Chapter 3

Experimental Setup

3.1 The DESY Laboratory

The analysis presented in this thesis was performed with data from the ZEUS detector, which was situated on the Hadron-Elektron Ring Anlage (HERA), at The Deutsches Elekronen-Synchrotron (DESY) Laboratory in Hamburg Germany. DESY is part of the Helmholtz Association, and has two locations in Germany: one in Hamburg, and one in Zeuthen. DESY's facilities are used primarily for the study of natural sciences, specifically pertaining to the use of particle accelerators of varying size to probe the structure of matter. DESY hosted on average approximately 3000 scientists from 33 different countries for research related to HERA and HASYLAB, the associated syncrotron complex.

3.2 The HERA Accelerator

HERA was the world's first and only lepton-nucleon beam collider, and was the largest accelerator at the DESY complex. A nearly circular construction with a circumference of 6.3km, HERA was approved for construction in 1984, and built between 1984 and 1991. The commissioning of the electron ring and proton ring occurred in 1989 an 1991, respectively. HERA provided luminosity to its experiments from mid 1992 until 2 July, 2007, when it was officially decomissioned. Figure ?? is a schematic representation of HERA and the pre-accelerator elements. Particles were produced at low energies, and sequentially passed between different pre-accelerators before reaching HERA.

3.2.1 Proton Injection and Acceleration

To produce protons for collisions, hydrogen gas was ionized, and accelerated in the LINAC III linear accelerator to 50 MeV. Ions were then passed through a thin metal foil to strip the remaining electron, and then passed to the DESY III syncrotron for further acceleration to 7.5 GeV. DESY III is a 317 m circumference storage ring which could hold up to 11 proton bunches with approximately 10^{11} protons per bunch. From DESY III, protons were injected into PETRA II, which accelerated bunches up to 40 GeV. Protons were then injected into HERA for acceleration up to and maintained at an energy of 920 GeV.

3.2.2 Lepton Injection and Acceleration

During periods of electron-proton collisions, electrons were produced by a hot metal filament. During periods of positron-proton collisions, positrons were produced by scattering electrons on tungsten sheets, resulting in the production of e^+e^- pairs by Bremsstrahlung. Throughout the rest of this chapter, the term *electron* will denote either electrons or positrons, unless otherwise stated. HERA provided both electron-proton and positron-proton collisions during separate periods. Electrons were then accelerated up to an energy of 450 MeV in the LINAC II accelerator, which is a 70 m linear accelerator. They were then gathered in PIA, a 29 m accumulator. Bunches of approximately 3.5×10^{10} electrons were then injected into DESY II, a 293 m circumference synchrotron, which accelerated them to an energy of 8 GeV. From DESY II, electrons were injected into PETRA II, a 2.3 km circumference synchrotron, which accelerated bunches to 12 GeV. Electrons were then injected into HERA, and were accelerated to and maintained at an energy of 27.5 GeV.

3.2.3 Beam Circulation and Collisions

Within HERA, electron and proton beams were stored in separate beam pipes, each with a vacuum pressure of 3×10^{-11} Torr. The bunches circulated in opposite directions, with a separation of approximately 96 ns, and a frequency of ??? Mhz. HERA could theoretically have held 210 electron and 210 proton bunches, but in practice about 10 bunches of each type were left unfilled to so that a filled bunch of the opposing type could circulate without collisions. This allowed the HERA Machine group to study beam dynamics separately from interactions. Additionally, approximately 15 neighboring bunches of each type were left unfilled to allow time for deflection magnets to energize for beam dumps.

At two places on the ring, labled north and south halls in Figure ?? the two beam pipes merged into one and the beams were forced to collide with nearly zero crossing angle. Two experiment halls were located there, providing space for the general purpose detectors H1 and ZEUS. The HERMES and HERA-B detectors were located at experiment halls labled east and west, respectively. HERA-B used collisions between the proton beam and wire targets to study B hadron production, while HERMES used collisions between the electron beam and proton gas jets to study the spin structure of the proton.

