Charged Current Interactions at HERA
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Chapter 5

Charged Current Event Selection

5.1 Introduction

Charged current scattering events are characterized by a substantial missing transverse momentum $P_T$, which is carried off by the undetected neutrino. This also causes the $(E_{tot} - P_z)$ of the event to be lower than the $2E_e$ which should be measured for fully contained events. Furthermore, the events should have characteristics consistent with the event having originated from the nominal interaction point.

The selection criteria are thus designed to extract events with the above characteristics. Some additional cuts are necessary to remove events which are caused by detector malfunctions. Moreover, cosmic ray muons, either alone or overlaying a bona fide $e$-$p$-interaction need to be rejected. Finally, cuts are needed to remove events which are due to resolution effects in $e$-$p$-interactions with large cross sections such as neutral current events with a poorly measured scattered positron and photoproduction events with imbalance caused by an incomplete measurement of the produced final state.

The event selection consists of an online trigger and an offline selection process. The main task of the online trigger system is to select events which are true high-$P_T$ positron-proton scattering events while the offline selection procedure selects from those events the charged current events.

In this chapter we will first describe the online trigger and then the offline selection procedure for charged current events.

5.2 The ZEUS Trigger and Data Acquisition System

The ZEUS trigger system consists of three trigger levels. Events are analyzed by a trigger level and if they pass certain trigger criteria they will be passed on to the next level. With increasing level the precision as well as the complexity of the algorithms applied to the data increases. Table 5.1 gives an overview over the different trigger levels.

5.2.1 First Level Trigger

The first level trigger (FLT) is a fully pipelined system implemented in hardware which analyses the data produced by the ZEUS detector at the HERA bunch crossing frequency of $10\text{MHz}$. The trigger logic and cuts are configured such that the rate of positive decisions is kept below...
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<table>
<thead>
<tr>
<th>Level</th>
<th>Input Rate</th>
<th>Output Rate</th>
<th>Quantities and Algorithms</th>
</tr>
</thead>
<tbody>
<tr>
<td>FLT</td>
<td>10 MHz</td>
<td>&lt; 1 kHz</td>
<td>coarse gain resolution and segmentation, massively parallel, dedicated hardware</td>
</tr>
<tr>
<td>SLT</td>
<td>&lt; 1 kHz</td>
<td>&lt; 100 Hz</td>
<td>full resolution and segmentation, massively parallel, software programmable algorithms</td>
</tr>
<tr>
<td>TLT</td>
<td>&lt; 100 Hz</td>
<td>&lt; 5 Hz</td>
<td>full resolution and segmentation, complex algorithms</td>
</tr>
</tbody>
</table>

Table 5.1: Comparison of ZEUS trigger levels.

1 kHz, the maximum input rate of the SLT. The FLT has the uncalibrated detector data only available in coarse gain resolution, and its algorithms can only calculate global event properties.

5.2.2 Second Level Trigger

The second level trigger system (SLT) has the full detector resolution and segmentation available but is a massively parallel system of transputers which operate each on a small region of the detector data and combine their results in a tree-like structure. Algorithms are implemented in software but only have limited access to the data of neighboring regions. This puts considerable constraints on the possible trigger algorithms. Moreover, it has to operate at 1 kHz, so only relatively simple calculations are possible. The SLT uses partly calibrated detector information and a simple tracking algorithm is available.

5.2.3 Third Level Trigger

The third level trigger system (TUT) uses the full detector resolution and segmentation. It consists of a farm of workstations which receive full events. The algorithms have access to all data and so the only limit on the complexity of the algorithms is given by the fact that the TUT has to operate at 100 Hz. The TUT uses partly calibrated data and full tracking information is available.

5.2.4 Reconstruction

The first three trigger levels reject events, while at a fourth “reconstruction” step the data are reconstructed with the latest calibration information. This reconstruction is performed on archived event data. The data are then made available for further analysis.

5.3 Trigger Selection of Charged Current Events

$R_y$ is calculated on all trigger levels and in the offline event selection programs. At the first level trigger the calculation is based on calorimeter trigger towers which each contain several calorimeter cells. The result is therefore less accurate than the calculation of $R_y$ at higher trigger levels where the full readout information is available. Moreover the calculation is based on uncalibrated detector information. The cut imposed is $R_y > 9$ GeV. Figure 5.1 shows the
distribution of $R_t$ for the Monte Carlo data sample with and without the FLT-cut as well as the ratio of both distributions, the turn on curve for the FLT: The FLT trigger turn on is quite slow, only at about 18 GeV is it fully efficient for charged current events.

Figure 5.1: Figure (a) shows the distribution of $R_t$ for the Monte Carlo data sample with $Q^2 > 10 \text{GeV}^2$ without any additional cuts (open histogram) and after the first level trigger cut which is based on $R_t$ (shaded histogram). The FLT uses calorimeter trigger towers which contain several calorimeter cells. Figure (b) shows the ratio of the distributions in figure (a), the turn on curve for this trigger.

