution of physics background to the asymmetry.

### 6.3.1 Asymmetry in $t\bar{t}$ simulation

Observables that we obtain from the reconstructed objects we denote by ‘detector level’ simulation. At detector level, we make a distinction between events after ‘minimal selection’ and ‘full selection’. To be able to reconstruct two top quarks at detector level we need four jets, a lepton and missing transverse energy. This corresponds to the minimal selection. The full selection includes, in addition, the multijet-reducing cut (triangular cut) and the requirement of at least one $b$-tagged jet.
Integrated asymmetry

In the electron channel, for the simulation at detector level after minimal selection, we measure a value for the integrated asymmetry $A_{\text{int}}$ of $-0.002 \pm 0.003$. After the full selection is applied the same quantity is equal to $-0.009 \pm 0.008$. This deviates from the parton level value of $+0.006 \pm 0.001$ and suggests that generation and simulation influences the observable. The statistical uncertainty on $A_{\text{int}}$ after full selection is larger, since we select only a fraction of the events. However, even within 1σ uncertainty the detector level value does not agree with the parton level calculation. This means we can expect a similar shift in the value we measure in data. In the muon channel the detector level value of $A_{\text{int}}$ is $-0.003 \pm 0.003$ after minimal selection and $-0.007 \pm 0.007$ with full selection. Similar to the electron channel we therefore expect the data value in the muon channel to be shifted towards negative values as well.
Differential asymmetry

We show the distributions for $A_{\text{diff}}(y)$ at parton and detector level in Figure 6.13. The asymmetry is plotted with respect to the rapidity. The parton level distribution in both plots is identical to the one shown as “Total” in Figure 6.4. Furthermore, triangles depict the distributions after reconstruction after minimal selection and full selection. They correspond to an integrated luminosity of 1.04 fb$^{-1}$. Potentially, asymmetric detector effects are folded in this distribution and may affect it.

The electron channel (left) distribution of the asymmetry at detector level shows statistical fluctuations. Especially in the forward regions only a few top quarks are reconstructed. The large uncertainties in the entire range assure that the detector level distributions agree with the parton level, but are also compatible with a straight line through $A_{\text{diff}}(y) = 0$. In the muon channel (right), similar arguments can be employed. But, at detector level after minimal and full selection, a deviation emerges at $y > 1$. All values of $A_{\text{diff}}(y)$ are below zero in this range. When summing the bins between $y = 1$ and $y = 3$, the asymmetry in simulation at parton level is $-0.005 \pm 0.001$, whilst simulation after full selection is $-0.028 \pm 0.012$. This is a difference of 2.5 standard deviations that could indicate the presence of asymmetric behavior of the detector. We further investigated the individual distributions of the top quarks reconstructed on the leptonic and hadronic side of the decay, but could not find a source of this deviation.

We have to conclude that we are not sensitive to measure the differential asymmetry as predicted by the Standard Model, in either of the channels. Secondly, in the muon channel for positive rapidities a significant deviation occurs, and behavior opposite to expectation is expected in data as well in this case. This is consistent with what we see in the integrated asymmetry $A_{\text{int}}$: the asymmetry at parton level (theory level) looses significance after detector simulation, event selection and reconstruction are applied.
Mapping the simulation and detector effects is important as it may modify the observable to a large extent.

6.3.2 Asymmetry in Standard Model background simulation

A substantial part of background events originates from $W$ + jets and single top production. These standard model processes are charge-asymmetric, due to their electroweak production mechanisms. The valence quarks of the colliding protons are two up quarks and one down quark. The probability of an up quark interacting with an antiquark of the down-type is therefore higher than a down quark with an antiquark of the up-type. This is described in Chapter 1.

As a result, there are more background events in the sample of events with a positively

Figure 6.12 – $E_T$ and $m_W$ in the electron channel (left) and the muon channel (right).
charged lepton. Additional to the charge asymmetry, $W^+\text{ jets}$ and single top events are produced less centrally than top quark pairs, on average. These two effects combine and propagate through to our analysis: the lepton in background events will be used by the reconstruction algorithm to form the ‘leptonic’ top quark, whose charge will be positive more often than negative. Consequently, there are more fake top quarks reconstructed in the forward region.

We measured the integrated asymmetry in $W^+\text{ jets}$ and single top simulation events, after minimal selection. The result is summarized in Table 6.2. Both backgrounds induce an asymmetry that is an order of magnitude larger than that of $t \bar{t}$, and of the same sign. In the electron channel the asymmetry is smaller than in the muon channel. Notice that this is an observable that can only be measured after reconstruction, since there are no two top quarks at parton level for these background events.

