Radiation hardness of the ZEUS MVD frontend chip
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Chapter 2
ZEUS and HERA

The Hadron Elektron Ring Anlage is a particle accelerator located in Hamburg, Germany. A schematic drawing is shown in figure 2.1. The accelerator has a circumference of 6.3 km. In the machine bunches of protons are accelerated to an energy of 920 GeV and bunches of electrons or positrons to an energy of 27.5 GeV. The beams are brought into collision at two points of the ring: inside the ZEUS and inside the H1 detector. The bunch spacing is 96 ns.

Figure 2.1: The HERA accelerator and its experiments.

Two other experiments are also located at the HERA ring: HERMES and HERA-B. The HERMES experiment measures the spin-structure of the nucleon and only uses the
electron/positron beam. The HERA-B experiment has been designed to measure CP-violation in the B-system. It only uses the proton beam.

The first electron-proton collision at HERA took place on the 19th of October 1991. The experiments started collecting data in June 1992. Since then the HERA accelerator delivered a total integrated luminosity of 27 pb$^{-1}$ running with electrons and 166 pb$^{-1}$ running with positrons. The ZEUS experiment collected 17 pb$^{-1}$ with electrons and 114.6 pb$^{-1}$ with positrons. A breakdown of the physics luminosity versus days of running for different years is shown in figure 2.2. During the data collection period, the energy of the electrons$^1$ has been increased from 26.7 GeV to 27.5 GeV and of the protons from 820 GeV to 920 GeV. In the beginning of 2001 the HERA machine has been shutdown for an upgrade. During the shutdown new magnets have been installed that can improve the focusing of the beam yielding larger instantaneous luminosity.

$^1$To avoid circumlocution electrons also means positrons unless denoted specifically.
2.1 Deep inelastic scattering

In electron-proton collisions a gauge boson can be exchanged between the electron and the proton. Depending on the type of boson the collision can be characterised as a neutral current, with $\gamma$ or $Z$ exchange, or as a charged current event, with a $W^\pm$ exchange. In figure 2.3 a "schematic drawing" of the two event-types is shown. An important difference between charged current and neutral current interactions is that in the latter the struck quark remains the same quark after the interaction, while in the former the outgoing quark is of a different type than the struck quark.

![Diagram of deep inelastic scattering](image)

Figure 2.3: Schematic view of a deep inelastic scattering event for neutral current interactions (a) and charged current interactions (b). A gauge boson, $\gamma$, $Z$ or $W^\pm$, is exchanged between the incoming proton, $P$, and electron, $e^\pm$, producing in the neutral current event a scattered electron, $e'$, and a struck quark, $q$ and in the charged current event a (anti)neutrino, $\nu$, and a struck quark, $q$.

2.1.1 Kinematics

In figure 2.4 a schematic view of a deep inelastic scattering event is shown. The interactions are usually described by three Lorentz-invariant variables. At HERA a proton with a four-momentum $p$ and an electron with four-momentum $k$ collide. In the interaction a gauge boson with virtuality $Q^2$

$$Q^2 \equiv -(k - k')^2 = -q^2 \quad (2.1)$$

is exchanged between the electron and the parton. After the interaction the electron (or neutrino) has a four-momentum $k'$. The fraction of the electron energy taken up by the
2.1. Deep inelastic scattering

**Figure 2.4:** Schematic view of a deep inelastic scattering event indicating the meaning of the kinematical variables.

The struck parton carries a fraction $x$ of the proton four-momentum

$$x = \frac{Q^2}{2q \cdot p} \quad (2.3)$$

The kinematic variables are related through

$$Q^2 = s x y \quad (2.4)$$

where $s$ is the centre of mass energy of the lepton-proton system. Because the energy and momentum of the proton and electron are very accurately known, the kinematic variables can be reconstructed just by measuring the angle and the energy of the scattered lepton. From equations (2.1), (2.2) and (2.3) it follows that

$$Q^2 = 2E_e E'_e (1 + \cos \theta) \quad (2.5)$$

$$y = 1 - \frac{E'_e}{2E_e} (1 - \cos \theta) \quad (2.6)$$

$$x = \frac{E_e}{P} \frac{E'_e (1 + \cos \theta)}{2E_e - E'_e (1 - \cos \theta)} \quad (2.7)$$

where $E_e$ is the electron energy, $E'_e$ the electron energy after scattering, $\theta$ the angle with respect the proton axis\(^2\) and $P$ the energy of the proton. The customarily used

\(^2\)The ZEUS coordinate system is a right-handed Cartesian system, with the z axis pointing in the proton beam direction, referred to as the “forward direction”, and the x axis pointing left towards the centre of HERA. The coordinate origin is at the nominal interaction point.
methods to reconstruct the kinematic variables from measured quantities will be described in section 8.3.1.