The second and third level trigger calculation of $R_t$ is more accurate because here the full readout information and granularity of the UCAL are available.

The DST selection programs have the calibrated detector information available. Furthermore $R_t$ is calculated using the reconstructed vertex which yields the most accurate results possible.

Figure 5.2 shows the distribution of $R_t$ for random events triggered in the unpaired and open bunches before and after the first level trigger $R_t$ cut. There are many events at $R_t$ close to zero, which are due to empty triggers by the FLT. These events are rejected at the SLT.

5.4 Trigger Rejection of Non Positron-Proton Collision Events

Common to all ZEUS physics data analyses is the need for the rejection of events which stem from non positron-proton collisions. At a nominal HERA luminosity of $1.6 \times 10^{31} \text{cm}^{-2}\text{s}^{-1}$ the event rate due to deep inelastic positron-proton scattering is only about 10 Hz while the rate of background events is in the order of 100 kHz.

If the trigger $R_t > 9 \text{GeV}$ as described in section 5.3 were the only trigger used to identify charged current events a large number of background events present at HERA would be picked up.
Figure 5.2: The distribution of $R_t$ for events triggered in the unpaired proton bunches (a) and open bunches (b) without (open histogram) and with (hatched histogram) the first level trigger $R_t$-cut. The events at low $R_t$ stem from events for which the FLT has fired but no energy was recorded (empty triggers).

Figure 5.3: The distribution of $R_t$ for events triggered in the unpaired proton bunches (a) and open bunches (b) which pass the first level trigger, excluding the $R_t$-cut. The histograms indicate that for both beam-gas as well as cosmic muon events many events with $R_t > 9$ GeV occur.
To illustrate the problem the $R_y$ distribution of a random selection of events which have passed the first level trigger excluding the $R_y$ cut for unpaired proton and open bunches is shown in figure 5.3. Triggers in the open bunch are mostly due to cosmic muons traversing the detector, while the triggers in the unpaired proton bunch stem from proton beam-gas interactions. The histograms indicate that for both beam-gas and cosmic muon events many events with $R_y > 9$ GeV occur. From those histograms it is possible to give an estimate of the number of events which would pass the cut $R_y > 9$ GeV:

The data shown in figure 5.3 correspond to about 1/4 of the running period. They are events that have been randomly selected at the SLT with a pre-scale of 1%. This results in about $4 \times 10^6$ proton beam gas events and about $3 \times 10^6$ cosmic muon events in the data for this period.

The trigger system rejects most events which are inconsistent with positron-proton collisions. The various cuts are briefly described here.

5.4.1 Cuts based on Timing

Due to the short bunch length of the positron (0.83 cm) and proton beam bunches (8.5 cm) positron-proton interactions occur within a window of less than 1 ns around the time the bunch centers cross in the center of ZEUS. The detector timing is set for all sub-detectors such that for particles originating from the nominal interaction point a time of 0 ns is reconstructed.

Any event which occurs outside of ZEUS can therefore be recognized if a sub-detector reports an event time outside a window around 0 ns. This is illustrated in figure 5.4 for a beam-gas collision event.

Figure 5.4: Schematic 2D view of a beam gas event. Shown here is the beam pipe (horizontal parallel lines) and a part of the FCAL and RCAL (hatched structures). The nominal vertex is at $(0, 0)$. The particles originating from the beam-gas event that occurred behind the RCAL also hit FCAL. Since FCAL and RCAL are about 5 m apart the average time of FCAL and RCAL for such an event differs by about 15 ns.
A rejection cut on the event time is orthogonal to the cuts used to accept events for a physics analysis and does not introduce any bias. The online trigger system uses the information from the Vetowall, the C5 and UCAL to reject events based on timing.

Vetowall FLT Timing Cut

For the Vetowall detector (see section 3.2.4) a coincidence of two opposing plates within a short time window (±8 ns) is considered as a hit. When a hit occurs within a time window of ±8 ns centered at 25 ns before the bunch crossing time of the event the event is vetoed.

C5 FLT Timing Cut

For the C5 detector (see section 3.2.4) a hit requires coincidence of the two opposing scintillator plates within a short time window (±1 ns). An event is vetoed if the hit occurs within a time window of ±3 ns centered around 8 ns before the bunch crossing time. Any activity from an event occurring at the nominal interaction point would have a time later by 8 ns and the C5 timing resolution is 1 ns.

The C5 detector is also used to make fine adjustments of the ZEUS data acquisition system internal clock to the HERA clock. Since all sub-detectors have a known and fixed time offset to each other the only quantity to be determined is the exact time with respect to the ZEUS time at which the interactions occur inside ZEUS. This is done by measuring the average time at which the proton bunches pass the C5 detector, $T_{proton}$. This time is then corrected for the time of flight distance from the C5 detector to the nominal interaction point, resulting in a time offset. This offset is small, typically less than 1 ns. It is measured before data taking starts and used as a constant time offset by the ZEUS higher level triggers.

