Charged Current Cross Section Measurement at HERA
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Chapter 5

Event Selection

In this chapter the selection of charged current deep inelastic scattering events will be discussed. The main characteristic of CC DIS events in the ZEUS detector is the absence of balancing transverse momentum in the calorimeter. The missing transverse momentum, $P_{T,\text{miss}}$, is carried by the final state neutrino which leaves the ZEUS detector undetected and is defined as

$$P_{T,\text{miss}}^2 = P_X^2 + P_Y^2 = \left( \sum_i E_i \sin \theta_i \cos \phi_i \right)^2 + \left( \sum_i E_i \sin \theta_i \sin \phi_i \right)^2$$

(5.1)

where the sum runs over all calorimeter cells, $E_i$ is the energy deposited in a calorimeter cell, $\theta_i$ is the polar angle at the $Z$ position of the primary vertex of the event, and $\phi_i$ is the azimuthal angle with respect to the beam axis. Other types of processes (both $e^-p$, and non-$e^-p$ interactions) can also have $P_{T,\text{miss}}$, and have the signature of a genuine CC DIS event. Due to the much higher event rates for some of these processes, the removal of these background events is an important issue in the charged current event selection procedure.

The same selection cuts were applied on both the $e^-p$ and the $e^+p$ data samples. A few additional cuts were necessary in the analyses of the $e^-p$ data sample in order to remove background of beam-gas events, which was much less severe in the $e^+p$ data sample.

5.1. Trigger and Preselection

The majority of interactions which leave a signal in the ZEUS detector are not $e^-p$ interactions. The total interaction rate is dominated by interactions of the proton beam with the residual gas in the beampipe, beam-gas interactions, with a rate in the order of 10–100 kHz whereas the rate for "interesting" $e^-p$ physics events is only a few Hertz. Section 2.3.6 gives a general description of the trigger layout used by the ZEUS detector. In this section, the specific
Chapter 5: Event Selection

charged current trigger filters will be discussed which led to the data sample used in the unfolding of the charged current cross sections.

5.1.1. First Level Trigger

The first level trigger, FLT, accepts an event as a charged current event when it passes at least one out of six different filters, trigger slots. In total 64 slots are defined at the FLT were the most important CC trigger slot is slot60. Its logic can be expressed as an OR of the following criteria:

- \( P_{T,\text{miss}}^{\text{FLT}} > 5 \text{ GeV} \) AND \( E_T^{\text{FLT}} > 5 \text{ GeV} \) AND \( N_{\text{good.trk}}^{\text{FLT}} \geq 1 \);
- \( P_{T,\text{miss}}^{\text{FLT}} > 8 \text{ GeV} \) AND \( N_{\text{trk}}^{\text{FLT}} \geq 1 \);
- \( E_T^{\text{FLT}} > 8 \text{ GeV} \) AND \( E_{\text{FCAL}(-2\text{ir})}^{\text{FLT}} \geq 10 \text{ GeV} \);

where \( P_{T,\text{miss}}^{\text{FLT}} \) and \( E_T^{\text{FLT}} \) are vector and scalar sums of the transverse energies deposited in the CAL cells, respectively, and \( E_{\text{FCAL}(-2\text{ir})}^{\text{FLT}} \) the total energy deposited in the FCAL. Both \( E_T^{\text{CAL}} \) and \( E_{\text{FCAL}(-2\text{ir})}^{\text{FLT}} \) are reconstructed without the energy deposited in the cells of the two inner rings of the FCAL. The \( P_{T,\text{miss}} \) in beam-gas interaction generally originates from energy deposits in the cells of the inner rings of the FCAL. Excluding these cells in the reconstruction of the detector observables allows for lower cut values, while maintaining a high selection efficiency for charged current events and keeping the trigger rates manageable by rejecting beam-gas events. \( N_{\text{trk}}^{\text{FLT}} \) is the total number of tracks in the CTD and \( N_{\text{good.trk}}^{\text{FLT}} \) is the number of CTD tracks at the FLT that point towards the nominal interaction point.

In addition to slot60, five other trigger slots were used to increase the charged current event selection efficiency:

41) \( E_T^{\text{FLT}} > 20 \text{ GeV} \);

42) \( N_{\text{good.trk}}^{\text{FLT}} \geq 1 \) AND \( E_{\text{CAL}}^{\text{FLT}} > 15 \text{ GeV} \) OR \( E_{\text{EMC}}^{\text{FLT}} > 10 \text{ GeV} \) OR \( E_{\text{BEMC}}^{\text{FLT}} > 3.4 \text{ GeV} \) OR \( E_{\text{REMC}}^{\text{FLT}} > 2 \text{ GeV} \);

43) \( E_T^{\text{FLT}} > 11.5 \text{ GeV} \) AND \( N_{\text{good.trk}}^{\text{FLT}} \geq 1 \);

44) \( E_{\text{BEMC}}^{\text{FLT}} > 4.8 \text{ GeV} \) AND \( E_{\text{REMC}}^{\text{FLT}} > 3.4 \text{ GeV} \) OR \( N_{\text{trk}}^{\text{FLT}} \geq 1 \);

61) \( P_{T,\text{miss}}^{\text{FLT}} > 3 \text{ GeV} \) AND \( E_{\text{FCAL}(-1\text{ir})}^{\text{FLT}} > 1.3 \text{ GeV} \) AND \( N_{\text{good.trk}}^{\text{FLT}} \geq 1 \);
where $E_{\text{EMC}}^{\text{FLT}}$, $E_{\text{BEMC}}^{\text{FLT}}$ and $E_{\text{REMC}}^{\text{FLT}}$ are the total energy deposited in the EMC cells of the CAL, BCAL and RCAL respectively, and $E_{\text{CAL}}^{\text{FLT}}$ the total energy deposited in the CAL. These trigger slots were also used in the determination of the charged current event selection efficiency of slot60 [74].

