Charged Current Interactions at HERA
Kruse, A.

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Chapter 7

Results

7.1 Charged Current Event Sample

The final event sample selected for the extraction of the charged current cross section contains 49 events. We have a Monte Carlo sample of 1275 events (corresponding to about 30 times the integrated luminosity of the data) which have been passed through the same selection procedure as the data. In the following some comparisons are made between data and Monte Carlo samples for the general event characteristics. Figure 7.1(a) shows the $R_t$ spectrum. Although statistics in the data is poor it is clear that both shape and normalization of the data distribution are well reproduced by the Monte Carlo. The effect of the $R_t$ cut is clearly visible at low missing $P_t$. Most events are concentrated near the low end of the spectrum, near the cut value, but several events are observed with $R_t$ in excess of 50 GeV.

The agreement between data and Monte Carlo holds true also for the distributions in $E_{tot}$, $(E_{tot} - P_z)$ and the hadronic angle $\gamma_{had}$. The comparisons are shown in Figure 7.1(b), (c) and (d) respectively. From the $\gamma_{had}$ distribution it is clear that most events have their hadronic activity concentrated in the forward direction. In fact only seven of the events have a hadronic angle larger than 90°. At small forward angles the effect of the beam pipe hole is clearly visible. All events have large total energies ranging from 50 GeV to over 300 GeV.

Figures 7.2 through 7.5 show event pictures of some typical events from the sample, shown with the ZEUS event display program LAZE [41]. The kinematic variables for those events are listed in table 7.1.

<table>
<thead>
<tr>
<th>Figure</th>
<th>$R_t$ (GeV)</th>
<th>$Q^2_{jb}$ (GeV$^2$)</th>
<th>$x_{jb}$</th>
<th>$y_{jb}$</th>
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<td>4983.0</td>
<td>0.181</td>
<td>0.304</td>
</tr>
</tbody>
</table>

Table 7.1: $R_t$, $Q^2_{jb}$, $x_{jb}$ and $y_{jb}$ for the events shown in figures figure 7.2 through 7.5.

In general the events in the final sample have characteristics which are in good agreement with the expectation we have for charged current scattering events.
We now turn to the reconstruction of the kinematic variables $x$ and $Q^2$ for the events in the final sample. As mentioned previously (see section 2.4) the absence of a measurable lepton in the final state in charged current scattering forces us to reconstruct the kinematics of the events from the hadronic system alone. Therefore the only reconstruction method available is that of the Jacquet-Blondel estimators:

$$y_{jb} = \frac{E_{tot} - P_z}{2 \times E_e}$$

$$Q^2_{jb} = \frac{P_t^2}{1 - y_{jb}}$$

$$x_{jb} = \frac{Q^2_{jb}}{4 \times E_e \times E_p \times y_{jb}}$$
7.1. CHARGED CURRENT EVENT SAMPLE

Figure 7.2: The charged current event shown has the highest $R_t$ in the sample. $R_t = 64.8$ GeV.

In our case the value of $(E_{\text{tot}} - P_z)$ is calculated from the energy deposits in the calorimeter and the angle of the center of the calorimeter cells with respect to the measured vertex, i.e.:

$$y_{jb} = \frac{1}{2 \cdot E_c} \sum_{\text{cell}} E_{\text{cell}} (1 - \cos \theta_{\text{cell}})$$  \hspace{1cm} (7.1)

$$P_x = \sum_{\text{cell}} E_{\text{cell}} \sin \theta_{\text{cell}} \cos \phi_{\text{cell}}$$  \hspace{1cm} (7.2)

$$P_y = \sum_{\text{cell}} E_{\text{cell}} \sin \theta_{\text{cell}} \sin \phi_{\text{cell}}$$  \hspace{1cm} (7.3)

$$P_t^2 = (P_x^2 + P_y^2)$$  \hspace{1cm} (7.4)

Figure 7.6 and figure 7.7 show the distribution in $x_{jb}$ and $Q_{z,b}^2$ of the final event sample and the selected Monte Carlo events respectively. The events are distributed at $Q^2$ values greater than 100 GeV$^2$ due to the $R_t$ cut required in the selection of the data. Shown by the dotted lines in the figure are the lines of constant $P_t = 9, 12, 15, 18$ GeV indicating the range over which the selection efficiency turns on. Also shown (dash dotted) is the line for $\gamma_{\text{had}} = 15^\circ$, where the effect of the beam pipe restricts our selection. The beam pipe hole does not result in a strict angle cut because it depends on the event topology, whether or not an event with $\gamma_{\text{had}}$ close to the cut leads to the rejection of the event. Finally the dashed line indicates the line $y = \frac{35}{2E_c}$. 
above which the \((E_{\text{tot}} - P_z)\) of the event would be greater than the cut of \(E_{\text{tot}} - P_z > 35\, \text{GeV}\).