Table 6.2 – Asymmetries induced by a pure sample of background events, after detector simulation and minimal selection.

<table>
<thead>
<tr>
<th></th>
<th>$e^+\text{jets}$</th>
<th>$\mu^+\text{jets}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^+\text{ jets}$</td>
<td>$0.020 \pm 0.004$</td>
<td>$0.031 \pm 0.002$</td>
</tr>
<tr>
<td>Single top</td>
<td>$0.012 \pm 0.006$</td>
<td>$0.030 \pm 0.005$</td>
</tr>
</tbody>
</table>

The differential asymmetry of single top and $W^+\text{ jets}$ events is shown in Figure 6.14, again for the $e^+\text{jets}$ (left) and $\mu^+\text{jets}$ (right) channels. The top graph depicts the $W^+\text{jets}$ contribution after minimal selection. This corresponds to what we named ‘detector level at minimal selection’ before. A parabolic shape forms, similar to what we saw in top pair events. The parabolic fit results in values of $c_1$ of 0.014 ($W^+\text{jets}$) and 0.011 (single
top), for the electron channel. For the muon channel $c_1 = 0.022$ ($W+\text{jets}$) and 0.023 (single top). The parton level value for $t\bar{t}$ events for this quantity is $3.6 \cdot 10^{-3}$. We checked that if we apply the full selection, the background effect is eliminated and the remaining asymmetry cannot be distinguished from a straight line at $A_{\text{diff}}(y) = 0$. This is due to the low number of remaining background events after selection.

To conclude, we showed that distortion and biases that result from the detector, reconstruction and selection steps, are present and form a nuisance to measuring the charge asymmetry. In the following section we adopt an unfolding procedure to map the distortion and bias.

### 6.4 Results for $A_{\text{int}}$

The observed distributions of $\Delta|y|$ for the electron and muon channel are shown in Figure 6.15, on top of the sum of expected events. The yield of the expected events is somewhat lower than the data, in both channels, as we already saw in the previous section. The shapes of the data in the distributions match the expectations reasonably well.

We measure the integrated asymmetry $A_{\text{int}}$ from the background-subtracted data, following the same procedure as we did for the control plots. The results are summarized in Table 6.3. The data should compare to the values of the $t\bar{t}$ sample at detector level after full selection. For the electron channel we obtain in data $A_{\text{int}} = 0.008 \pm 0.019$ (stat), compared to $-0.009 \pm 0.008$ (stat) in simulation. Note that the uncertainty on simulation is obtained from the complete set of events, if we scale the uncertainty of simulation to the integrated luminosity of data, we obtain $-0.009 \pm 0.021$.

The uncertainty in this measurement is large enough to accommodate the differences in the central values. In the muon channel $A_{\text{int}} = -0.013 \pm 0.016$ (data) compared to $-0.007$
6.4. Results for $A_{\text{int}}$

![Distribution of $\Delta |y| = |y_t| - |y_{\bar{t}}|$, after all selections, for the electron (a) and muon channel (b).](image)

Figure 6.15 – Distribution of $\Delta |y| = |y_t| - |y_{\bar{t}}|$, after all selections, for the electron (a) and muon channel (b).

$\pm 0.007$ (or $-0.007 \pm 0.0019$, when scaled to $1.04 \text{ fb}^{-1}$). The data is in full agreement with Standard Model expectations.

<table>
<thead>
<tr>
<th>Det. level (min sel.)</th>
<th>Det. level (full sel.)</th>
<th>Data - bkg</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e$+jets</td>
<td>$-0.002 \pm 0.003$</td>
<td>$-0.009 \pm 0.008$ $[\pm 0.021]$ $0.008 \pm 0.019$</td>
</tr>
<tr>
<td>$\mu$+jets</td>
<td>$-0.003 \pm 0.003$</td>
<td>$-0.007 \pm 0.007$ $[\pm 0.019]$ $-0.013 \pm 0.016$</td>
</tr>
</tbody>
</table>

Table 6.3 – Results for integrated asymmetry $A_{\text{int}}$ for data compared to simulation at different levels. The uncertainties in this table reflect only the statistical uncertainty, with in brackets the uncertainty when simulation is scaled to $1.04 \text{ fb}^{-1}$.