3.2.4 HERA Luminosity

HERA began operation providing electron-proton collisions, and has alternately provided positron-proton collisions as outlined in Table ??. Between 1992 and 1997, HERA collided 27.52 GeV leptons with 820 GeV protons, giving a CME of $s \approx \sqrt{4E_pE_e} \approx 300$ GeV. *Instantaneous luminosity*, L can be described as the incoming flux of participant particles to a reaction. At a two-particle intersecting storage ring collider like HERA, this is calculated as $L = f\,(N_1N_2/A)$, where f is the frequency of bunch crossings, N_i is the number of particles in each bunch in beam i, and A is the area of overlap of the two beams. Thus, a crude estimate of instantaneous luminosity of HERA would be

$$L_{HERA} = f\frac{N_1N_2}{A} \approx 10.4 \times 10^6 \frac{10^{20}}{3.36 \times 10^{-5}cm^2} = 3.1 \times 10^{31}cm^{-2}s^{-1} \qquad (3.1)$$

During this period, the average specific luminosity was approximately 2×10^{31} cm^{-2} s^{-1}. Between 2000 and 2002, HERA underwent a luminosity upgrade, which was primarily achieved by installing improved focusing magnets which diminished the interaction area of the two beams. The periods before and after the upgrades are referred to as $HERAI$ and $HERAII$, respectively. The resulting specific luminosity for HERA II was approximately 3.8×10^{31} cm^{-2} s^{-1}. The energy of the proton beam was also increased for HERA II to 920 GeV, providing a CME of approximately 320 GeV.

3.2.5 Polarized Collisions

3.3 The ZEUS Detector

Located at the southernmost experiment hall of HERA, the ZEUS detector was a general purpose detector designed for studying various aspects of electron-proton scattering. It was constructed from several independent subdetectors, which were built by universities from more than 11 countries. The ZEUS collaboration used a right-handed cartesian coordinate system to describe the design and operation of the ZEUS detector. The origin is located at the nominal interaction point, the positive z-axis pointed in the direction of the proton beam, the positive y-axis pointed upwards, and the x-axis pointed toward the center of HERA. The polar angle, θ, is defined by 0° in the direction of the proton, and 90° in the direction of the positive y-axis. The azimuthal angle, ϕ is defined as being 0° in the direction of the positive "x"axis, and 90° in the direction of the positive y-axis. The direction of positive and negative z will sometimes be referred to as *forward* and *backward*, respectively. Objects in these halves of the coordinate system will be described as being in the *front* and *back* of the detector, respectively. Because the central part of the ZEUS detector is cylindrically shaped, objects this region will be referred to as in the *barrel.*

The ZEUS detector was built around the HERA beampipe at the nominal interaction point, and was roughly symmetric in ϕ. The most central components were, in order from the beam pipe to the outside, the micro-vertex detector, tracking system, toroid magnet, and calorimeter. These components were directly used in this analysis and will be described in more detail in the sections which follow. Around the calorimeter are the iron yoke/backing calorimeters, muon chambers, and the concrete encasement. In the negative z direction, in the direction which protons enter the detector, the "veto wall" detector was located to cancel the recording of data caused by particles associated with the proton beam, but not caused by ep interactions.

3.3.1 ZEUS Tracking Detectors

The tracking system of the ZEUS detector was subdivided into three regions, in the forward (FTD), barrel, or central (CTD), and rear (RTD). The CTD is of greatest importance to this thesis, so the FTD and RTD will not be discussed here.

3.3.1.1 The ZEUS Micro Vertex Detector

The ZEUS Microvertex detector was only used for triggering purposes in this analysis.

So... describe it!