### 5.1.2. Second Level Trigger

At the second trigger level, SLT, calorimeter timing information is available. This information is used to apply additional cuts to reject cosmic muon events and beam-gas events. Charged current events were selected by the SLT through the EXO_SLT4 branch, which is defined as an AND of the following criteria:

- $|t_{\text{global}}| < 7\,\text{ns}$ OR $(N_{\text{trk}}^{\text{SLT}} \geq 1$ AND NOT CTDBeamGas); 
- NoOffBeamProton
- CC1 OR CC2 OR CC3 OR CC4;

where $t_{\text{global}}$ is the average CAL time and CTDBeamGas is a CTD-SLT flag indicating that the event is a beam-gas event [75]. All events were required to have a $t_{\text{global}}$ consistent with an $ep$ collision timing.

The NoOffBeamProton requirement was defined to remove a background originating from off-beam protons, due to bad beam conditions, entering the CAL at a specific position, and is defined as:

- $|P_{Y}^{\text{SLT}}| > 3\,\text{GeV}$ OR $P_{T,\text{miss}}^{\text{SLT}} > 15\,\text{GeV}$ OR $P_{T,\text{CAL}(-1\text{ir})}^{\text{SLT}} > 6\,\text{GeV}$ OR $P_{T,\text{miss}}^{\text{SLT}}/P_{Z}^{\text{SLT}} > 0.06$;

The CC1, CC2, CC3 and CC4 requirements are defined as:

CC1 = $P_{T,\text{miss}}^{\text{SLT}} > 6\,\text{GeV}$ AND $E_{T,\text{CAL}(-2\text{ir})}^{\text{SLT}} > 6\,\text{GeV}$ AND $N_{\text{good.trk}}^{\text{SLT}} \geq 1$;

CC2 = $P_{T,\text{miss}}^{\text{SLT}} > 9\,\text{GeV}$ AND $P_{T,\text{CAL}(-1\text{ir})}^{\text{SLT}} > 8\,\text{GeV}$ AND $E_{\text{FCAL}}^{\text{SLT}} > 20\,\text{GeV}$;

CC3 = $P_{T,\text{miss}}^{\text{SLT}} > 9\,\text{GeV}$ AND $\left(P_{T,\text{miss}}^{\text{SLT}}\right)^{2}/E_{T}^{\text{SLT}} > 2.31\,\text{GeV}$ AND $E_{\text{FCAL}}^{\text{SLT}} > 80\,\text{GeV}$;

CC4 = $E_{\text{SLT}}^{\text{SLT}} - P_{Z}^{\text{SLT}} > 6\,\text{GeV}$ AND $\left(P_{T,\text{miss}}^{\text{SLT}}\right)^{2}/E_{T}^{\text{SLT}} > 2.25\,\text{GeV}$ AND $N_{\text{good.trk}}^{\text{SLT}} \geq 1$;
where \( N_{\text{SLT}_{\text{good}}_{\text{trk}}} \) is the number of tracks fitted to a vertex. The \(-1\text{ir}\) \((-2\text{ir})\) subscript denotes that the energy deposited in the cells in the 1st (2nd) inner ring of the FCAL is not included in the reconstruction of the observables. All CAL variables used in the SLT were calculated assuming the interaction vertex at the nominal position.

### 5.1.3. Third Level Trigger

After the SLT decision the data of all detector components are passed to the Event Builder, EB, where the full event is reconstructed. The third level trigger, TLT, used the information from all detector components for its decision. Charged current events were selected by the TLT through the branches EX0_TLT2 or EX0_TLT6 which aim to trigger events with high-\(\gamma_0\) and low-\(\gamma_0\) (see Sect. 5.2) respectively. Both branches further removed cosmic muon events by requiring:

- \(|t_{\text{up}} - t_{\text{down}}| < 8\text{ ns}\);

where \( t_{\text{up}} \) and \( t_{\text{down}} \) are the event time obtained from the upper half and lower half of the CAL respectively. Generally cosmic muon events will have an earlier time in the upper half than in the lower half of the detector, since they traverse the detector from top to bottom. The additional criteria imposed by the EX0_TLT2 branch were:

- \( P_{T,\text{miss}}^{\text{TLT}} > 6\text{ GeV}\);
- \( N_{\text{good}_{\text{trk}}}^{\text{TLT}} \geq 1\);
- \( -60\text{ cm} < Z_{\text{vtx}}^{\text{TLT}} < 60\text{ cm}\);

where \( N_{\text{good}_{\text{trk}}}^{\text{TLT}} \) is the number of vertex fitted tracks with \( P_{T,\text{trk}}^{\text{vtx}} > 0.5\text{ GeV}\) and a distance of closest approach of the helix described by the original (not vertex fitted) track to the beam axis less than 1.5 cm. The additional criteria imposed by the EX0_TLT6 branch were:

- passed the EX0_SLT4 branch (see Sect. 5.1.2);
- \( P_{T,\text{miss}}^{\text{TLT}} > 8\text{ GeV}\);
- \( E_{\text{FCAL}}^{\text{TLT}} > 10\text{ GeV}\);
- NOT OffBeamProton;
5.1. Trigger and Preselection

where the OffBeamProton requirement is defined as:

- \( P_{T,\text{CAL}(-\text{ir})}^{\text{TTLT}} < 10 \text{ GeV and} \ P_{T,\text{miss}}^{\text{TTLT}} > 25 \text{ GeV and} \)
- \( P_{T,\text{miss}}^{\text{TTLT}}/E_{T}^{\text{TTLT}} < 0.7 \text{ and} \ E_{T}^{\text{TTLT}} - P_{T}^{\text{TTLT}} < 10 \text{ GeV and} \)
- \( P_{T,\text{miss}}^{\text{TTLT}}/P_{Z} < 0.08 \text{ and} \ |P_{Y}^{\text{TTLT}}| < 4 \text{ GeV}; \)

Events that passed all three trigger levels were written to Data Summary Tape, DST. Based on the trigger decisions the online data system categorises events and assigns a DST bit to each category. These bits are accessible when selecting ZEUS data from DST for an off-line analysis. DST bit 34 is reserved for events which passed the trigger criteria outlined above for CC events.