6.4.1 Unfolding

To be able to compare the measured values of the charge asymmetry with the theoretical predictions, we take into account the full event generation, acceptance and reconstruction effects by applying an ‘unfolding’ procedure. This means that we take into account how the four-vectors of the generated top quarks transform after all these steps and accordingly transform back the four-vectors of the top quarks as measured in the ATLAS detector. The binned spectrum of an observable can be written as a function of the original (‘true’) spectrum by applying a response matrix to it:

$$m_i = B_{ij} s_j,$$

where $m_i$ is the measured spectrum in terms of $i$ bins, $s_j$ is the simulated spectrum at parton level and $B_{ij}$ is the response matrix. The response matrix thus represents
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the showering and hadronization steps in event generation, the detector effects, selection efficiency, and the top quark reconstruction, including the potential migration from one bin to another during each of these steps. Hence, the inverse of the matrix, $B^{-1}_{ij}$, can be applied to the measured spectrum to obtain the spectrum equivalent to the simulated spectrum, at parton level, $s_j$.

Inverting the matrix can lead to singularities or unphysical peaks, therefore a smoothing and regularization algorithm is applied. The method used in this analysis is Bayesian unfolding [89] and is implemented using the software package RooUnfold [90].

The motivation for applying the unfolding procedure to the data is to obtain a detector-independent value of the measurement that can be compared directly to theoretical predictions and other experiments. That holds true for existing models predictions and measurements, but especially for future models.

Response matrix

The integrated asymmetry, $A_{\text{int}}$, is calculated from the distribution of $\Delta |y| = |y_t| - |y_{\bar{t}}|$. We divide this distribution in six equally-sized bins and define the response matrix of this quantity. This is done by filling a matrix with the simulated true and reconstructed value of $\Delta |y|$, per event. When the event does not pass the selection criteria and hence no reconstructed value exist, it adds to the inefficiency. The resulting matrices for the electron and muon channel are shown in Figure 6.16. The matrices are similar for both channels. Both show large off-diagonal contributions, proving that full event generation and reconstruction indeed cause bin migration.

**Figure 6.16** – Response matrices $B_{ij}$ for the electron (a) and muon (b) channel. The value of the matrix element is visualized by the size of the boxes.

Unfolding parameters

There are a number of parameters that influence the unfolding procedure. We studied the number of iterations during unfolding that were necessary to converge to a stable
result and the bin size of the matrix and distribution. There is a trade-off between the number of iterations and uncertainty of the unfolded result, therefore we keep the number of iterations as low as possible.

We define the unfolded results as ‘stable’ when the difference with respect to the asymmetry after the previous iteration is smaller than 0.001. The number of iterations required to obtain a stable result is obtained by producing pseudo data in the form of a set of varied \( \Delta |y| \) distributions that are obtained by pulling events from a probability distribution function that is based on the reconstructed Standard Model \( t\bar{t} \) spectrum of \( \Delta |y| \). The unfolding procedure is applied to each pseudo experiment, and the number of iterations that is required to converge to a stable value for the asymmetry is measured. The results show that, regardless of the bin sizes, the unfolding converges 100% of the time within 50 iterations, for the nominal asymmetry. In the chosen configuration of six bins, all pseudo experiments converged within 40 iterations, with an average of 13.4 iterations.

In Figure 6.17 the statistical uncertainty on the unfolded asymmetry is plotted as a function of the number of iterations, for different bin sizes. It shows that a higher number of iterations leads to a larger uncertainty. This is a property of the unfolding procedure. The six- and eight-bin samples reach a plateau. The plot shows that for larger bin sizes, and therefore better populated bins, the increase in uncertainty is smaller.

![Figure 6.17 - Expected statistical uncertainty on the unfolded asymmetry as a function of the number of iterations, for electron channel (a) and muon channel (b).](image)

We check whether the unfolding procedure can reproduce the original (‘parton level’) asymmetry on average, for different sizes of the asymmetry. We obtain samples with an artificial asymmetry of +10%, +5%, 0%, -5% and -10%, by reweighting the original, simulated samples. From each reweighted sample we extract 1000 pseudo data sets and apply the unfolding procedure. Figure 6.18 shows the unfolded asymmetry as a function of the original asymmetry, for different numbers of iterations. It shows that the five data points belonging to the same number of iterations form a straight line and prove the linearity of the operation. With increasing number of iterations, the slope of the line changes, in both channels. We fit a second order polynomial \( f(A) = c_1 A + c_2 \) to the five...
Chapter 6. Measurement of the top quark charge asymmetry

points. In the electron channel, the slope converges to 0.999, with an offset of 0.001, at 160 iterations. This is close to the reference \( (c_1 = 1, c_2 = 0, \text{dashed line in plot}) \). This means that although we concluded that for an asymmetry close to zero 40 iterations is sufficient, for larger asymmetries more iterations may be required. At 40 iterations, a deviation of 11% from the true value is expected, at 80 iterations only 5%. In the muon channel, these numbers are 9% and 3%, respectively.