Neutral current scattering

For neutral current interactions, see figure 2.3(a), the dependence of the cross section on $x$ and $Q^2$ can be expressed as

$$\frac{d^2\sigma_{\text{NC}}^{\text{Born}}}{dx dQ^2} (e^+ p) = \frac{4\pi\alpha^2}{xQ^4} \left[ y^2 x F_1(x, Q^2) + (1 - y) F_2(x, Q^2) + y \left( 1 - \frac{y}{2} \right) x F_3(x, Q^2) \right]$$ (2.8)

where $F_i$ are the proton structure functions. In the naive parton model, where the quarks are massless, the quarks cannot interact with longitudinally polarised photons due to helicity conservation. Omitting this part of the cross section yields the Callan-Gross relation

$$2xF_1(x, Q^2) = F_2(x, Q^2)$$ (2.9)

and $F_2$ and $xF_3$ can be written as

$$F_2(x, Q^2) = \sum_q A_q(Q^2) \left( xq(x) + x\bar{q}(x) \right)$$ (2.10)

$$xF_3(x, Q^2) = \sum_q B_q(Q^2) \left( xq(x) - x\bar{q}(x) \right)$$ (2.11)

where $q(x)dx$ and $\bar{q}(x)dx$ are the probabilities of finding a quark or antiquark with a momentum fraction between $x$ and $x + dx$. The coefficients $A_q$ and $B_q$ describe the dependence on the different couplings.

$$A_q(Q^2) = e_q^2 + 2e_q e_v e_q v q \mathcal{P}(Q^2) + (v_q^2 + a_q^2) \left( v_q^2 + a_q^2 \right) \mathcal{P}^2(Q^2)$$ (2.12)

$$B_q(Q^2) = 2e_q a_v e_q v_q \mathcal{P}(Q^2) + 4v_q a_q e_q a_q \mathcal{P}^2(Q^2)$$ (2.13)

with

$$\mathcal{P}(Q^2) = \frac{1}{4\sin^2\theta_w \cos^2\theta_w} \frac{Q^2}{Q^2 + M_Z^2}$$ (2.14)

The first term in $A_q$ describes the photon exchange, the second term the interference between the photon and the $Z$ and the third term the $Z$ exchange. The used symbols are $e_{q,l}$ the electric charge of the fermion, $v_{q,l} = T_{3F} - 2e_l \sin^2\theta_w$ the vector coupling and $a_{q,l} = T_{3F}$ the axial coupling of the fermion expressed in the third component of the weak isospin $T_{3F}$ and the Weinberg angle $\theta_w$ and $M_Z$ the mass of the $Z$-boson.
2.1. Deep inelastic scattering

Charged current scattering

In charged current interactions, see figure 2.3(b), a $W^{\pm}$-boson is exchanged. The cross section dependence of $x$ and $Q^2$ can be expressed as

$$\frac{d^2\sigma_{CC}^{\text{Born}}}{dx dQ^2}(e^\pm p) = \frac{G_F^2}{4\pi x} \frac{M_W^4}{(Q^2 + M_W^2)^2} \left[(1 + (1 - y)^2)W_2^+(x, Q^2) \mp (1 - (1 - y)^2)W_3^+(x, Q^2)\right]$$

(2.15)

where $G_F$ is the Fermi constant, $M_W$ the mass of the $W$-boson and $W_i$ analogous to $F_i$.