5.1.4. Preselection

For the analysis described in this thesis the ZES facility has been used for the preselection of CC DIS events from DST. The ZES facility is an object-oriented database using Objectivity [76] as the database management system. For each event a number of variables are stored as a tag, to provide a fast and flexible way of selecting events. Its efficient event selection method reduced considerably the number of candidate events passed to the off-line analysis. The following ZES selection criteria were used:

- \( P_{T,\text{miss}} > 7 \text{ GeV}; \)
- \( P_{T,\text{miss}}' > 7 \text{ GeV}, \) where \( P_{T,\text{miss}}' \) is the missing transverse momentum reconstructed without the information from the FCAL cells closest to the beamhole;
- \( P_{T,\text{miss},0}/\delta_{0} > 4.37 \text{ or} \ N_{\text{trk}} > 0, \) where \( P_{T,\text{miss},0} (\delta_{0}) \) is \( P_{T,\text{miss}} (\delta) \) calculated assuming the position of the event vertex at the nominal interaction point, \( \delta = \sum (E_{i} - E_{i} \cos \theta_{i}) = \sum (E_{i} - P_{Z})_{i}, \) where the sum runs over all calorimeter cells;
- \( E_{\text{BCAL}} < 6 \text{ GeV or} \ E_{\text{BHAC}}/E_{\text{BCAL}} < 0.95; \)

Figures 5.1(a)–(d) show the distributions of the four most important quantities used in the preselection of charged current events. Each figure shows the \( e^{+}p \) data and Monte Carlo distributions after all the preselection cuts have been applied except for the cut indicated by the vertical line. The Monte Carlo events in the plots were scaled to the luminosity of the data shown, which is a
Chapter 5: Event Selection

Figure 5.1. The four most important quantities used in the event preselection (see text): (a) the missing transverse momentum, $P_{T,\text{miss}}$; (b) the missing transverse momentum excluding the FCAL inner ring, $P'_{T,\text{miss}}$; (c) the number of tracks per event, $N_{\text{trk}}$; (d) the BHAC energy over the BCAL energy, $E_{\text{BHAC}}/E_{\text{BCAL}}$. The selection cuts applied are shown by the vertical lines in the figures.

fraction (2.66 pb$^{-1}$) of the full $e^+p$ data sample used in the analysis (60.9 pb$^{-1}$, See Sect. 2.4). The CC MC distribution shown in Fig. 5.1 is described in Sect. 3.2. It is clear from the figures that there is still a lot of background in the data sample since the preselection cuts were looser than the final charged
current selection cuts, though the amount of data to be analysed is reduced considerably. The same preselection was applied to the $e^-p$ event sample. In the next sections the selection criteria which led to the final CC DIS event sample will be discussed.

5.2. Event Vertex

Depending on the hadronic angle $\gamma_0$, the angle of the hadronic system calculated with the vertex at the nominal position, different methods were used to reconstruct the primary vertex of the event. For events with $\gamma_0 > 0.4$ rad (high-$\gamma_0$) the CTD was used; for events with $\gamma_0 < 0.4$ rad (low-$\gamma_0$) the vertex reconstruction by the CTD became unreliable and in stead the timing information of the FCAL was used to reconstruct the position of the primary vertex. The hadronic angle of the event, $\gamma_h$, is reconstructed by

$$\cos \gamma_h = \frac{P_{T,\text{miss}}^2 - \delta^2}{P_{T,\text{miss}}^2 + \delta^2},$$

where $\delta = \sum (E_i - E_i \cos \theta_i) = \sum (E - P_Z)_i$. 
Figures 5.2(a) and 5.2(b)\(^1\) show the \(Z\)-position of the vertex for low-\(\gamma_0\) and high-\(\gamma_0\) events separately. In this plot all charged current selection cuts are applied. The vertical lines indicate the event vertex threshold:

- \(-50 \text{ cm} < Z_{\text{vtx}} < 50 \text{ cm}.

Events with a vertex outside this range originate from interactions of the lepton beam with protons in the satellite bunches. The satellite bunches are formed by protons travelling in the neighbouring bucket of the accelerator radio frequency, RF. These events are genuine \(ep\) collisions but are nevertheless removed from the sample. The main reason to remove these events is that the acceptance of the CTD and the calorimeter is best understood for events occurring in the central region of the detector. Furthermore, the vertex determination is more precise in the central region. A minor aspect is that beam-gas events are randomly distributed in \(Z\) with the consequence that the fraction of beam-gas events is larger outside the main vertex peak.

### 5.3. Transverse Momentum and Kinematic Region

In charged current events the incoming lepton exchanges a \(W\) boson with one of the (anti)quarks in the proton and changes into a neutrino or antineutrino. The final state (anti)neutrino escaping the detector undetected causes missing transverse momentum, \(P_{T,\text{miss}}\). Figures 5.3(a)–(d) show the distributions of the missing transverse momentum for events with low-\(\gamma_0\) and high-\(\gamma_0\) separately. To select charged current events the following cuts on \(P_{T,\text{miss}}\) have been applied:

- \(P_{T,\text{miss}} > 12 \text{ GeV}\), for high-\(\gamma_0\) events;
- \(P_{T,\text{miss}} > 14 \text{ GeV}\), for low-\(\gamma_0\) \(e^+p\) events;
- \(P_{T,\text{miss}} > 25 \text{ GeV}\), for low-\(\gamma_0\) \(e^-p\) events.

Since for events with high-\(\gamma_0\) tracking is possible the cut on missing transverse momentum could be relaxed with respect to events with low-\(\gamma_0\). The cut value for low-\(\gamma_0\) \(e^-p\) events is larger than for low-\(\gamma_0\) \(e^+p\) events because the background from beam-gas was larger in the \(e^-p\) data sample. This background has been removed from the high-\(\gamma_0\) \(e^-p\) data sample with additional cuts which are described in Sect. 5.4.1.