Based on the balance between the increase of the uncertainty and the reduction of a bias for a high number of iterations, we use 80 iterations in combination with six evenly distributed bins and assign the systematic uncertainty due to a potential bias to the final result.

6.4.2 Systematic uncertainties

The sources of systematic uncertainties that contribute to the final result are in principle equal to those in the cross section measurement. However, since we investigate asymmetric effects, most of these sources are expected to have either negligible or relatively small contributions: they simply cancel in the ratio. For example, the jet energy scale uncertainty does not behave differently for events containing positively or negatively charged leptons. Since the statistical uncertainty is large, we only evaluate the expected major sources of uncertainty on the charge asymmetry:

- **Background normalization.** The uncertainty on the data-driven techniques of obtaining the multijet and \( W^+ \text{ jets} \) background events are 100% and 30% respectively. The other electroweak background of importance are single top events, to which we apply a 30% uncertainty too. We varied the amounts of backgrounds during the background subtraction step to estimate the impact on the final result.

- **Event generator.** We repeated the analysis, including the unfolding procedure, with the \( tt \) shape and normalization estimates obtained with POWHEG, instead

Figure 6.18 – Unfolded asymmetry as a function of the the inserted asymmetry, for electron channel (a) and muon channel (b).

The other electroweak background of importance are single top events, to which we apply a 30% uncertainty too. We varied the amounts of backgrounds during the background subtraction step to estimate the impact on the final result.

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6.4. Results for $A_{int}$

of MC@NLO. In both cases HERWIG is used to perform parton showering and hadronization.

- Unfolding bias. The linearity tests showed that for 80 iterations a 5% bias may arise.

The largest uncertainty comes from the difference in event generators, a shift of 0.021 (0.024) is observed in the electron (muon) channel. The background subtraction and unfolding biases lead to shifts of 0.008 maximally, where the subtraction of $W + \text{jets}$ is the major source of this shift. We include these systematic uncertainties into the final result by quadratically adding their contribution to the uncertainty.

6.4.3 Final results after unfolding $A_{int}$

Figure 6.19 shows the unfolded results of $\Delta|y|$ compared to the parton level values.

![Figure 6.19](image)

**Figure 6.19** – Unfolded distribution of $\Delta|y|$ on top of the MC@NLO prediction at parton level, for electron channel (a) and muon channel (b). The error bars reflect the sum of the statistical and systematic uncertainties.

The measured unfolded value of $A_{int}$ in the electron channel is

$$A_{int}^{unf}(e) = 0.074 \pm 0.058(\text{stat}) \pm 0.023(\text{syst}),$$

and in the muon channel

$$A_{int}^{unf}(\mu) = -0.024 \pm 0.050(\text{stat}) \pm 0.026(\text{syst}).$$

The combination of the results of the two statistically independent samples is

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

where we assumed that all sources of systematic uncertainty are uncorrelated, except the contribution of the $t\bar{t}$ modeling. These values are within the uncertainties well compatible
with the Standard Model. We compare these numbers to similar measurements of the CMS collaboration [91] and the ATLAS paper [70] referred to earlier. CMS quotes \( A_{int} = 0.013 \pm 0.028 \) (stat) \( +0.029 \) (syst), as a result combined between the electron and muon channel, for 1.09 fb\(^{-1}\). The measurement in ATLAS shows \( A_{int} = 0.018 \pm 0.028 \) (stat) \( \pm 0.023 \) (syst) for 1.04 fb\(^{-1}\). The main difference of the results in this chapter with respect to the ATLAS result comes from different choices in event selection (namely, \( b \)-tagging algorithm, muon momentum, jet pseudorapidity) and different choices in the unfolding procedure.

With the combined result for the asymmetry, we can exclude a value of \( A_{int} \) larger than 0.102, or smaller than -0.074, with a confidence level of 95%. This is under the assumption that the uncertainties are Gaussian distributed and that the statistical and systematic uncertainties are uncorrelated.

