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Study of kinematical variables of deep inelastic e - p scattering at HERA with the H1 detector

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Notations

E, E_p	electron and proton beam energies
$e = (0, 0, -E, E)$	four momentum of incoming electron
$p = (0, 0, E_p, E_p)$	four momentum of incoming proton
$e' = (E' sin\theta, 0, E' cos\theta, E')$	four momentum of scattered electron
$s = (e+p)^2 = 4EE_p$	square of total centre of mass energy
$q^2 = (e-e')^2 = -2EE'(1+cos\theta) = -Q^2$	square of four momentum transfer
$Q^2_{max} = s$	maximum possible Q^2 value
$\nu = q.p/m_p$	energy of interaction carrier in proton rest frame
$\nu_{max} = s/(2m_p)$	maximum energy transfer
$y = (q.p)/(e.p) = \nu/\nu_{max}$	fraction of energy transfer
$x = Q^2/2q.p = Q^2/2m_p\nu = Q^2/(ys)$	Bjorken scaling variable
$W^2 = (p+q)^2 = m_p^2 - Q^2 + 2m_p\nu$	mass squared of the total hadronic system
$= m_p^2 + Q^2(1/x - 1)$	produced
ηp	incident momentum of the struck quark
$j = \eta p + q$	outgoing momentum of the struck quark
$j^2 = \eta^2 p^2 + 2\eta p.q - Q^2$	mass squared of the outgoing struck quark

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Introduction

The study of inelstic electron scattering at high energies (DIS) is of great historical importance because it lead to the first clear evidence for scattering from individual quark constituents confined within the proton. Previous experiments used liquid or gasious targets (fixed target experiments) like deuteron. They are replaced now by the colliding beam experiments which are performed at $e_{\pm} - p$ HERA collider. HERA represents the latest refinement of an experimental method introduced around 1910 by Lord Rutherford in Manchester: Rutherford shot alpha-particles (of a radioactive substance) at the atoms of a gold foil. Most of the alpha-particles penetrated the foil without suffering any measurable deviation and only a few were deflected and even recoiled backwards. From these results and after some interesting calculations, Rutherford concluded that most of the mass of the atoms must be concentrated in a very small nucleus carrying an electric charge. The outer orbital electrons are light and relatively slow in motion, which in practice can not deflect Rutherfords projectiles.

By 1964 it was possible to experiment at the DESY-synchrotron with electrons reaching 6 GeV and two years later 16GeV using a linear accelerator at Stanford (USA). In 1968, on the basis of the results of these experiments, J. Bjorken and R. Feynman found that the high energy electrons did not only collide with the protons as a whole but occasionally also with much smaller and lighter constituents of the proton, called partons. Later on they were identified with "quarks" already postulated in 1964 by Murry Gell-Mann. After the Stanford/MIT experiments, other experiments of the same type were performed at still higher energies. Nucleons (protons and neutrons) were bombarded with muons and neutrinos. Leptons used as beams are particularly suited to such investigations because they are not directly effected by the strong forces.

From another point of view DIS processes study is very important. Inside the nucleus protons and neutrons are quite close to each-other which exchange quarks, antiquarks and gluons. Under certain conditions this causes an attractive nuclear force between them. This force, thus, can be deduced from much stronger force between the quarks. Therefore, it is clear that a better understanding of complicated nucleon is of great interest for further development of nuclear physics.

Much of our present knowledge about the internal structure of the nucleon is the result of high energy experiments. It is not easy to extrapolate these results to the much lower energy of atomic nuclei. The theory of quark forces, the "quantum chromodynamics"(QCD), must still be developed in its details for these purposes. High energy experiments, in particular those being performed at HERA, should provide valuable fundamental information for this.

Chapter 1

Theoretical aspects

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Theoretical aspects

1.1 The kinematics of deep inelastic lepton nucleon scattering

In deep inelastic scattering the incoming electron probes the structure of the proton via virtual electromagnetic or weak interaction carrier. One can distinguish between the neutral current and charged current by a final electron or a neutrino. The basic process is shown in figure 1.1.

For Q^2 much greater than the mass squared of the proton, the proton can be thought of as a group of quasi-free constituents: quarks,gluons etc,one of which interacts while the rest of the group moves on unperturbed.