\(^1\)The Monte Carlo distributions shown in the figures are described in Sect. 3.2. This is the case for all figures presented in this chapter, unless stated differently.
5.3. Transverse Momentum and Kinematic Region

Figure 5.3. The missing transverse momentum distributions for: (a), (c) events with low-$\gamma_0$ and; (b), (d) events with high-$\gamma_0$. The figures show the event distribution after the final CC selection without the cuts on $P_{T,\text{miss}}$, which are indicated by the vertical lines in the figures.

The transverse momentum of an event is related to $Q_{JB}^2$ by $Q_{JB}^2 = P_{T,\text{miss}}^2/(1 - y_{JB})$; in Fig. 5.20 and Fig. 5.21 this is shown by the lines in the distribution of $x$ versus $Q^2$ of the $e^-p$ and $e^+p$ events respectively. Due to this correlation, the applied cuts in $P_{T,\text{miss}}$, results in the following kinematic requirements:

- $Q_{JB}^2 > 200$ GeV;
- $y_{JB} < 0.9$. 

71
Figure 5.4. The missing transverse momentum reconstructed without the FCAL cells closest to the beamhole, $P_{T,\text{miss}}'$, for: (a), (c) events with low-$\gamma_0$ and; (b), (d) events with high-$\gamma_0$. The figures show the event distribution after the final CC selection without the cuts on $P_{T,\text{miss}}'$, which are indicated by the vertical lines in the figures.

The cut on $y_{JB}$ has been applied because of the poor resolution in $x_{JB}$ and $Q_{JB}^2$ for high $y_{JB}$ (see Sect. 4.2).
5.4. Beam-gas/pipe Background

Beam-gas events occur when protons in the proton bunch interact with residual gas molecules in the beampipe, whereas beampipe events occur when off-bunch protons interact with the wall of the beampipe. Beampipe events cause $P_{T,\text{miss}}$ in the detector, while beam-gas events generally do not cause $P_{T,\text{miss}}$ in the detector. However, since energy escapes through the beamhole, this could result in a $P_{T,\text{miss}}$ and due to the high occurrences of beam-gas/pipe events they form a severe background in the charged current event sample. Since beam-gas/pipe interactions have a similar signature in the ZEUS detector, the cuts described in this section removed both event types. Typically, beam-gas/pipe interactions show a lot of activity in the forward region of the detector. The $P_{T,\text{miss}}$ of these events originates mainly from energy deposits in the FCAL cells closest to the beamhole. Therefore, for each event the missing transverse momentum has been reconstructed without the information from the cells in the inner ring of the FCAL, cells which are closest to the beamhole, $P'_{T,\text{miss}}$, and the following cuts have been applied to remove the beam-gas/pipe events from the sample:

- $P'_{T,\text{miss}} > 10\,\text{GeV}$, for high-$\gamma_0$ events;
- $P'_{T,\text{miss}} > 12\,\text{GeV}$, for low-$\gamma_0$ $e^+p$ events;
- $P'_{T,\text{miss}} > 25\,\text{GeV}$, for low-$\gamma_0$ $e^-p$ events.

Figures 5.4(a)-(d) show the $P'_{T,\text{miss}}$ distributions for events with high-$\gamma_0$ and low-$\gamma_0$ separately. The cut values are indicated by the vertical lines.

Beam-gas/pipe events are hadron-hadron collisions with many particles in the final state. For high-$\gamma_0$ events a lot of activity in the CTD is expected. Figures 5.5(a) and 5.5(b) show the distribution of $N_{\text{trk}}$ versus $N_{\text{trk}}^{\text{good}}$ of measured and simulated $e^+p$ events respectively. $N_{\text{trk}}$ is the number of tracks in an event, and $N_{\text{trk}}^{\text{good}}$ is the number of vertex fitted tracks with additional quality criteria:

- $15^\circ < \theta_{\text{trk}}^{\text{vtx}} < 165^\circ$, where $\theta_{\text{trk}}^{\text{vtx}}$ is the polar angle with respect to the beam axis of the vertex fitted track. In this angular range the track passes at least 5 super-layers of the CTD;
- $P_{T,\text{trk}}^{\text{vtx}} > 0.2\,\text{GeV}$, where $P_{T,\text{trk}}^{\text{vtx}}$ is the transverse momentum of the track;
- $\text{DCA}_{\text{trk}}^{\text{vtx}} < 1.5\,\text{cm}$, where $\text{DCA}_{\text{trk}}^{\text{vtx}}$ is the distance of closest approach of the helix described by the original (not vertex fitted) track to the beam line.
Figure 5.5. Different representations of the tracking cut applied in the analysis: (a) the tracking cut for data and; (b) Monte Carlo; (c) \((N_{\text{trk}} - 20)/N_{\text{trk}}^{\text{good}} < 4\), see text. The figures show the event distribution after the final CC selection without the tracking cut. This cut is only applied for events with high-\(\gamma_0\).

The beam-gas/pipe events have many tracks but a relatively low number of good tracks, \(N_{\text{trk}}^{\text{good}}\). Using this property, these events were removed from the charged current event sample by the following selection threshold (see Fig. 5.5(c)):

- \((N_{\text{trk}} - 20)/N_{\text{trk}}^{\text{good}} < 4\);  

These cuts were sufficient to remove the beam-gas background from the \(e^+p\) event sample. Additional cuts were necessary to remove the beam-gas back-
5.4. Beam-gas/pipe Background

![Graphs showing distributions of Q^2 and P_{T,miss}](image)

Figure 5.6. Distribution of: (a) Q^2 and; (b) P_{T,miss} in the e^-p data with the e^+p charged current event selection applied. An excess of data events over MC events is observed.

ground from the e^-p event sample. They will be described in the next section.