$$W_2(x, Q^2) = \sum_q (xq(x) + x\bar{q}(x))$$

(2.16)

$$xW_3(x, Q^2) = \sum_q (xq(x) - x\bar{q}(x))$$

(2.17)

the $A_q$ and $B_q$ are already absorbed outside of the square brackets in equation 2.15. Due to charge conservation at the $qW$ vertex, several $q(x)$ and $\bar{q}(x)$ are zero. Thus, only certain combinations of quarks and antiquarks contribute to the cross section. Therefore, equation (2.15) can be rewritten as

$$\frac{d^2\sigma_{CC}^{\text{Born}}}{dx dQ^2}(e^+ p) = \frac{G_F^2}{2\pi x} \frac{M_W^4}{(Q^2 + M_W^2)^2} [(1 - y)^2(xd + xs) + x\bar{u} + x\bar{c}]$$

(2.18)

$$\frac{d^2\sigma_{CC}^{\text{Born}}}{dx dQ^2}(e^- p) = \frac{G_F^2}{2\pi x} \frac{M_W^4}{(Q^2 + M_W^2)^2} [(1 - y)^2(xd + xs) + xu + xc]$$

(2.19)

The cross section in charged current scattering is much smaller than for neutral current scattering until the value of $Q^2$ becomes of the same order as $M_W^2$, because the propagator in charged current carries a term $M_W^2/(Q^2 + M_W^2)^2$ while in neutral current this term for $\gamma$ exchange goes as $1/Q^4$.

The measurement of the structure of the proton is one of the main goals of the HERA program. The proton structure function $F_2$ was measured by the ZEUS collaboration in a very large kinematical range with very high precision[1, 2]. In figure 2.5 the part of $F_2$ originating purely from photon exchange is shown. Note the small error bars and the large kinematical range spanning 5 orders of magnitude in $x$ and $Q^2$.

3This does not mean that there are no $\bar{u}$ quarks in the proton when scattering with $e^-$, but just that the $\bar{u}$ do not contribute to the cross section.
Figure 2.5: $F_2$ as a function of $x$ and $Q^2$ measured by ZEUS. Also shown are the results from fixed target experiments. The line is the result of a ZEUS Next-to-Leading-Order QCD fit.
2.2 The ZEUS detector

A detailed description of the ZEUS detector can be found in [3]. A schematic drawing is shown in figure 2.6. Coming from the interaction region, particles first traverse the beampipe before entering a tracker placed in a magnetic field. Charged particles are tracked using the wire chamber detectors: the central (CTD), the forward (FDET) and the rear tracking detector (RTD). Here the momentum of the tracks is measured and using the tracks the vertices are reconstructed. The vertex detector (VXD) indicated on the picture was taken out before the 1996 running and was replaced by the MicroVertex Detector (MVD) in the shutdown of 2001. A superconducting magnet provides a solenoidal magnetic field of 1.43 T. The tracking detectors are surrounded by a high resolution uranium-scintillator calorimeter, split in a forward part (FCAL), barrel part (BCAL) and rear part (RCAL). The calorimeter is again surrounded by a backing calorimeter (BAC). The active part of the BAC is a gaseous detector used to measure the energy of particles or jets that are not completely absorbed in the CAL. Particles like high-energy muons are not even stopped by the BAC. They are detected using the muon chambers (BMUO, FMUO, RMUO). These chambers are also used to trigger on cosmes.

2.2.1 The Calorimeter

The sampling calorimeter consists of layers depleted uranium interleaved with scintillators, see figure 2.7. Particles entering the calorimeter lose energy due to interactions with the material and produce showers of particles. The energy of the shower is proportional to the amount of light measured with the scintillators.

For photons, electrons and positrons bremsstrahlung and electron pair production are the dominant energy loss processes. The hadronic showering process is dominated by inelastic hadronic interactions. When using a material with a large cross section for pair production, a high Z material, the electromagnetic showers can be contained in only a few layers. The hadronic showers will extend over larger depth.

High-energetic muons can traverse the calorimeter completely. The deposited energy is then spread evenly over the entire depth. These muons are also recognised by activity in the backing calorimeter and the muon chambers.