### 7.2 Measurement of the Differential Cross Sections

To measure the differential cross sections we have divided the data in bins of \(x\) and in bins of \(Q^2\). The present statistics does not allow for the determination of the double differential cross section. The bins in \(Q^2\) have been chosen as indicated in table 7.2. The number of selected data events in the bins is also given. The bins have been chosen equidistant in \(\log Q^2\), in such a way that the statistics in each bin is acceptable and the widths are relatively large compared to the resolution in \(Q^2\). Figure 7.8 shows the distribution of the deviation of the reconstructed \(Q^2\) from the true value for each of the chosen bins for events in the selected sample of Monte Carlo events. The r.m.s. width of the distributions is also indicated in table 7.2. Figure 7.8 shows that even though the distributions are reasonably Gaussian and the r.m.s. is relatively small, the central value is shifted, indicating a reconstruction of \(Q^2\) which is systematically low. This is an effect of the energy loss in the hadronic system due to inactive material in the detector in front of the calorimeters. The relative bias is also given for each bin in table 7.2.

Table 7.3 gives the chosen bins in \(x\) together with the number of reconstructed events from the final data sample in each. Figure 7.9 shows the distributions for the deviation of reconstructed \(x\) from the true value again for the final selected Monte Carlo sample. Particularly in the higher
7.3 RECONSTRUCTION OF THE TRUE DISTRIBUTIONS

The reconstructed $x$ and $Q^2$ are biased and spread. Consequently one is forced to correct for this using the Monte Carlo. The method we use here is to calculate a transport matrix which quantifies the migration of events: It gives for all true bins the fraction of the events that end up in a certain bin of the measured distribution.

Figure 7.10 shows the transport matrix for $Q^2$. Obviously the inverse of this matrix, applied to the events in reconstructed bins gives the measured true number of events in the $Q^2$ bins. Table 7.2 gives the corrected number of events in bins of $Q^2$.

Figure 7.11 shows the transport matrix for $x$ which has been obtained in the same way as for $Q^2$. Table 7.3 gives the corrected number of events in the $x$ bins.
Figure 7.5: The charged current event shown has the lowest hadronic angle $\gamma_{\text{had}}$ in the sample: $\gamma_{\text{had}} = 18.2^\circ$.

7.4 Detector and Trigger Acceptance

The detector and trigger acceptance can be determined with the Monte Carlo data sample. The detector acceptance is defined as the fraction of generated events which pass the trigger and all selection cuts. The acceptance of the trigger and selection cuts is shown in figure 7.12 in bins of $Q^2$ and $x$ respectively.

For $Q^2$ the acceptance grows from $Q^2 = 100\text{ GeV}^2$ reaching a maximum acceptance of 60% at $Q^2 = 300\text{ GeV}^2$.

The acceptance loss of 40% is due to the loss of events at high $x$ due to the beam pipe hole.

In $x$ the acceptance starts at $x = 10^{-2.5}$ and rises to a maximum of 55% at $x = 10^{-1.5}$ falling again at large $x$ due to the beam pipe cut.

The measured distributions (see tables 7.2 and 7.3) need to be corrected for acceptance. This is done by multiplying each bin with the inverse of the acceptance measured for the Monte Carlo data sample. The final columns in tables 7.2 and 7.3 show the number of events corrected for acceptance together with the statistical error. The measured differential cross section is then determined by dividing the corrected number of events by the luminosity and the bin width. The point at which we quote the cross sections is determined as the mean value of $x$ and $Q^2$ from the Monte Carlo true distributions. Tables 7.4 and 7.5 give the differential cross sections as a function of $Q^2$ and $x$ respectively.
7.4. DETECTOR AND TRIGGER ACCEPTANCE

Figure 7.6: The distribution of the kinematic variables $Q^2$ versus $x$ for the selected data, calculated using the Jacquet-Blondel estimators. The lines indicate the effect of the major various selection cuts: $E_{tot} - P_z = 35 \text{ GeV}$ (dashed), $\gamma_{had} = 15^\circ$ (dash-dotted) and $R_t = 9, 12, 15, 18 \text{ GeV}$ (dotted). The solid line indicates the kinematical limit ($y = 1$).
Figure 7.7: The distribution of the kinematic variables $Q^2$ versus $x$ for the Monte Carlo data that passes the selection cuts, calculated using the Jacquet-Blondel estimators. The lines indicate the effect of the major various selection cuts: $E_{tot} - P_z = 35$ GeV (dashed), $\gamma_{had} = 15^\circ$ (dash-dotted) and $p_t = 9, 12, 15, 18$ GeV (dotted). The solid line indicates the kinematical limit ($y = 1$).
Figure 7.8: The distribution of the difference between the reconstructed kinematic variable $Q^2$ using the Jacquet-Blondel method and the generated value for the different bins in $Q^2$. The vertical lines indicate the size of the bin.