The C5 detector also determines $T_{electron}$, the average time at which the positron bunches pass the C5 detector. This value, together with $T_{proton}$ can be used to calculate the average location of the interaction point. This is used as an online check to ensure stable data taking conditions.

UCAL Beam-Gas Timing Cuts

Beam gas events which occur upstream of ZEUS and for which the UCAL is hit are rejected using the calorimeter timing. This is based on calculating an average event time in the UCAL regions and comparing the results to reference values.

In figure 5.5 the distribution is shown of the average time in RCAL, $T_{RCAL}$, as calculated by the UCAL SLT algorithm for a random selection of events which pass the first level trigger. Events are rejected if $|T_{RCAL}| > 8$ ns. Events are also rejected if $(T_{RCAL} - T_{RCAL}) > 8$ ns.

More timing cuts are implemented on the third level trigger system. Here the average event time is calculated with higher precision using an energy-weighting algorithm and tighter cuts are used. At the TLT the systematic time shift of the ZEUS detector with respect to the bunch crossing time which is calculated by the C5 detector (see section 3.2.4) is taken into account.

The TLT also uses the error on the time average to reject events (see section 3.2.2 for $\sigma(T)$). Time averages are calculated by the TLT as error weighted averages and both the average time and the error on that time measurement are used:

One of the cuts is based on the global event time $T_{global}$ which is an average over the time reported by all calorimeter channels. An event is rejected if $T_{global}$ is outside a window around
5.4. TRIGGER REJECTION OF NON POSITRON-PROTON COLLISION EVENTS

Figure 5.5: The distribution of the average RCAL time for events at the second trigger level. Events in the hatched area ($|T_{RCAL}| > 8$ ns) are rejected.

zero given by the maximum of 8 ns and $3\sigma(T_{global})$. This ensures that events with a poorly measured time average are still accepted. Table 5.2 list all timing cuts used at the TLT.

UCAL Cosmic Muon Timing Cut

Cosmic muons that traverse the ZEUS detector can cause high $R_\gamma$ to be measured by the calorimeter. Therefore these events are background to the charged current events. The rate of cosmic muons traversing the ZEUS detector is estimated to be about 20 Hz. This rate poses a significant problem in the ZEUS trigger system, so cosmic rejection is performed on both the second and third level trigger system.

A cosmic muon traversing BCAL can be recognized by calculating the average time in both the upper ($T_{up}$) and lower halves ($T_{down}$) of BCAL. For a cosmic muon, the time difference, given the dimensions of BCAL (see figure 3.2) is significant: If the muon traverses BCAL from top to bottom in the center, the average distance of the cells in the top to the bottom half is about 4 m which results in a time difference of about 12 ns.

The cut requires that there be no energy in either FCAL or RCAL and more than 1 GeV is deposited in both the upper and lower half of BCAL. Events are rejected if $|T_{up} - T_{down}| > 10$ ns. The cut is illustrated in figure 5.6.

Events are also rejected if $T_{FCAL} > 8$ ns, this rejects events where an out-of-time cosmic muon traverses the FCAL as well as events stemming from positron beam-gas collisions.

Table 5.2 lists the various timing cuts used on all trigger levels to reject events which have a time inconsistent with positron-proton collisions at the nominal interaction point.
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Figure 5.6: Schematic cross sectional view of BCAL. The average time in the upper and lower halves of BCAL can be used to identify a traversing cosmic muon.

<table>
<thead>
<tr>
<th>Trigger Level</th>
<th>Timing Cut</th>
<th>rejected event type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level-1</td>
<td>Vetowall timing cut.</td>
<td>beam-gas</td>
</tr>
<tr>
<td></td>
<td>C5 timing cut.</td>
<td>beam-gas</td>
</tr>
<tr>
<td>Level-2</td>
<td>veto if $</td>
<td>T_{RCAL}</td>
</tr>
<tr>
<td></td>
<td>or $</td>
<td>T_{FCAL} - T_{RCAL}</td>
</tr>
<tr>
<td></td>
<td>or $T_{FCAL} &gt; 8\text{ ns}$</td>
<td>beam-gas + cosmics</td>
</tr>
<tr>
<td>Level-3</td>
<td>veto if $</td>
<td>T_{RCAL}</td>
</tr>
<tr>
<td></td>
<td>or $</td>
<td>T_{FCAL}</td>
</tr>
<tr>
<td></td>
<td>$</td>
<td>T_{global}</td>
</tr>
</tbody>
</table>

Table 5.2: The table lists the various timing cuts used by the ZEUS trigger system.

5.4.2 Second Level Trigger Beam-Beampipe Wall Collision Rejection

At the SLT $R_\ell$ is calculated both with the first ring of calorimeter cells around the FCAL beam pipe hole and without. An additional cut is placed on $R_\ell$ without the first ring of calorimeter cells to reject beam-beampipe wall collision events. This class of events is described in more detail in section 5.5.6. This cut which is placed at 8 GeV only removes very few events of the CC Monte Carlo event sample (1\%) because of the higher $R_\ell$ cut at the FLT and SLT level (see section 5.3).