The energy resolution of the calorimeter for single particles is \( \sigma(E)/E = 0.18/\sqrt{E} \) for electromagnetic particles and \( \sigma(E)/E = 0.35/\sqrt{E} \) for hadrons (with \( E \) in GeV).
Figure 2.6: Schematic view of the ZEUS detector along the beamline.
2.2. The ZEUS detector

2.2.2 The Central Tracking Detector

The bulk of the tracking is done using a cylindric wire chamber, the Central Tracking Detector, consisting of nine superlayers, each having 8 signal wires, see figure 2.8. Numbering the layers from one to nine from the inside outwards, the wires of the odd numbered superlayers are oriented parallel to the beam-axis. The four even numbered stereo layers have a small angle with respect to the beam-axis, to be able to reconstruct the z-position along the tracks. The angles are indicated in the figure. Potential wires are installed to shape the electric field and to allow adjustment of the gain and drift fields.

The inner radius of the CTD is 16.2 cm. The first signal wire is located at a radius of 18.2 cm. The outer radius is 85 cm and the last signal wire is located at a radius of 79.4 cm. The length of the active region is 241 cm. It covers the polar angle region between 15° and 164°. The position resolution of a hit varies between 100 and 120 μm depending on the polar angle. The corresponding resolution in z varies between 1.0 and 1.4 mm. The transverse momentum resolution $\sigma(P_T)/P_T$ is $0.0058P_T+0.0065+0.0014/P_T$ ($P_T$ in GeV). Tracking with the CTD will be discussed in section 2.4.
Figure 2.8: A track traversing the CTD displaying the 9 superlayers and a CTD segment showing the wire locations. Also the angles of the stereo wires are indicated.

2.3 Event reconstruction

Most of the collisions detected in the ZEUS detector are not the results of electron-proton collisions, but are interactions between beam particles and residual gas in the beampipe. The interesting electron-proton interactions are separated from the beam-gas interactions using a trigger system. In the trigger chain, the event rate is brought down from the 10.4 MHz beam crossing frequency to approximately 5 Hz. For comparison it is interesting to note that the rate of neutral current events with $Q^2 > 100$ GeV$^2$ is about 0.1 Hz at the typical specific luminosity and for charged current in the same kinematic region it is about 1.3 mHz.

The trigger consists of three levels. In the first level unsophisticated cuts are made to lower the output rate to about 800 Hz. Things considered at the first level trigger are for instance: clusters of hit cells, the presence of scattered electron candidates, veto signals, event timing$^4$, transverse energy. At the second level trigger more complicated cuts are made by combining energy sums in the hadronic and electromagnetic calorimeter cells, calculating angles of energy deposits, crude tracking and vertex finding. This reduces the event rate to about 60 Hz. The third level trigger uses a streamlined version of the offline event reconstruction. The track finding and vertex fitting is redone in a more sophisticated manner. Here the values of kinematic variables are calculated and the compatibility of the reconstructed vertex position with the nominal interaction point is checked. The remaining events are stored on disk. The resulting event rate is about 5 Hz.

$^4$A cut is made on the time of the energy deposits in the calorimeter to ensure that the event takes place in a fiducial region.
Figure 2.9 shows a neutral current event in the ZR and XY-projection. The proton enters from the right and the electron from the left. The energy deposit on the left is due to the proton remnant. Also clearly visible are the two jets, nicely separated in $\phi$. The measured value for $Q^2$ was 5285 GeV$^2$, the values of $x$ and $y$ are 0.0782 and 0.746.

2.4 Tracking

Each track candidate begins as a track seed consisting of hits in three separate axial superlayers of the CTD. To extrapolate the track to the beamline, it is assumed that the track originates from the nominal interaction point. Since this is a rough approximation of the vertex location, a large error is assigned to it in a preliminary fit. Next, the track is followed inwards and new CTD hits are added. Tracks can be described by a 5 parameter helix model

$$h = \left\{ \frac{Q}{R} \cot(\theta), \phi, D_h, Z_h \right\}$$

(2.20)

where $Q$ is the track charge, $R$ the radius of the circle in the (x,y)-plane, $\theta$ the angle with respect to the z-axis, $\phi$ the angle tangent to the helix in the (x,y)-plane, $D_h$ the distance between (0,0) and the point of closest approach to (0,0) signed by the angular momentum.
around the z-axis and $Z_h$ the z-position at the point of closest approach to (0,0). The parameter definitions are illustrated in figure 2.10.