5.4.1. Beam-gas Background in the 1998–1999 Data

After four years of running with positrons, and having the beam orbit completely optimised for that, HERA switched in 1998 to electron running. Although the beam conditions allowed ZEUS to take data, the beam-gas background was worse compared to the positron running. Figure 5.6 shows the Q^2 and P_{T,miss} distributions in the e^-p data with the e^+p charged current event selection applied. As can clearly be observed, there is an excess of data events over Monte Carlo events in the Q^2 range 600–2000 GeV and in the transverse momentum range of 22–32 GeV.

Due to the higher beam-gas interaction rate in the 98–99 e^-p data, beam-gas events overlap with "genuine" ep interactions. To study these events, the event sample was "enriched" with beam-gas events by the following looser cuts:

- P_{T,miss} > 8 GeV;
- P'_{T,miss} > 8 GeV;
- Q^2 > 50 GeV;
Chapter 5: Event Selection

Figure 5.7. Distribution of: (a) $Q^2$; (b) $P_{T,\text{miss}}$ and $N_{\text{trk}}$ versus $N_{\text{trk}}^{\text{good}}$ of; (c) data events and (d) Monte Carlo events in the $e^-p$ data with an enhanced beam-gas background. The solid lines in the two dimensional histograms shows the additional selection threshold for removing the beam-gas background in the $e^-p$ data.

- No tracking cuts as described in Sections 5.4 and 5.5.

A large enhancement of the excess of data events over MC events is observed in the $Q^2$ and $P_{T,\text{miss}}$ distribution shown in Figs. 5.7(a) and 5.7(b). Figures 5.7(c) and 5.7(d) show the distribution of $N_{\text{trk}}$ versus $N_{\text{trk}}^{\text{good}}$ of measured and simulated $e^-p$ events for the beam-gas "enriched" event sample in data and Monte Carlo.
5.5. Additional Selection Thresholds Based on Tracking

![Graphs of (a) $Q^2$ and (b) $P_{T,\text{miss}}$ distribution after all charged current event selection criteria were applied.]

Figure 5.8. Distribution of: (a) $Q^2$ and; (b) $P_{T,\text{miss}}$ in the $e^- p$ data after all charged current event selection criteria were applied.

The data distribution shows an excess of events with a large number of tracks and a relatively low number of good tracks over the Monte Carlo simulation. To remove these events the following cut, indicated by the solid lines in the figure, was applied:

- $N_{\text{trk}}^{\text{good}} > N_{\text{trk}} - 5$ OR $N_{\text{trk}}^{\text{good}} > 10$.

This cut removed the beam-gas background events in the $e^- p$ event sample for events with high-$\gamma_0$. Figure 5.8 shows the $Q^2$ and $P_{T,\text{miss}}$ distributions after all selection cuts have been applied. Since no tracking information is available for events with low-$\gamma_0$, the beam-gas events with low-$\gamma_0$ were removed by raising the $P_{T,\text{miss}}$ and $P_{T,\text{miss}}'$ selection threshold values as described in Sects. 5.3 and 5.4.

5.5. Additional Selection Thresholds Based on Tracking

In events with high-$\gamma_0$ the current jet is within the angular acceptance of the CTD. Hence tracks should be apparent in the event, and additional tracking requirements in the selection of charged current events were set:

- $N_{\text{trk}} > 0$;
- $N_{\text{trk}}^{\text{good}} > 0$;
where $N_{\text{trk}}$ is the total number of tracks in the event and $N_{\text{trk}}^{\text{good}}$ is described in Sect. 5.4. Figures 5.9(a) and 5.9(b) show the distributions of $N_{\text{trk}}$ and $N_{\text{trk}}^{\text{good}}$, respectively. In charged current events, the difference in azimuthal angle from the $P_T$ calculated with the calorimeter and the $P_T$ calculated from tracks, $|\phi| = \phi_{\text{trk}} - \phi_{P_T}$, should be very small, since they are highly correlated. This is not
5.6. Neutral Current Background

The case for events other than charged current interactions with $P_{T,\text{miss}}$, where the missing transverse momentum is due to particles leaving tracks in the CTD, but incompletely measured by the CAL (e.g. due to the super crack region). Figure 5.9(c) shows the distribution of $|\phi|$ for $P_{T,\text{miss}} < 20$ GeV and Fig. 5.9(d) shows it for $P_{T,\text{miss}} > 20$ GeV. The following cuts have been applied:

- $|\phi| < 0.5\,\text{rad}$, for $P_{T,\text{miss}} < 20$ GeV;
- $|\phi| < 2.0\,\text{rad}$, for $P_{T,\text{miss}} > 20$ GeV.

5.6. Neutral Current Background

Over a large range in $Q^2$ the neutral current, NC, $ep$ cross section is orders of magnitude larger than the charged current cross section. Usually NC events do not pass the cuts on missing transverse momentum, since the final state scattered electron\(^2\) balances the event in $P_T$, and $\delta = \sum (E - P_Z)_i = 55$ GeV. However, due to energy loss in the final state, e.g. fluctuations in the energy

\(^2\)Note that in this section the scattered electron can be replaced by the scattered positron.
Chapter 5: Event Selection

Figure 5.11. Distributions of two quantities used in the selection and rejection of neutral current events from the charged current event sample: (a) and (b) the energy of the electron, $E_{\text{elec}}$; (c) and (d) the ratio of the momentum of the track associated with the electron and the energy of the electron from the calorimeter, $p_{\text{elec}}^{\text{trk}}/E_{\text{elec}}$. Figures (a) and (c) show the distributions with an enhanced NC background by omitting all NC rejection cuts. Figures (b) and (d) show the distributions with the final CC selection without the NC rejection cuts shown in the figures by the vertical line. All figures show the combined $e^-p$ and $e^+p$ data samples.
5.6. Neutral Current Background

measurement, or mismeasurement of the energy of the scattered electron, NC events can have \( P_{T,\text{miss}} \). Notice that the rejection of NC events from the CC sample is based on the selection of NC events in the event sample. The main characteristic of a NC DIS event is the presence of a scattered electron. A scattered electron hitting the calorimeter deposits most of its energy in the electromagnetic part of the calorimeter and very little energy in the hadronic part. In addition, electrons have different shower profiles in the calorimeter than other particles. These features were used by a neural network, SINISTRA95 [77], to identify isolated electromagnetic clusters in the calorimeter as candidate scattered electrons in \( ep \) interactions. Events with a candidate scattered electron were tagged as candidate NC events when they satisfied the following conditions:

- \( P_{\text{elec}} > 0.9 \), where \( P_{\text{elec}} \) is the probability of the most likely electron candidate calculated by the neural network;
- \( E_{\text{elec}} > 4 \text{ GeV} \), where \( E_{\text{elec}} \) is the electron energy;
- \( E_{\text{cone}}^{\text{cone}} - E_{\text{elec}}^{\text{elec}} < 5 \text{ GeV} \), a criterion for the isolation of the electron; \( E_{\text{cone}}^{\text{cone}} \) is the energy contained in a cone with \( R = \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2} = 0.8 \) around the electron, excluding the energy of the electron itself;
- \( \theta_{\text{elec}} > 15^\circ \), to ensure that the electron is within the acceptance of the calorimeter.

Candidate neutral current events with the scattered electron in the rear direction outside the angular acceptance of the CTD, going towards the RCAL, were rejected from the event sample if they satisfied the following conditions:

- \( E_{T,\text{elec}} < 2 \text{ GeV} \), where \( E_{T,\text{elec}} \) is the transverse energy of the electron;
- \( P_{T,\text{miss}} < 30 \text{ GeV AND } \delta > 30 \text{ GeV} \).

For candidate NC events with the polar angle of the scattered electron within the angular acceptance of the CTD, a track was matched to the electromagnetic cluster of the electron by requiring:

- \( \text{DCA}^{\text{trk}}_{\text{elec}} < 15 \text{ cm} \), where \( \text{DCA}^{\text{trk}}_{\text{elec}} \) is the distance of closest approach between the track extrapolated to the CAL surface and the electron cluster centre;
- \( 15^\circ < \theta_{\text{elec}}^{\text{trk}} < 165^\circ \), track passed at least 5 super layers of the CTD;
Chapter 5: Event Selection

- $p_{\text{elec}}^{\text{trk}}/E_{\text{elec}} > 0.25$

Candidate NC events with the polar angle of the scattered electron within the angular acceptance of the CTD were rejected from the event sample if they satisfied the following conditions:

- a scattered electron with matching track was found;
- $P_{T,\text{miss}} < 30 \text{ GeV AND } \delta > 30 \text{ GeV}.$

Figures 5.10 and 5.11 show a number of quantities which were used in the selection and later rejection of NC events. It was not necessary to look for NC events with a scattered electron in the FCAL since the $Q^2$ of these events is very high and therefore the NC cross section, with a $Q^2$ dependence $\propto 1/Q^4$, is very low. All NC rejection cuts discussed in this section were applied to high-$\gamma_0$ events. For low-$\gamma_0$ events, it is easily shown that $\delta < 0.2P_T$ using Equation (5.2). Hence, for $P_{T,\text{miss}} < 30 \text{ GeV}$, $\delta$ must be less than 6 GeV. No NC events enter this region, and hence no cuts were required.

5.7. Photoproduction Background

In the case that a proton interacts with an almost real photon ($Q^2 \approx 0 \text{ GeV}^2$), one speaks of photoproduction ($\gamma p$) interactions. The photon with which the proton interacts originates from an incoming electron, which escapes the detector undetected through the beampipe. In resolved photoproduction one of the quarks in the photon interacts with one of the quarks in the proton, whereas in direct photoproduction the photon interacts directly with one of the quarks in the proton. Both types of photoproduction were treated in the same way, since they have an identical signature in the detector. In photoproduction events the $P_T$ of the event is balanced. So the $P_{T,\text{miss}}$ requirements described in Sect. 5.3 removed most photoproduction events from the CC sample. However, due to energy loss in the final state (e.g. fluctuations in the energy measurement for events with high $E_T$ or events with a jet going into the crack region), photoproduction events can have $P_{T,\text{miss}}$. The rejection of photoproduction events from the event sample was based on the energy distribution in the calorimeter. In photoproduction events the energy is usually less localised in the calorimeter, and the ratio $P_{T,\text{miss}}/E_T$ will be smaller than in the case of charged current events where the energy is more collimated in the direction of $P_T$. The background from photoproduction events decreases rapidly with increasing $Q^2$, and
5.7. Photoproduction Background

Figure 5.12. Distributions of $P_T/E_T$ for events with: (a) $P_{T,miss} < 20$ GeV; (b) $20 < P_{T,miss} < 30$ GeV; (c) $P_{T,miss} > 30$ GeV; (d) the charged current sample after all selection cuts are applied. Figures 5.12(a)–(c) show the $P_T/E_T$ distributions for events with high-$\gamma_0$, without any photoproduction rejection cuts applied. The vertical lines show the photoproduction rejection cuts. All figures show the combined $e^-p$ and $e^+p$ data samples.

therefore with increasing $P_{T,miss}$. Two different $P_{T,miss}/E_T$ selection cuts were applied:

- $P_{T,miss}/E_T > 0.55$, for $P_{T,miss} < 20$ GeV;
- $P_{T,miss}/E_T > 0.4$, for $20 < P_{T,miss} < 30$ GeV.
For $P_{T,\text{miss}} > 30 \text{ GeV}$ no $P_{T,\text{miss}}/E_T$ cut was applied since no photoproduction events enter this region. The selection cuts were applied only for events with high-$\gamma_0$. Figures 5.12(a)–5.12(d) show the $P_{T,\text{miss}}/E_T$ distributions for the different $P_{T,\text{miss}}$ regions.