5.4.3 Second Level Trigger Empty Event Rejection

The FLT calorimeter trigger sometimes triggers even though no energy is recorded by the readout system. This is due to noise in the calorimeter-FLT electronics. On the second level trigger system these events are rejected because they fail the $R_\ell$-cut which is repeated here: $R_\ell > 9$ GeV.
5.4.4 Second Level Trigger Track Requirement

The rate of beam gas events is further reduced on the second level trigger by requiring that there be any charged track found by the first level trigger system. This requirement is not very different from requiring a vertex to be found by the offline track reconstruction program.

To find a vertex offline requires at least a single track to be found. The only difference is that the first level trigger tracking system is based on the Z-by-timing system rather than the more accurate FADC data used by the offline tracking reconstruction system.

5.4.5 SIT Calorimeter Spark Rejection

Photomultiplier sparks are caused by charge buildup between the base and the housing. A sudden discharge, a “spark”, leads to a large pulse seen by the analogue readout electronics and fakes the deposit of energy.

The fact that an event has triggered because of a spark that occurred in a photomultiplier can easily be detected because of the structure of the readout electronics. For every calorimeter cell two photomultipliers are used. If only one of them records a large energy while the other one does not a spark is the most likely cause of the energy deposit.

The first level trigger system can not detect or reject a spark event because it operates on analogue sums of the photomultiplier pulses of a super-tower, in general some 10 photomultipliers. The FLT is not capable of distinguishing between an energetic particle that hit the super-tower and a spark in one photomultiplier.

The second level trigger system however has access to the full readout information but only on a per-cell, not a per-photomultiplier basis. The algorithm is based on the fact that for the calculation of average event times, the number of individual channels with energy above 200 MeV is known. An event is rejected if the event was only triggered by the UCAL in the FLT and if there is only a single channel with energy above 200 MeV and the energy in each of the calorimeter sections, when the energy of the cell with the sparking photomultiplier is removed, is small. A more detailed description of the spark rejection at the SLT can be found in [34].

5.4.6 Second Level Trigger Summary

Figure 5.7 shows the distribution of $R_f$ for random events triggered in the unpaired and open bunches before and after the second level trigger cuts. The number of events in the open and unpaired bunches is reduced considerably.

5.4.7 TLT Cosmic and Halo Muon Rejection

At the third level trigger a more complicated muon finder algorithm is used [35]. Here a rough muon track reconstruction is performed and compared to central tracking detector tracks. Also, since for the muon traversing the calorimeter the time when it traversed a given cell can be measured, this is used to further improve the efficiency and purity.
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Figure 5.7: The distribution of $R_t$ for events which have passed the first level trigger cuts and were triggered in the unpaired proton bunches (a) and open bunches (b) without (open histogram) and with (hatched histogram) the second level trigger cuts.

Figure 5.8: The distribution of $R_t$ for events which have passed the first and second level trigger cuts and were triggered in the unpaired proton bunches (a) and open bunches (b) without (open histogram) and with (hatched histogram) the third level trigger cuts.
5.4.8 TLT Calorimeter Spark Rejection

The spark rejection strategy followed in the third level trigger system is to remove calorimeter cell data if the imbalance between the energies recorded by the two photomultipliers is too large: Test beam results show that for a particle hitting the calorimeter at any position and angle the cell imbalance which is defined as

\[
\left| \frac{E_L - E_R}{E_L + E_R} \right|, E_L (E_R) : \text{Energy recorded in left (right) channel} \tag{5.1}
\]

is smaller than 0.9. The third level trigger system simply omits all cells with an imbalance bigger than 0.9. This way, events with sparks are rejected.

5.4.9 Third Level Trigger Summary

Figure 5.8 shows the distribution of $R_f$ for random events triggered in the unpaired and open bunches before and after the third level trigger cuts. The number of events in the open and unpaired bunches is reduced considerably and only very few events are left. The data used for figure 5.8 are randomly selected and correspond only to a fraction of the running period. The data have to be scaled up by about $5 \times 10^4$ to reflect the true number of background events left in the sample.

5.4.10 Online Trigger Summary

In total 81540 events pass all trigger levels. Figure 5.9(a) shows a distribution of $R_f$ for the Monte Carlo event data without any cuts (open histogram) and after all trigger cuts (hatched histogram). Figure 5.9(b) shows the efficiency of the ZEUS online trigger system depending on $R_f$: The ZEUS trigger is about 90% efficient for charged current events with $R_f > 15 \text{ GeV}$. Figure 5.10 shows the $R_f$ spectrum for Monte Carlo and data events normalized to the same luminosity. Clearly there are still a lot of background events present in the data sample. These are rejected during the offline selection process to be discussed below.
Figure 5.9: Figure (a) shows the distribution of $P_t$ for the Monte Carlo data sample without any cuts (open histogram) and after the ZEUS online trigger cuts ($FLT$, $SLT$ and $TLT$). Figure (b) shows the turn on of the ZEUS trigger for charged current events: ZEUS is about 90% efficient for charged current events with $P_t > 15$ GeV.