Figure 7.9: The distribution of the difference between the reconstructed kinematic variable $x$ using the Jacquet-Blondel method and the generated value for the different bins in $x$. The vertical lines indicate the size of the bin.
Figure 7.10: The migration of events from a higher $Q^2$ to a lower $Q^2$ because of detector effects: For events in a $Q^2_{\text{true}}$ bin the numbers in the column above show what percentage of those events is reconstructed in a $Q^2_{\text{measured}}$ bin. Only about 50% of the events remain in their bin. Towards the lower and higher ends of the histogram the statistics are poor and so the numbers inaccurate.

Figure 7.11: The migration of events in $x$ because of detector effects: For events in a $x_{\text{true}}$ bin the numbers in that bin show what percentage of those events is reconstructed in a $x_{\text{measured}}$ bin. Only about 50% of the events remain in their bin.
7.5. SYSTEMATIC ERRORS

Relevant systematic errors on the determination of the differential cross sections are the energy scale of the calorimeter, the error in the determination of the luminosity and the effects of the cuts employed in the extraction of the data sample.

7.5.1 Energy Scale

The ZEUS calorimeter has been calibrated in a test beam [19] and in situ with halo muons [42] and neutral current scattered positrons. The absolute scale is known to about 3%. In order to calculate the resulting systematic error the analysis was repeated with the energy in the Monte Carlo data sample increased and decreased by 3%. The difference in the resulting cross sections is only due to the change in absolute calibration and therefore a measure for the systematic uncertainty introduced. The systematic error due to the energy scale of UCAL varies from 2% in the lowest to about 30% in the highest bin in $Q^2$ and varies from 2% to 10% in $x$.

7.5.2 Luminosity

The ZEUS luminosity is known to 1% ([21, 22]). The resulting systematic uncertainty was calculated by changing the total luminosity by the error and taking the difference in the results.


Figure 7.12: The acceptance of the trigger and selection cuts for Monte Carlo events in bins of the measured $Q^2$ (a) and $x$ (b). Events have been generated with $Q^2 > 10\text{ GeV}^2$ but through the trigger cuts none of the events at low $Q^2$ is left in the sample.

as a measure for the systematic uncertainty. Since the resulting differential cross sections are inversely proportional to the luminosity the systematic error due to the uncertainty in the luminosity measurement is 1%.

7.5.3 Background from Non $e$-$p$-Collision Events

Beam gas and cosmic muon events are rejected by the online trigger system and in the offline selection through a series of algorithms and cuts which are described in chapter 5. From the vertex distribution and scanning of the events we concluded that there were no obvious non $e$-$p$ events left in the sample. We thus assign an upper limit of 1 event for the non $e$-$p$ background. This corresponds to about 2% of the sample, so we assign a systematic error of $-2\%$ to all bins.

7.5.4 Background from $e$-$p$ Events

Neutral current events are rejected by requiring $R_t > 9\text{ GeV}$ and $E_{tot} - P_z < 35\text{ GeV}$. Photoproduction events are rejected by requiring $R_t > 9\text{ GeV}$ and $\frac{P_t}{E_t} > 0.5$. It is not possible due to the low statistics to systematically study these backgrounds. We rely on the scanning of the events and find no events which are inconsistent with CC event topology except in the lowest $Q^2$-bin.

Here 5 events were found that were not clear background events but are not guaranteed CC-events either. One of these events is shown in figure 7.13. These events are all characterized by two muons in the final state. The momentum of the muon tracks is so large that the momentum measurement by the CTD leads to large errors and so it is not possible to calculate whether the muon momentum would balance the $R_t$ of the event and base a cut on that. Even though it is possible to clearly identify these events through scanning we do not want to use scanning as a means of rejecting events. The efficiency and purity of the scanning method can not be
7.6 Statistical Errors

The statistical uncertainty was calculated assuming that the distributions in each bin follow a Poisson statistic.

7.7 Results

Table 7.4 lists the differential cross section $\frac{d\sigma}{dQ^2}$ for $e^+p$ scattering together with the statistical and systematic error and in figure 7.14 the values are shown together with a theoretical calculation using the CTEQ4D parton densities. The results are in good agreement with the theoretical prediction. Also shown are the results for the differential cross section as measured by the H1
Figure 7.14: The differential cross section for $e^+p$ CC scattering $\frac{d\sigma}{dQ^2}$ versus $Q^2$. Also shown are the data obtained by H1 for the same running period. The outer error bar represents the total error which is the quadratic sum of the systematic error and statistical error given by the inner error bar. The curve shows the theoretical expectation based on the CTEQ4D parton densities.
collaboration [43]. Agreement is good. The H1 data do not extend as low in $Q^2$ as the present data due to a requirement of $p_T > 25$ GeV imposed in the analysis.