3.3.1.2 The ZEUS Central Tracking Detector

The CTD was a cylindrical drift chamber which is filled with a mixture of argon, CO_2 and ethane. It had an active volume with length 205cm, inner radius of 18.2cm and an outer radius of 79.4cm, covering a polar angle range from 15° to 164°. It was divided into eight sections called *octants*, which occupied 45° of azimuthal angle each, spanning the entire length of the CTD. Each octant was divided into nine radial *super layers*, numbered one to nine, numbered from central to exterior. Each odd-numbered superlayer contained wires which were parallel to the beam axis. Each even-numbered superlayer contained wires which were tilted relative to the beam axis by an angle of 4.98°, −5.53°, −5.51°, and 5.62° for layers 2,4,6,8, respectively. These angles are referred to as a *stereo angle*, because the path of particles which caused a signal in two adjacent superlayers could be identified within $2mm$ in the z direction.

The CTD operated in a $1.43T$ magnetic field, which caused charged particles to arc as they passed. The momentum and charge of the particles could then be determined by this curvature. As particles passed though the CTD, they imparted energy to the gas, and their energy loss as a function of distance, $\frac{dE}{dx}$, was also used in particle identification. The resolution of the measured momentum for particles in the CTD was

$$Somethin, Somethin. \tag{3.2}$$

3.3.2 The ZEUS Calorimeter

Similar to the Tracking system, the ZEUS uranium calorimeter (CAL) was constructed in three separate parts: forward (FCAL), barrel (BCAL), and rear (RCAL). These covered polar angles of 2.2° − 39.9°, 36.7° − 128.1°, and 128.1° − 176.5° respectively. Each of these three main main regions were constructed from independent sections called *modules*, which were further divided into sections called *CAL towers*, which were then divided into *cells*. Each tower in the CAL was subdivided into electromagnetic *EMC* or hadronic *HAC* sections. In the FCAL and BCAL Each EMC section contained four longitudinal separations into EMC cells, while each HAC section was transversely separated into two HAC cells. In the RCAL each tower contains only two EMC cells and one HAC. In terms of readout, cells are the most fundamental unit of the CAL.

Each cell was roughly shaped like a rectangular prism, and was constructed of alternating layers of $3.3mm$ thick absorber plates and $2.6mm$ thick plastic scintillator. Each absorber plate was constructed by encasing the Depleted Uranium ^{238}U in a steel jacket. Incident particles on the absorber showered, producing many more particles, which stimulated the scintillator tiles, producing light. Light from the scintillators was passed from two opposite sides of each cell along two separate wavelength shifters. Each wavelength shifter was attached to one photo-multiplier tube (PMT), located on the exterior of the CAL. The two PMT's for each cell were labled as *left* and *right*. The scintillator material was designed to produce a spectrum centered on ???nm. As light travelled down a wavelength shifter from a cell to one of its two PMTs, the peak wavelength of the spectrum became slightly longer, proportional to the distance it travelled. Based on the resultant peak of the wavelength spectrum, a rough r position of the energy deposit, with an uncertainty smaller than the size of the cell could be made. Using this with timing information between left and right channels for each cell, improvement in three dimensional positioning could be made. The agreement between pairs of PMTs also allowed a systematic check of response, and redundancy in case of equipment failure.

^{238}U was chosen as absorber material for its density, stability & radiation-hardness, and its natural low level of radiation. This low radiation provided a stable and well understood signal for calibration of the readout. Hadrons incident on ^{238}U create a high number of spallation neutrons, which can then excite the hydrogen nuclei of a scintillator. Electrons do not radiate the same manner because they mostly interact with atomic electrons, rather than nuclei. These EM interactions typically produce photons and e^+e^- pairs. The CAL was designed with a careful balance between the quantity of uranium and steel in each absorber plate which allowed the CAL to reach a nearly equal response from hadronic and leptonic energy. Test beam studies showed the response to be equal within 3%. This is improtant for jet physics, because it removes the need for assumptions about the leptonic and hadronic content of jets. The single particle energy resolution for electrons and hadrons was determined in test-beams to be $\frac{\sigma_E^e}{E} = 18\%/\sqrt{E}$ and $\frac{\sigma_E^h}{E/GeV} = 35\%/\sqrt{E/GeV}$, respectively. This can be contrasted with the equivalent H1 energy resolutions of $\frac{\sigma_E^e}{E} = 12\%/\sqrt{E}$, $\frac{\sigma_E^h}{E} = 50\%/\sqrt{E}$.