Figure 5.10: The distribution of $P_t$ for the data after the trigger cuts ($FLT$, $SLT$ and $TLT$) (open histogram) and for Monte Carlo events (hatched histogram) normalized to the same luminosity. It is clear that there are still a lot of background events in the sample.
5.5 Offline Charged Current Event Selection

5.5.1 Introduction

The online trigger uses algorithms which are safe and suitable for a wide range of different physics event samples. It is for this reason that they can not reject all non $e-p$ background, as can be seen in figures 5.8 and 5.10. Further rejection is needed. All cuts are described in the following subsections in the order they are applied to the data.

5.5.2 Detector Effects

For a successful analysis the ZEUS sub-detectors whose data are used in the analysis have to work properly. This is determined by data quality monitoring, a procedure in which the detector response to normal or special test events is monitored and compared to expectations. As output a list of data taking runs is produced for which the detector behaved as expected. Only these runs are used in the analysis. The runs accepted correspond to a total luminosity of $2.573\text{ pb}^{-1}$, i.e. 78% of the total.

5.5.3 Calorimeter Noise and Readout Holes

The ZEUS calorimeter readout system has been designed and developed such that the effect of electronics noise is minimized, but electronics noise exists and can cause large $R_y$. Data taking periods during which the calorimeter electronics noise caused cells to pass the offline threshold cuts are excluded for this analysis.

The UCAL readout system possesses two independent readout channels for a single cell. Thus the number of “dead” cells is kept very small. Data taking periods during which a readout cell in the EMC section of the calorimeter was inoperational, i.e. with both channels of the same cell dead, are excluded for this analysis. This is done in order to reduce the possibility for a neutral current event to fake a charged current event when the scattered positron hits this dead cell.

5.5.4 Vertex Requirement

The calculation of the event kinematics requires that for the events a vertex has been reconstructed. This is the first cut applied to the event data which also removes beam-gas and cosmic muon events. The total number of events excluded by this cut is 76252 events and 5288 events remain in the sample.

5.5.5 Calorimeter Sparks

Events due to UCAL sparks are rejected on the second and third level trigger through special algorithms (see section 5.4.6 and section 5.4.8) which are safe for all types of physics events that occur at HERA. Consequently the rejection is not fully efficient. Moreover the trigger system does not take into account channels which are switched off because of a malfunction. For such a channel the imbalance (see (5.1)) is zero and so the cell (and therefore the event) is not rejected. Since the energy of the other channel is unknown it is not safe to simply assume the energy in the other channel is zero and thus the imbalance 1 because this would simply remove all cells with one dead channel. For the charged current analysis it is useful to consider why a spark event enters the charged current event sample: It is because the spark channel increases the $R_y$.
of the event. The spark events where the spark occurred in a cell with one disabled readout channel can therefore be found with the following algorithm: First the cell with maximum $R_V$ is identified. If the cell imbalance (see section 5.4.8) is bigger than 0.7 or if one of the channels is disabled and the event would have $R_V < 9$ GeV (the trigger cut) if that cell was removed, the event is rejected.

Figure 5.11 shows the $R_V$ distribution for all events that have passed the cuts described so far if the spark cell is removed. The events at $R_V < 9$ GeV are rejected.

![Figure 5.11: The figure shows the $R_V$ distribution for all events that have passed the cuts described so far if the spark cell is removed. The events at $R_V < 9$ GeV are rejected.](image)

Through this cut 3518 events are rejected and 1770 events remain in the sample.
5.5.6 Proton Beam Wall Collisions

Off-axis protons from the proton beam can collide anywhere in HERA with the beam pipe or other objects. Due to the final bend and focus of the machine magnets before the intersection region it is possible that these interactions take place at such a position that they cause energy deposits which pass all timing cuts and pass the trigger rejection cuts.

Events stemming from beam-wall collisions constitute a particularly difficult background because the vertex of such collisions is not near the center of the beam pipe but displaced at the beam-pipe wall. As a result particles which would disappear down the forward beam pipe hole for a beam-gas event can now hit the detector and fake large $R_y$. This is illustrated in a schematic view in figure 5.12. Also an off-axis proton intrinsically has non negligible $R_y$.

![Figure 5.12: Schematic view of a beam wall collision event. Shown is the beam pipe (parallel lines) with the nominal beam trajectory (dotted line) and a part of the FCAL (hatched structures). The vertex is displaced in X-direction by the radius of the beam pipe. As a result the calorimeter measures a $P_x$, much higher than the true $P_x$.](image)

The second and higher level triggers reject a large fraction of these events by calculating $R_y$ without the first ring of calorimeter cells around the FCAL beam pipe hole and requiring that this value be bigger than 8 GeV. However, a small fraction of events still passes this criterion.