In dijet photoproduction events missing transverse momentum can be caused by one of the particle jets going into a crack region in the calorimeter. In that case the direction of the $P_T$ is opposite the direction of the poorly measured jet. Tracks in these events point in the direction of the $P_T$, but also in the direction of the poorly measured jet. In CC events tracks point only in the direction of the $P_T$. This feature has been used to apply the following selection criteria for events with $P_{T,\text{miss}} < 20 \text{ GeV}$:

- $N_{trk}^{dn} < 2$;
- $\text{Imb}_{trk} = (N_{trk}^{up} - N_{trk}^{dn})/(N_{trk}^{up} + N_{trk}^{dn}) > 0.7$;

where $N_{trk}^{up}$ ($N_{trk}^{dn}$) is the number of tracks in the (opposite) direction of $P_T$. A track is in the (opposite) direction of $P_T$ when the azimuthal angle difference between the track and $P_T$ is less (greater) than 0.5 rad ($\pi - 0.5 \text{ rad}$). Figure 5.13 gives a schematic view of the regions in $(x, y)$ of $N_{trk}^{up}$, $N_{trk}^{dn}$ and the corresponding direction of $P_T$. 

Figure 5.13. Schematic view of the regions in $(x, y)$ of $N_{trk}^{up}$, $N_{trk}^{dn}$ (see text) and the corresponding direction of $P_T$. 

\[\]
5.8. Sparks

Not all background is caused by external sources, also malfunctioning of the detector can cause fake charged current events. Especially sparks in the calorimeter can give rise to large $P_{T,\text{miss}}$. Sparks occur when one of the photo-multiplier tubes, PMTs, in a calorimeter cell has a short, hence faking an energy deposit. However, in this case only one of the two PMTs of the cell has a high signal and the imbalance, $\text{Imb}_{\text{cell}} = (E_{\text{PMT}_1} - E_{\text{PMT}_2})/(E_{\text{PMT}_1} + E_{\text{PMT}_2})$, for these cells is very large. Comparing $P_{T,\text{miss}}$ with the missing transverse momentum calculated using only cells with $\text{Imb}_{\text{cell}} < 0.7$, yielded the following selection cut which removed events with sparks:

- $0.5 < P_{T,\text{miss}}^{\text{imb} < 0.7}/P_{T,\text{miss}} < 2$.

For events for which the $P_{T,\text{miss}}$ is caused by a spark in a cell of which one of the PMTs is malfunctioning, the imbalance can not be used. For these cells the malfunctioning PMT was ignored and the energy deposit measured by the functioning PMT was doubled and the imbalance of the cell was zero. To remove these events the following cut has been applied:

- $P_{T,\text{cell}}/P_{T,\text{miss}} < 0.5$;

where $P_{T,\text{cell}}$ is the $P_T$ of the cell with the highest $P_T$.

5.9. Cosmic and Halo Muon Background

The contamination of the charged current event sample with events containing cosmic or halo muons was considerable. Cosmic muons are muons produced in cosmic ray showers. Cosmic muons usually do not deposit their energy symmetrically in the detector, therefore producing $P_{T,\text{miss}}$, and consequently enter the CC sample.

Halo muons are muons produced in collisions between protons and residual gas in the beampipe or between protons in the halo of the beam with material upstream in the beampipe. The pions produced in the collisions will decay into muons and follow the beam trajectory in time with the proton bunch at some distance from the beampipe. Halo muons with enough energy can traverse the veto wall, the rear calorimeter, the barrel calorimeter and finally the forward calorimeter depositing a trail of energy. Hence, giving rise to a missing transverse momentum.
Figure 5.14. Distributions of: (a) the ratio of $P_{T,\text{miss}}$ reconstructed using cells with an imbalance less than 0.7 over $P_{T,\text{miss}}$; (b) ratio of $P_T$ of cells with highest $P_T$ over $P_{T,\text{miss}}$. The figures show the event distribution after the final CC selection without the cuts indicated by the vertical lines.

Muons act as minimum ionising particles in the ZEUS detector. Therefore, the characteristic of muon events is the observation of long and narrow energy deposits in the calorimeter, which corresponds to a straight line trajectory through the detector often in overlap with an $ep$ interaction or beam-gas interaction.

### 5.9.1. MUFFIN

The muon finder program MUFFIN [78, 79] searches for halo and cosmic muons in events which pass the charged current trigger selection. MUFFIN is especially suited to find events with a halo or cosmic muon overlapping with a genuine $ep$ interaction or beam-gas interaction. MUFFIN uses the fact that events containing a halo or cosmic muon, pass the CC trigger selection due to the energy deposits in the CAL of the traversing muon creating $P_{T,\text{miss}}$ in the events. Candidate muons are searched for by applying three-dimensional trajectory fits to the CAL clusters in an event. If a muon candidate is found, the CAL cells belonging to that candidate are removed, and the $P_{T,\text{miss}}$ of the event is recalculated. If the $P_{T,\text{miss}}$ is larger than 7 GeV, then the candidate muon is rejected as a halo or cosmic muon and other possible CAL cluster patterns are investigated. If, on
5.9. Cosmic and Halo Muon Background

Figure 5.15. The ZEUS event display, ZEVIS, showing a halo muon event in overlap with a beam-gas interaction. Shown are the $x-y$ projection (left side of the figure) and the $z-r$ projection of the event.

Figure 5.16. The ZEUS event display, ZEVIS, showing a cosmic muon event traversing the detector in overlap with a beam-gas interaction.
the other hand, the recalculated $P_{T,\text{miss}}$ is below 7 GeV a more precise line fit is performed and a series of parameters [78] are calculated for the event and the candidate muon trajectory. These parameters are then compared with a list of reference parameters characterising a halo or cosmic muon transversing the detector. If the candidate muon matches the characteristics of a halo or cosmic muon the event was discarded from the CC event sample.

Figures 5.15 and 5.16 show a halo and a cosmic muon event identified as such by MUFFIN from the data sample collected in 2000. Both events passed all CC DIS selection cuts.