![Figure 2.10: Illustration of the track parameters.](image)

Tracks of interest originate from the initial $ep$-collision or the subsequent decay of particles produced in that collision. Hence, most tracks will traverse the first superlayer. In order to perform a good track fit, sufficient hits have to be attributed to a track. Therefore, the track candidate is required to span at least the first three superlayers and have a $\chi^2$ per number of degrees of freedom, $\chi^2/ndf$, of the track fit smaller than 5. Due to the layout of the CTD the measurement of the R and $\phi$-coordinates is substantially better than the measurement of the z-coordinate. To remove track candidates that have badly reconstructed z information, an additional cut is made on the error of $Z_h$; tracks with an $\sigma_{Z_h}$ smaller than 2 cm are accepted. Since the primary vertex is spread around (0,0,0) a good track candidate has a $|Z_h|$-value smaller than 30 cm and a $|D_h|$-value smaller than 10 cm. Tracks with too small transverse momentum produce loops inside the CTD and are removed. Here track candidates with $P_T$ less than 250 MeV are rejected.

The track distributions found in data are compared with tracks from a Monte Carlo simulation$^5$. It was found that the track finding efficiency is slightly smaller in the data than in Monte Carlo. To enhance the correspondence, track candidates in the Monte Carlo are removed. The $P_T$ distribution is used to check the procedure. The track parameter distributions for both data and Monte Carlo after cuts are shown in figure 2.11. In figure 2.11(a) and (b) the outer superlayer and the $\chi^2/ndf$ distribution are shown. The error and the distribution over $Z_h$ can be found in figure 2.11(c) and (d).

$^5$The used data sample and Monte Carlo simulation are discussed in chapter 7 and chapter 8.
Figure 2.11: The distribution in data and Monte Carlo after reweighting of the tracks for the outer superlayer (a), the $\chi^2/\text{ndf}$ (b), the error on $Z_h$ (c) $Z_h$ (d), $D_h$ (e) and $P_T$ (f).
The bumps in the $\sigma_{Z_h}$ spectrum are due to the different number of used stereo hits in the track. Figure 2.11(e) and (f) display the distributions over $D_h$ and $P_T$. The resulting number of good tracks per event is shown in figure 2.12. The correspondence between data and Monte Carlo is very good, especially for the number of good tracks per event.

2.5 Vertex reconstruction

After selecting good tracks, a primary vertex is reconstructed. The standard ZEUS vertexing package determines the vertices by minimising the total $\chi^2/\text{ndf}$ of a vertex fit. It relies on a local parametrisation of the tracks around the expected vertex location[4]. In this thesis a different method is used for reasons that will be discussed in section 8.2.2. The vertex is determined by minimising the $\chi^2$ of a vertex fit using a Kalman filter[5, 6]. This is an iterative procedure where an initial vertex position is estimated, next the estimate of the vertex is improved with the information of the tracks one by one. A final vertex position with a covariance matrix and new track parameters for each track are obtained. Since the Kalman filter updates the estimates of the track parameters and of the vertex at each iteration it is to be expected that the vertex resolution of the Kalman method is better.
Mathematical description of the Kalman filter

The vertex position before addition of track $k$ is estimated to be at $\tilde{x}_0$. The subscript $0$ denotes the original value and no subscript the value after adding the track. Let the momentum of particle be given by

$$\tilde{q} = \{ \bar{Q} \cdot \cot(\theta), \phi \} \quad (2.21)$$

and let $G^{-1}$ be the covariance matrix of the track parameters and $C_0$ the covariance matrix of the vertex before adding the track. Then the track parameters $\bar{p}_0$ can be linearised as $\tilde{h}$

$$\tilde{h}(\tilde{x}, \tilde{q}) = \tilde{h}(\tilde{x}_0, \tilde{q}_0) + A(\tilde{x} - \tilde{x}_0) + B(\tilde{q} - \tilde{q}_0)$$
$$= \tilde{h}_0 + A\tilde{x} + B\tilde{q} \quad (2.22)$$

where

$$A = \left. \frac{\delta \tilde{h}}{\delta \tilde{x}} \right|_{(\tilde{x}_0, \tilde{q}_0)} \quad B = \left. \frac{\delta \tilde{h}}{\delta \tilde{q}} \right|_{(\tilde{x}_0, \tilde{q}_0)} \quad (2.23)$$