This can be seen when the transverse momentum in the $X$ and $Y$ direction is plotted. In figure 5.13 the distribution $P_y$ versus $P_x$ for all events that pass all cuts described so far is shown. The distribution should be symmetric around $(0,0)$ but a clear enhancement is visible around $P_x = -20$ GeV and $P_y = 0$ GeV i.e. in the plane of the HERA machine.

The fact that this enhancement is due to off-axis protons colliding with the beam pipe can be shown using the event vertex. The vertex reconstruction normally uses a pseudo beam particle at $(x, y, z) = (0, 0, undefined)$. For the primary vertex finding all tracks that are incompatible with this "pseudo beam particle" are discarded. This method improves the reconstruction of the primary vertex position in particular for events with very few charged particle tracks but introduces a bias for events with primary event vertex not near the beam axis.

In figure 5.14 (a) the vertex position in the $X - Y$ plane is shown when the vertex reconstruction is run without this "pseudo beam particle".

Most events have the primary vertex still in the center but now there is a clear enhance-
Figure 5.13: $P_y$ vs. $P_x$ for all events passing the cuts described so far. The plot only contains events with $R_t < 40 \text{GeV}$. The enhancement of events at negative $P_x$ and moderate $P_y$ is due to collisions of off-axis protons with the beam pipe.

Figure 5.14: Vertex position in the $X - Y$ plane for all data events (figure (a)) and Monte Carlo events (figure (b)) passing the cuts described so far. The vertex reconstruction is performed without a “pseudo beam particle”, thus allowing for vertices far away from the beam axis. In figure (a) an enhancement of the number of events can be observed near the beam pipe (The beam pipe is indicated by two circles.). The distribution for the Monte Carlo events (figure (b)) shows that the reconstructed vertex is not always close to the beam axis. It is therefore not possible to use the vertex position as a cut criterion.
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ment of events visible around $X = -10 \text{ cm}$ and $Y = 0 \text{ cm}$. In fact there is an enhancement of events along a circle with center at $X = -1 \text{ cm}$ and $Y = 0 \text{ cm}$ and radius of $9 \text{ cm}$. These are the coordinates of the inner beam pipe in ZEUS. The effect is clearly visible for all running periods.

The vertex calculated without the beam particle can not be used for rejecting beam wall events, however. In figure 5.14 (b) the vertex distribution is shown for charged current Monte Carlo events that pass all the cuts described so far. This distribution indicates that one should not use the vertexing to reject beam wall events. The problem stems from the topology of charged current events: Most charged current events are single jet events and for those almost all charged particles are scattered off within a narrow cone. For such a configuration the tracking resolution has to be very good to assure a good vertex resolution if the pseudo beam particle is not taken into account.

But for small scattering angles the track $Z$ resolution is rather poor because only few, if any, stereo layers are hit. This results in tracks that might cross each other far away from the beam axis. This problem can be solved if only the $X - Y$ information of the tracks is used. The resolution in this plane is much better. Clearly an event with a vertex on the beam axis will have most of its tracks passing very close to the beam axis. For a beam wall event only few tracks are close to the beam axis.

It is necessary to select tracks that fulfill certain quality requirements: For some beam wall events there are so many hits in the tracking chamber that many ghost tracks are constructed. The same is true for events with the primary vertex far away from the nominal interaction region.

Good tracks can be selected using the following requirements:

1. When the track is swum towards the UCAL it has to hit calorimeter cells with energy.
2. The track has to be well within the CTD: $45^\circ < \theta < 135^\circ$.
3. The track fit quality has to be good: $PROB(\chi^2, NDF) > 0.1$.
4. Track momentum $P > 0.1 \text{ GeV}$.
5. Radius of curvature of track $R > 20 \text{ cm}$.

Because of the homogeneous magnetic field inside ZEUS parallel to the beam axis a track can be approximated by a helix in three dimensions or a simple circle in the $X - Y$ plane. One of the parameters of the helix is the distance of closest approach $\rho_H$ of the helix to the beam axis as depicted in figure 5.15.

In figure 5.16 $\rho_H$ is shown for good tracks in charged current Monte Carlo and real data. Most of the tracks in the Monte Carlo event sample come closer than $0.5 \text{ cm}$ to the beam axis. For real data many tracks stay far away from the beam axis.

In figure 5.17 the ratio of good tracks that are closer than $0.5 \text{ cm}$ to the beam axis over the total number of good tracks is shown for charged current Monte Carlo data and real data.

Events with a ratio bigger than 0.4 are kept. Figure 5.18 shows the distribution $P_y$ versus $P_x$ for all events which pass the cut described above. The enhancement visible in figure 5.13 has disappeared.