5.9.2. Additional Muon Rejection

Additional cosmic muon rejection was required for events with a small angle of the hadronic system. Cosmic muons traversing the forward calorimeter can produce a large bremsstrahlung shower. Typically, those events lose a lot of energy in the HAC section of the FCAL and can contaminate the CC sample. The following cuts were applied to remove these events:

- $E_{\text{FEMC}}/E_{\text{FCAL}} > 0.1$;  
- $E_{\text{FHAC1}}/E_{\text{FCAL}} > 0.1$;  
- $E_{\text{FHAC2}}/E_{\text{FCAL}} < 0.4$.

In Figs. 5.17(a)–(c) these ratios are shown. Since these events have a small hadronic angle, the cuts were applied only in the low-$\gamma_0$ region. In addition the following rejection cut has been applied to remove events with a muon traversing the HAC section of the BCAL:

- $E_{\text{BHAC}}/E_{\text{BCAL}} < 0.9$

This cut has been applied only for events with at least 5 GeV in the BCAL.

Finally nine events containing cosmic or halo muons, which were not removed by the CC event selection or the muon rejection cuts, were rejected by a visual scan from the $e^-p$ data sample and 16 from the $e^+p$ data sample.

5.10. Summary

In this chapter the charged current event selection has been presented. Major background contributions from beam-gas interactions, photoproduction and
5.10. Summary

Figure 5.17. Four distributions of calorimeter quantities are shown: (a) $E_{\text{FEMC}}/E_{\text{FCAL}}$; (b) $E_{\text{FHAC1}}/E_{\text{FCAL}}$; (c) $E_{\text{FHAC2}}/E_{\text{FCAL}}$; (d) $E_{\text{BHAC}}/E_{\text{BCAL}}$ for $E_{\text{BCAL}} > 5$ GeV. The figures show the event distribution after the final CC selection without the cuts indicated by the vertical lines. The Figs. 5.17(a)–(c) show only the low-$\gamma_0$ region.

Cosmic/halo muons, were effectively removed. A summary of the effect of the charged current event selection on data and MC simulation is given in Table 5.1. In the $e^-p$ data a total of 627 data events were left after the charged current event selection compared with 630 Monte Carlo events. In the $e^+p$ data a total of 1456 data events and 1468 of Monte Carlo events were left after the event
Table 5.1. The result of the charged current DIS event selection on data and MC simulation. The second column shows the fraction of the expected number of $e^- p$ MC events after application of the selection shown in the first column. The third and fourth column show the number of $e^- p$ data events and the fraction of $e^- p$ data events after application of the selection shown in the first column, respectively. Column five to seven shows the same for the $e^+ p$ CC DIS selection.

<table>
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<th>data ($e^- p$)</th>
<th>MC ($e^+ p$)</th>
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<td>627</td>
<td>53.3</td>
<td>1456</td>
</tr>
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</table>

selection. The key distributions from which the kinematic variables were determined are presented in Figs. 5.18 and 5.19. The distributions of the various quantities are well reproduced by the Monte Carlo simulation. Figures 5.20 and 5.21 show the final $e^- p$ and $e^+ p$ CC events distributed in $(x, Q^2)$ phase space.
Figure 5.18. Comparison of the final $e^- p$ CC data sample (solid points) with the predictions from the sum of signal Monte Carlo and $e p$ background Monte Carlo (light shaded histogram). The $e p$ background Monte Carlo is shown as the dark shaded histogram. (a) the missing transverse momentum, $P_{T,\text{miss}}$; (b) $P_{T,\text{miss}}$ excluding the very forward cells, $P'_{T,\text{miss}}$; (c) $\delta = \sum (E - P_Z)$; (d) the ratio of missing transverse momentum to total transverse energy, $P_{T,\text{miss}}/E_T$; (e) $\gamma_h$; (f) the number of good tracks, $N_{\text{trk}}^{\text{good}}$; (g) the $Z$ position of the CTD vertex for the high-$\gamma_0$ sample and (h) the $Z$ position of the timing vertex for the low-$\gamma_0$ sample.
Figure 5.19. Comparison of the final $e^+p$ CC data sample (solid points) with the predictions from the sum of signal Monte Carlo and ep background Monte Carlo (light shaded histogram). The ep background Monte Carlo is shown as the dark shaded histogram. (a) the missing transverse momentum, $P_{T,\text{miss}}$; (b) $P_{T,\text{miss}}$ excluding the very forward cells, $P'_{T,\text{miss}}$; (c) $\delta = \sum(E - P_z)_i$; (d) the ratio of missing transverse momentum to total transverse energy, $P_{T,\text{miss}}/E_T$; (e) $\gamma_h$; (f) the number of good tracks, $N_{\text{trk}}^{\text{good}}$; (g) the Z position of the CTD vertex for the high-$\gamma_0$ sample and (h) the Z position of the timing vertex for the low-$\gamma_0$ sample.
Figure 5.20. Distribution of the final $e^- p$ CC DIS event sample in the ($x, Q^2$) phase space. The open circles represent the events reconstructed using the FCAL timing vertex ($\gamma_0 < 0.4$ rad). The dots represent the events reconstructed using the CTD tracking vertex ($\gamma_0 > 0.4$ rad). ISO lines for $\gamma_h = 0.1$ rad, $\gamma_h = 0.4$ rad, $P_T,\text{miss} = 12$ GeV, $P_T,\text{miss} = 14$ GeV and also for $y = 1$ are shown in the figure (note that the ISO lines for $\gamma_h$ are plotted and not for $\gamma_0$).
Figure 5.21. Distribution of the final $e^+p$ CC DIS event sample in the $(x, Q^2)$ phase space. The open circles represent the events reconstructed using the FCAL timing vertex ($\gamma_0 < 0.4 \text{ rad}$). The dots represent the events reconstructed using the CTD tracking vertex ($\gamma_0 > 0.4 \text{ rad}$). ISO lines for $\gamma_h = 0.1 \text{ rad}$, $\gamma_h = 0.4 \text{ rad}$, $P_{T,\text{miss}} = 12 \text{ GeV}$, $P_{T,\text{miss}} = 14 \text{ GeV}$ and also for $y = 1$ are shown in the figure (note that the ISO lines for $\gamma_h$ are plotted and not for $\gamma_0$).