The $\Delta \chi^2_k$ obtained by adding track $k$ can then be expressed as

$$\Delta \chi^2_k = (\tilde{x}_k - \tilde{x}_{0,k})^T C_{0,k}^{-1} (\tilde{x}_k - \tilde{x}_{0,k}) +$$
$$\left( \bar{p}_{0,k} - \tilde{h}_{0,k} - A_k \tilde{x}_k - B_k \tilde{q}_k \right)^T G_k \left( \bar{p}_{0,k} - \tilde{h}_{0,k} - A_k \tilde{x}_k - B_k \tilde{q}_k \right) \quad (2.24)$$

After addition of a track and minimising the $\Delta \chi^2_k$ a new vertex position with a new covariance matrix and a new momentum vector for track $k$ are calculated using

$$\tilde{x}_k = C_k \left[ C_{k-1}^{-1} \tilde{x}_{k-1} + A_k^T G_k^B \left( \bar{p}_{0,k} - \tilde{h}_{0,k} \right) \right] \quad (2.25)$$
$$\tilde{q}_k = W_k B_k^T G_k \left( \bar{p}_{0,k} - \tilde{h}_{0,k} - A_k \tilde{x}_k \right) \quad (2.26)$$
$$C_k = \left[ C_{k-1}^{-1} + A_k^T G_k^B A_k \right]^{-1} \quad (2.27)$$

where

$$W_k = (B_k^T G_k B_k)^{-1} \quad (2.28)$$
$$G_k^B = G_k - G_k B_k W_k B_k^T G_k \quad (2.29)$$

After adding all tracks and finding the vertex, the momenta of all tracks are recalculated using the final vertex $(\tilde{x}_f)$.

$$\tilde{q}'_k = W_k B_k^T G_k \left( \bar{p}_{0,k} - \tilde{h}_{0,k} - A_k \tilde{x}_f \right) \quad (2.30)$$
2.5.1 Primary vertex estimate

Before reconstructing the primary vertex by adding all tracks to the initial estimate, first a \((\text{good})\) estimate has to be determined. Furthermore, if possible, tracks originating from secondary vertices have to be removed. This is achieved by testing the compatibility of the tracks with a beam constraint. For each track separately a vertex location is determined, the \textit{preliminary vertex} \(\vec{x}_{\text{track}}\). Since the actual primary vertex position varies in \(x\) and \(y\) only within approximately \(\pm 1\) mm and in \(z\) between +30 and -30 cm, the preliminary vertex estimate \(\vec{x}_{\text{track},0}\) is chosen to be at the average \(x, y\) and \(z\) position with a covariance matrix \(C_{\text{track}}^{0}\)

\[
C_{\text{track}}^{0} = \begin{pmatrix}
0.01 & 0 & 0 \\
0 & 0.01 & 0 \\
0 & 0 & 100
\end{pmatrix}
\]

Now for each track a preliminary vertex location with a covariance matrix and a \(\Delta \chi^2_{\text{init}}\) is obtained. The initial estimate for the primary vertex \(\vec{x}_{0}\) is obtained by averaging the \textit{preliminary vertex} locations resulting from tracks with a small \(\Delta \chi^2_{\text{init}}\), smaller than \(\Delta \chi^2_{\text{init, max}}\). The averaging yields the initial primary vertex estimate and the initial \(C_{0}\) for the primary vertex.

The primary vertex is then refined by adding all tracks to the primary vertex estimate. The tracks that survived the \(\Delta \chi^2_{\text{init, max}}\) cut are added first, starting with the tracks with a preliminary vertex closest to the primary vertex estimate. The vertex estimate is only updated if the \(\Delta \chi^2_{\text{prim, k}}\) is less than \(\Delta \chi^2_{\text{prim, max}}\).

In figure 2.13 the residual distributions for the primary vertex are shown for primary vertices consisting of at least three tracks. The number of tracks used for primary vertex reconstruction is shown in figure 2.14(a). The resulting primary vertex resolutions are given in table 2.1. Also listed are the vertex resolutions obtained using the standard ZEUS vertexing. The vertex resolutions obtained with the Kalman filter are significantly better than the ones obtained with the standard ZEUS vertexing. The obtained values are dependent on the used values for \(\Delta \chi^2_{\text{prim, max}}\) and \(\Delta \chi^2_{\text{init, max}}\). The optimisation of both \(\Delta \chi_{\text{max}}\) values will be discussed in section 8.2.2. The resulting \(z\)-vertex distribution for the data and the Monte Carlo simulation is shown in figure 2.14(b).