Through this cut 1077 events are rejected and 693 events remain.
Figure 5.15: A track in the central tracking detector can be approximated by a helix in three dimensions or a circle in the $X - Y$ plane as shown in this figure. Shown is also one of the parameters of the helix, $\rho_H$, the distance of closest approach to the beam axis.

Figure 5.16: Closest approach of the track helix to the beam axis for all "good tracks" in charged current Monte Carlo events (a) and real data (b). For charged current Monte Carlo events most tracks come very close to the beam axis while for real data many tracks stay far away from the beam axis.
Figure 5.17: Ratio of number of good tracks that come closer than 1 cm to the beam axis over the total number of good tracks for Monte Carlo (a) and real data events (b). Events with a ratio bigger than 0.4 are kept.

Figure 5.18: $P_y$ vs. $P_x$ for all events after applying the beam wall collision cut described in the text. The enhancement of the number of events visible in figure 5.13 has disappeared.
5.6 Offline Cosmic and Halo Muon Rejection

The muon rejection algorithms employed on the trigger level reject most of the events in which a traversing muon is the only particle detected by the ZEUS detector. However, there are events in which the traversal of a cosmic or halo muon coincides with a beam-gas background or even genuine positron proton collision event. The probability for this to happen is not small: Given the bunch crossing rate of 10 MHz and assuming that the detector is hit by a beam related event at a rate of 150 kHz and by a cosmic at a rate of 20 Hz this leads to a rate of overlap events of 0.3 Hz.

The event sample which has passed all the cuts described so far does not contain that many overlap events. The reason is that the probability for these events to have high \( R_Y \) is small: Given the mean energy loss of a minimum ionizing particle in the UCAL \( \frac{dE}{dx} = 20 \frac{MeV}{cm} \) a muon that traverses 1 m of material would only deposit 2 GeV of energy. A halo muon which traverses the entire length of the calorimeter of 7.6771 m can deposit about 15 GeV and can then indeed cause \( R_Y > 9 \) GeV. However, cosmics at very high momentum pose a problem because bremsstrahlung can cause large \( R_Y \).

A sophisticated muon finder algorithm which is described in detail in chapter 6 is used to reject the cosmic and halo muon events remaining in the event sample.

Through this cut 489 events are rejected and 204 events remain. After this cut no events remain in the unpaired bunches. This indicates that the background due to non-e-p collisions is small.
5.7 Vertex Cut

Events that survive the cuts so far have a reliable vertex determination. In figure 5.19 the vertex distribution is shown for the events which have passed all the cuts described so far together with Monte Carlo events normalized to the total number of events. The vertex distributions agree. The data show a large peak around the nominal interaction point and another peak close to 70 cm due to the proton satellite bunch. There are a few events with large \(|z|\) which are probably due to remaining non-\(e-p\) background in the sample. To remove these events we select events if 

\[-25 \text{ cm} < Z_{vtx} < +30 \text{ cm} \]

![Vertex Distribution](image)

Figure 5.19: The open histogram shows the vertex distribution for the Monte Carlo data after applying all the cuts up to the vertex cut. The data are shown as points with statistical errors. The Monte Carlo data are normalized to the number of data events.

Through this cut 25 events are rejected and 179 events remain. Scanning of the remaining events shows that no obvious non-\(e-p\) events are left in the sample.
5.8 Background from Neutral Current Events

The occurrence of neutral current events in the sample can be demonstrated by the $(E_{tot} - P_z)$-distribution in figure 5.20. The entries in the peak around 50 GeV correspond to neutral current events while the peak at low $(E_{tot} - P_z)$ corresponds to charged current and photo-production events.

Neutral current events can fake large $P_t$ for several reasons:

- High momentum particles of the proton remnant jet can escape through the beam pipe hole, carrying substantial $P_t$. Most of the NC-background events are in fact of this type and they cause the peak around 50 GeV in figure 5.20. For these events $(E_{tot} - P_z)$ is well measured because the escaped particle carried only little $(E_{tot} - P_z)$.

- The energy of the scattered positron might not be measured correctly because the positron enters the calorimeter in a crack between modules, because the scattered positron might hit an inactive region of the calorimeter (for example the chimney region in the RCAL) or because the scattered positron might hit the region between BCAL and RCAL or BCAL and FCAL.

- The struck quark jet energy might be measured inaccurately.

- Final state muon or neutrinos from the struck quark jet can escape the detector.