### 6.4.4 Discussion on new physics expectations

Since the nonzero measurement of the forward-backward asymmetry by the Tevatron experiments for events with \( m_{t\bar{t}} > 450 \) GeV, several new physics models have been evaluated at benchmark levels compatible with these results. A range of models that induce a non-zero forward-backward asymmetry have been proposed [92, 93]. The corresponding predictions for the LHC charge asymmetry of \( A_{int} \) as we measured in this chapter were included as well. These models predict values of \( A_{int} \) between 0.0 and 0.09. Figure 6.20 shows a number of such models, in a 2-dimensional plane. The x-axis depicts the forward-backward asymmetry for \( m_{t\bar{t}} > 450 \) GeV at the Tevatron, the y-axis the value of \( A_{int} (= A^\text{new}_C) \) to be measured at the LHC. The value reported by CDF is \( A_{FB}(m_{t\bar{t}} > 450 \text{GeV}) = 0.475 \pm 0.114 \) [43] (D0 only reports an overall asymmetry, \( A_{FB} = 0.08 \pm 0.04 \) (stat) \( \pm 0.01 \) (syst), consistent with the Standard Model [94]).

We cannot exclude any values in this range, using the combined result, although our measurement disfavors the \( Z' \) models (mass ranges from 100 to 360 GeV). The statistical limits of the measurements with the current data set (1.04 fb\(^{-1}\)) do not allow for stronger statements on exclusion of the models proposed here. Table 6.4 shows the expected uncertainty on the combined result, as a function of the size of the data set. It shows that conducting the same analysis on twice as much data, leads to an expected statistical uncertainty that is comparable to the systematic uncertainty. With a data set of 5 fb\(^{-1}\) the expected statistical uncertainty is reduced to 0.017 and taking into consideration that some systematic uncertainties may be reduced when knowledge of the detector and background estimates are improved, a part of Figure 6.20 could be excluded already.

### 6.5 Results for \( A_{diff}(y) \)

We already concluded before that for the amount of data we use in this analysis the differential asymmetry \( A_{diff}(y) \) is not sufficiently sensitive to measure the Standard Model asymmetry since detector and selection effects distort the results. Moreover, we have showed that the uncertainty on the integrated asymmetry itself already is large. For completeness we show the results of the measured differential asymmetry in Figure 6.21.
Figure 6.20 – New physics models in 2-d plane of asymmetry measured at the Tevatron (forward-backward asymmetry, x-axis) and at the LHC (charge asymmetry, y-axis). Figure obtained from Ref. [93].

Table 6.4 – Expected uncertainty on the combined value of $A_{int}$, as a function of the integrated luminosity of the data set.

<table>
<thead>
<tr>
<th>Size of data set (fb$^{-1}$)</th>
<th>Expected stat. uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.040</td>
</tr>
<tr>
<td>2</td>
<td>0.027</td>
</tr>
<tr>
<td>5</td>
<td>0.017</td>
</tr>
<tr>
<td>10</td>
<td>0.012</td>
</tr>
</tbody>
</table>

For both the electron and muon channel it shows the background-subtracted data versus the simulation at two levels. A parabola with a positive quadratic term does not fit the shape of the distribution of data, neither for the electron channel, nor for the muon channel. The data agree with the detector level simulation, and a horizontal line through zero. At this precision, we observe no extreme values of the asymmetry that would give indications towards non-Standard Model effects.
Figure 6.21 – Asymmetry $A_{\text{diff}}(y)$ for data, compared to simulation at different levels, for electron (a) and muons (b). The error bars only reflect the statistical uncertainties and the uncertainty on simulation is not scaled to the integrated luminosity of data in this plot.
6.6 Summary

In this chapter we have measured the top quark charge asymmetry in a data set that corresponds to an integrated luminosity of 1.04 fb\(^{-1}\). We defined two parametrizations of the top quark charge asymmetry, and showed that the predicted asymmetry is present in the NLO event generator that we use to model \(t\bar{t}\) events. It can be visualized in both parametrizations. The charge asymmetry is also present in physics background that is produced in electroweak processes, particularly in \(W+\)jets and single top events this can be observed. After our event selection, the amount of background is reduced to sufficiently low levels, to assure that the uncertainty on the measured asymmetry due to background is minimized. Insufficient \(t\bar{t}\) events pass the selection criteria to be able to measure the top quark charge asymmetry as present in the Standard Model. To avoid potential detector asymmetries, and to be able to compare results with other experiments and future models, we applied an unfolding procedure. We finally measured a value of the integrated asymmetry compatible with measurements by the CMS and ATLAS collaborations. The differential asymmetry to which no detector corrections were applied, showed no anomalous behavior. The measurement of \(A_{\text{int}}\) cannot exclude any of the models proposed in papers that are compatible with the forward-backward asymmetry, as they are all in the range 0.0-0.1. The measurements show that with the increasing amount of data that are recorded, the exclusion of new physics models will quickly become possible.