2.6 Charm tagging

One of the main goals, after the very precise measurement of \(F_2\), is the decomposition of \(F_2\) in the various flavours, especially the heavy flavours. Unfortunately, due to the
2.6. Charm tagging

<table>
<thead>
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<th>coordinate</th>
<th># tracks $\geq$ 3 ($\mu$m)</th>
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</thead>
<tbody>
<tr>
<td>x</td>
<td>$429 \pm 2$ ($517 \pm 18$)</td>
</tr>
<tr>
<td>y</td>
<td>$419 \pm 2$ ($500 \pm 18$)</td>
</tr>
<tr>
<td>z</td>
<td>$1265 \pm 4$ ($1335 \pm 37$)</td>
</tr>
</tbody>
</table>

Table 2.1: Primary vertex resolutions for events with three or more tracks. Also shown between brackets are the resolutions obtained using the standard ZEUS vertexing.

Figure 2.13: Residual distributions for the primary vertex using at least three tracks, a $\Delta \chi^2_{init, max}$ cut of 5 and a $\Delta \chi^2_{max}$ cut of 9.5.

limited beam energies, the $b$-production cross section is very low, but charmed particles are produced copiously.
Charm at ZEUS is studied using specific decay modes. The most popular is $D^{*\pm} \rightarrow D^0 \pi^\pm$. The nice feature of the $D^{*\pm}$ decay is that the mass difference between the $D^{*\pm}$ and the $D^0$ is only a little bit larger than the mass of the $\pi^\pm$. Hence, subtracting the $D^0$-candidate mass from the $D^{*\pm}$-candidate mass yields a very nice peak, as shown in figure 2.15 [7]. Unfortunately, the charm tagging efficiency is low. Charm quark hadronization yields in

![Figure 2.14: The number of tracks used for the primary vertex reconstruction (a). Distribution of the z-coordinate of the primary vertex (b).](image)

![Figure 2.15: Mass difference between the $D^{*\pm}$ and the $D^0$ candidates.](image)
\( \frac{3}{8} \) of the events a \( D^{*\pm} \). Half of the \( D^{*\pm} \) decays in a \( D^0 \pi^\pm \), where the \( D^0 \) has a branching fraction of \( \approx 4\% \) into \( K^\pm \pi^\mp \). Since the resulting particles are mainly produced in the forward direction, only \( \approx 10\% \) of the \( K \)’s can be reconstructed. Another problem is that the slow \( \pi^\pm \) originating from the \( D^{*\pm} \) decay carries \( \frac{1}{14} \) of the \( D^{*\pm} \) momentum. This means that only \( D^{*\pm} \) with a minimum momentum of \( \approx 1 \) GeV can be reconstructed. Hence, the efficiency for charm tagging can be estimated to be \( \approx 10^{-4} \).

The resulting contribution of charm to \( F_2 \), \( F_2^{\text{em}} \), is shown in figure 2.16 [7]. Note the difference in range and precision between this result and the measurement of the inclusive \( F_2 \), as displayed in figure 2.5. Both measurements, \( F_2^{\text{em}} \) and \( F_2^{\text{cc}} \), were performed using the same data sample.

Another way to tag charm would be via the displaced decay vertex of the \( D \)-mesons. The \( c\tau \) of the \( D^\pm \) is 315 \( \mu m \) and 123.7 \( \mu m \) for the \( D^0 \) and the boost factor \( \gamma \) is of the order of 2. Although the resolution on the primary vertex, as listed in table 2.1, is quite good and can even be improved significantly by using the Kalman filter vertexing, these decays cannot be seen separated from the primary vertex. This is mainly due to the absence of a well operating vertex detector. To improve this situation a silicon strip vertex detector has been designed and was installed in 2001.
Figure 2.16: $F_2^{\pi}$ as a function of $x$ and $Q^2$ measured by ZEUS.
2.6. Charm tagging