Neutral current events are removed from the sample by requiring that $E_{tot} - P_z < 35$ GeV. Through this cut 87 events are rejected and 92 remain.

```
(Figure 5.20: $(E_{tot} - P_z)$ for the events which pass all the cuts so far for data (upper histogram) and Monte Carlo (lower histogram). The entries in the peak around 50 GeV correspond to neutral current events while the entries at lower $(E_{tot} - P_z)$ correspond to charged current and photoproduction events.)
```
5.9 Background from Photoproduction Events

The occurrence of photoproduction background events in the sample can be shown with the luminosity monitor. In figure 5.21 the $P_t$ distribution of the events remaining in the sample are shown. Of these 11 events are tagged by the luminosity monitor positron tagger as genuine photoproduction events. These are shown as a hatched histogram. We tag an event as photoproduction if $(E_{tot} - P_z)$ of that event, together with the energy detected in the luminosity monitor positron tagger (see section 3.2.5) is close to $2E_e$:

$$40\text{GeV} < E_{tot} - P_z + 2E_{LumiETagger} < 70\text{GeV}$$ (5.2)

and no accompanying $\gamma$ in the photon tagger is observed which excludes that these events stem from overlay of bremsstrahlung with another event. However, only about 20% of the photoproduction events have a positron tagged by the positron tagger because of acceptance, so it is not possible to use the above condition to remove photoproduction background.

The background can be shown more clearly using the distribution in the variable $P_{E_t}$. Figure 5.22(a) shows the distribution of $P_{E_t}$ for the data events which have passed the cuts described so far with the hatched histogram showing the same variable for tagged photoproduction events. Charged current events have $P_{E_t} > 0.5$ as seen in figure 5.22 (b) which shows the distribution for the Monte Carlo events.

The events due to photoproduction are therefore to be found at low $P_{E_t}$: We find 43 events with $P_{E_t} < 0.5$. The 11 tagged events would be equivalent to $55 \pm 15$ in total which is consistent with the measurement of 43 events.

Through this cut 43 events are rejected and 49 events remain.
Figure 5.21: \( R_t \) for the data events remaining in the sample. The hatched histogram shows of those events the ones for which \( 40 \text{ GeV} < E_{\text{tot}} - P_z + 2E_{\text{LumiElTagger}} < 70 \text{ GeV} \), they correspond to photoproduction events.

Figure 5.22: The distribution of \( \frac{P_t}{E_t} \) for events that have passed the selection cuts described in section 5 for data (a) and Monte Carlo events (b). The hatched histogram in figure (a) shows tagged photoproduction events still in the data sample. Those events have been selected by requiring \( 40 \text{ GeV} < E_{\text{tot}} - P_z + 2E_{\text{LumiElTagger}} < 70 \text{ GeV} \).
5.10 Event Selection Summary

Table 5.3 gives a summary of the various selection steps required to select the final charged current event sample. It is interesting to note that for the Monte Carlo events the by far largest individual reason for loss of acceptance stems from the FLT. This is not a surprise, however, considering that the Monte Carlo events have been generated starting at a very low $Q^2$ of 10 GeV$^2$. The $R_\gamma$ cut at the FLT corresponds to a cut at about 100 GeV$^2$ to 300 GeV$^2$.

<table>
<thead>
<tr>
<th>Trigger Level</th>
<th>MC % accepted of total</th>
<th>Data % accepted in this step</th>
<th>Data % accepted of total</th>
<th>Data # remaining</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level-1</td>
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<td>100.0</td>
<td>100.0</td>
<td>107560345</td>
</tr>
<tr>
<td>Level-2</td>
<td>63.2</td>
<td>2.1</td>
<td>2.1</td>
<td>2283932</td>
</tr>
<tr>
<td>Level-3</td>
<td>63.2</td>
<td>3.5</td>
<td>7.5 x 10^{-2}</td>
<td>81540</td>
</tr>
<tr>
<td>Vertex Req.</td>
<td>62.4</td>
<td>6.4</td>
<td>4.9 x 10^{-3}</td>
<td>5288</td>
</tr>
<tr>
<td>Spark</td>
<td>62.4</td>
<td>33.5</td>
<td>1.6 x 10^{-3}</td>
<td>1770</td>
</tr>
<tr>
<td>Beam-Wall</td>
<td>58.0</td>
<td>39.2</td>
<td>6.4 x 10^{-4}</td>
<td>693</td>
</tr>
<tr>
<td>Cosmic &amp; Halo</td>
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<td>29.4</td>
<td>1.9 x 10^{-4}</td>
<td>204</td>
</tr>
<tr>
<td>Vertex Cut</td>
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<td>87.7</td>
<td>1.7 x 10^{-4}</td>
<td>179</td>
</tr>
<tr>
<td>Neutral Current</td>
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<td>51.4</td>
<td>8.5 x 10^{-5}</td>
<td>92</td>
</tr>
<tr>
<td>Photoproduction</td>
<td>44.7</td>
<td>53.3</td>
<td>4.5 x 10^{-5}</td>
<td>49</td>
</tr>
</tbody>
</table>

Table 5.3: Acceptance of the different trigger and selection steps. Shown are only numbers for runs for which the detector was in a good state (see section 5.5.2).
Figure 5.3(a) shows the distribution of $p_T$ for events that have passed the selection cuts described in section 5.4 for data (a) and Monte Carlo events (b). The binned histograms in Figure 5.3(a) show the projected event acceptance in the data sample. These shapes have been obtained by using the formula $B_{_{\text{MC}}} = \frac{B_{_{\text{data}}}}{B_{_{\text{MC}}}}$.