It is interesting to note that the total visible cross section for $Q^2 > 100$ GeV$^2$ is

$$\sigma_{CC}(Q^2 > 100 \text{ GeV}^2) = 19.0 \pm 2.72(\text{stat.}) + 0.19 - 2.48(\text{syst.}) \text{ pb}$$ (7.5)

after acceptance correction this becomes

$$\sigma_{CC}(Q^2 > 100 \text{ GeV}^2) = 37.4 \pm 5.36(\text{stat.}) + 0.38 - 4.92(\text{syst.}) \text{ pb}$$ (7.6)

The cross section extrapolation to $Q^2 > 1$ GeV$^2$ and $Q^2 > 10$ GeV$^2$ gives

$$\sigma_{CC}(Q^2 > 10 \text{ GeV}^2) = 42.4 \pm 6.08(\text{stat.}) + 0.43 - 5.58(\text{syst.}) \text{ pb}$$ (7.7)

$$\sigma_{CC}(Q^2 > 1 \text{ GeV}^2) = 43.0 \pm 6.2(\text{stat.}) + 0.44 - 5.66(\text{syst.}) \text{ pb}$$ (7.8)

using CTEQ4D. Given the acceptance of 50.4\% we have actually observed about half of all CC events that occurred in the running period.

In order to compare to the results obtained by the H1 collaboration [44] we have to use the same cuts, in particular $p_T > 25$ GeV. We then find 23 events, this results in a cross section of:

$$\sigma_{CC}(p_T > 25 \text{ GeV}) = 15.6 \pm 3.3(\text{stat.}) \text{ pb}$$ (7.9)

This is compatible with the result published by H1 in [44] for the same running period of

$$\sigma_{CC}(p_T > 25 \text{ GeV}) = 21.9 \pm 3.4(\text{stat.}) \pm 2.0(\text{syst}) \text{ pb}$$ (7.10)

and with the result published by H1 in [43] for the same running period of

$$\sigma_{CC}(p_T > 25 \text{ GeV}) = 23 \pm 3(\text{stat.}) \pm 2.0(\text{syst}) \text{ pb}$$ (7.11)

<table>
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<th>Bin (GeV$^2$)</th>
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<th># Evts.</th>
<th>$MC - Q^2$ (GeV$^2$)</th>
<th>$\frac{d\sigma}{dQ^2}$ (pb/GeV$^2$)</th>
<th>$\Delta \frac{d\sigma}{dQ^2}$ stat.</th>
<th>$\Delta \frac{d\sigma}{dQ^2}$ sys.</th>
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Table 7.4: For every $Q^2$-bin the number of events observed, the acceptance, the number of events after acceptance correction, the average $Q^2$ of all Monte Carlo Events in this bin, the measured differential cross section $\frac{d\sigma}{dQ^2}$ and statistical and systematical errors.
Figure 7.15: The differential cross section for $e^+ p$ CC scattering $\frac{d\sigma}{dx}$ versus $x$. The outer error bar represents the total error which is the quadratic sum of the systematic error and statistical error given by the inner error bar. The full line shows the theoretical prediction based on the CTEQ4D parton densities, the dashed line the valence quark contribution, the dotted line the $(d+s)_{sea}$ quarks and the dash-dotted line the $(c+\bar{u})$ contribution.
### 7.8. SUMMARY

Table 7.5 lists the differential cross section in $x$ and figure 7.15 shows these values together with the theoretical expectation based on the CTEQ4D parton densities.

We can see that the results are in good agreement with the theoretical expectation for charged current scattering. In figure 7.14 we also show the decomposition of the charged current spectrum in valence, $d+s$ and $u+c$ sea quark densities. It is interesting to see that a substantial fraction of the cross section is due to scattering off the anti-quark sea. Future larger statistics samples may be able to separate the different components.

### 7.8 Summary

In conclusion we have extracted the charged current cross sections in deep inelastic $e^+p$-scattering. The distributions in $Q^2$ and $x$ show good agreement with the expected distributions indicating that the parton densities in the proton extracted from other processes are applicable to the CC-process. The proton structure is thus understood also in terms of its decomposition in different quark flavors.
Figure 7.15: The differential cross section for $e^+p \rightarrow \ell^+ \ell^- \pi^0$ versus $\sqrt{s}$ for $\ell^+ = e^{+}$, $\ell^- = \mu^{-}$ and $\ell^- = \tau^{-}$. The outer error bars represent the total error which is the quadrature sum of the systematic error and statistical error given by the inner error bars. The full line shows the theoretical prediction based on the CTEQ4D parton distribution. The dashed line is the quantum quark contribution, the dotted line the $[J \cdot q\mu]_{\mu}$ quark and the dash-dotted line the $(\sigma + \delta)$ contribution.