3.3.3 Luminosity Monitor

The *luminosity* of a data sample, $L = N/\sigma$, is defined as the number of particles produced from a process, divided by the cross section for that process. Thus in order to determine a cross section from experimental data, one must know the luminosity used to generate that measurement. At HERA, the luminosity of ep collisions was determined by measuring the rate of Bremsstrahlung photons from the Bethe-Heitler process $ep \rightarrow ep\gamma$. The theoretical cross section for this process is known to an accuracy of .5%, so a precise measurement of this process allowed a precise measurement of the luminosity.

The Bethe-Heitler measurement was performed at $-107m$ in the ZEUS coordinate system by a lead-scintillator calorimeter. The lumi-γ system, gathered photons with a polar angle $\theta_\gamma < 0.5mrad$ with an test-beam energy resolution of $18\%/\sqrt{E}$. It was determined that the protective carbon/lead synchrotron radiation filter caused a slight degradation of performance to $18\%/\sqrt{E}$. The lumi-γ detector had 1cm scintillator strips located $.7\chi_0$ inside, granting the ability to resolve the impact position of photons to .2cm in x and y. This system was also used to measure the electron beam-tilt and measure photons from initial-state radiation (ISR). In addition to the lumi-γ calorimeter, a second lead-scintillator calorimeter called lumi-e was located at $-27m$, which captured electrons which were deflected from the beam by the HERA bending magnets. This was originally designed to compliment the lumi-γ system, but was found to be unneccessary for luminosity measurement. The total uncertainty in the luminosity measurement was determined for this analysis to be 2.5%.

3.3.4 Veto Wall and C5 Counter

3.3.5 Trigger and Data Acquisition

Assuming that ZEUS recorded one event from every crossing, it would have produced data at a rate of $10TB/s$. Because the data transmission from the detector to the event reconstruction computing farm (described in the next section) was less than 1MB/s, the rate of data was forced to be reduced by a factor of 10^6. A faster transmission rate would not have been beneficial, because not every crossing produced an ep interaction, and some that did produced products deemed uninteresting, or which were contaminated by signal from non-ep sources. Deciding which events were worth full reconstruction and storage was accomplished by the a 3-level trigger system.

3.3.5.1 First Level Trigger

The ZEUS First Level Trigger (FLT) was an analog hardware trigger, designed to reduce the event rate to $1kHz$. In order to hold the data while electronics make a decision, raw data was stored on the detector in an analog pipeline for $5\mu s$. This allows a decision to move data off the detector to be made roughly every 50 bunch crossings. The time during the first 25 of these 50 crossings is allocated to individual component FLTs. The rest of the cycles are given to the Global First Level Trigger (GFLT), which collects decisions from the local FLT's and issue. This is performed entirely without deadtime. If a particular event was accepted by the FLT, it was then digitized and transferred to the Second Level Trigger (SLT) Due to finite transfer of data between the components deadtime occurs here at $1-2\%$

3.3.5.2 Second Level Trigger

The SLT used more complete information than the first level trigger. It was designed to reduce the event rate to less than $100Hz$. Similarly to the FLT, each subdetector has its own SLT which passes information to the Global Second Level Trigger(GSLT). If the event is accepted by the SLT, all components send all information to the event builder (EVB), which then combines all data into a single event record to ADAMO database tables.

3.3.5.3 Third Level Trigger

Data was then passed to the Third Level Trigger (TLT), which was a purely software based trigger. The TLT partially reconstructed kinematic variables, and reduced the eventrate to 1Hz. If the event was accepted by the TLT, then it was written to data tape.