The imbalance between electron and proton beam momenta makes the kinematics at HERA quite different from those of the other colliders where both beams have equal momenta or from fixed target experiments where the nucleon is stationary.

The relevant kinematic variables are given in the begining of this report (notations).

1.1.1 The Bjorken variable x

The Bjorken variable defined above is equal to the fraction η of the proton momentum carried by the struck quark. This can be seen in the notations at the begining of this report.

If we neglect the mass of outgoing quark i.e $j^2 = 0$ and for $Q^2 \gg \eta^2 p^2 = m_p^2$ then

$$Q^2 = 2\eta p.q \tag{1.1}$$

i.e $\eta = x$. Thus for high Q^2 and for non-zero outgoing quark mass, the Bjorken variable x is the fraction of proton momentum that the struck quark carries.

1.2 Cross-sections for DIS

The electromagnetic and the weak interactions play the most important part in electron -nucleon collision (via electron-quark collision). For large values of Q^2, these forces are of comparable strength and quarks can be considered in good approxiation as "free" inside the proton. Therefore one should take account of γ and W^+ ,W^- and Z^o as exchanged quantas. The cross-sections for NC (neutral current interactions) and CC (charge current interactions) are related to the structure functions F_i^{NC} and F_i^{CC} of the proton[2].

1.2.1 NC, $ep \to eX$

After some simple algebra, one gets the expression for the differential cross-section, for $ep \to eX$ process, in terms of x,y and Q^2 as

$$\begin{aligned}\frac{d^2\sigma(\gamma + Z^o)}{dxdy} &= \frac{4\pi\alpha^2}{sx^2y^2}[(1 - y + \frac{y^2}{2})F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2) \\ &\pm (y - \frac{y^2}{2})xF_3(x,Q^2)] \qquad (1.2)\end{aligned}$$

The upper (lower) sign applies to $e^-(e^+)-p$ scattering . The longitudinal structure function F_L is is related to the structure functions F_1 and F_2 via

$$F_L(x,Q^2) = F_2(x,Q^2) - 2xF_1(x,Q^2) = 2xF_1(x,Q^2)R(x,Q^2) \qquad (1.3)$$

with

$$R(x,Q^2) = F_L(x,Q^2)/[2xF_1(x,Q^2)] = [F_2(x,Q^2)/2xF_1(x,Q^2)] - 1 \qquad (1.4)$$

For $Q^2 \gg 1GeV^2$ and not too small x, the contribution of the longitudinal structure function F_L is small. The F_3 term measures the parity-violating contribution due to Z^o exchange. It is significant only when Q^2 is comparable to or larger than Z^o mass squared.

1.2.2 CC, $ep \to \nu X$

For process $ep \to \nu X$ at high Q^2 the differential cross section is

$$\begin{aligned}\frac{d^2\sigma(W)}{dxdy} &= \frac{G_F^2 s}{2\pi}\frac{1}{(1 + Q^2/M_W^2)^2}[(1-y)F_2(x,Q^2) + y^2xF_1(x,Q^2) \\ &\pm (y - \frac{y^2}{2})xF_3(x,Q^2)] \qquad (1.5)\end{aligned}$$

where $G_F = 1.02.10^{-5}/m_p^2$ is the Fermi coupling constant. Again upper(lower) sign applies to $e^-(e^+)$ scattering.

1.3 DIS cross sections in the quark-parton model

The structure functions F_i^{NC} and F_i^{CC} scattering are in principle independent. They can be related via quark-parton model (QPM). The dominant process of the lowest order diagram is elastic electron -quark scattering, $eq \to eq$. Photon exchange leads to the following cross section for this process:

$$\frac{d\sigma}{dQ^2} = \frac{4\pi\alpha^2e_q^2}{Q^4}[1 - \frac{Q^2}{s_{eq}} + \frac{Q^4}{2s_{eq}^2}] \qquad (1.6)$$

where $s_{eq} = (e+q)^2$=xs and $Q^2 = xyz$. Let us define quark distributions q(x) by, q(x)dx= probability to find in the proton a quark of type q carrying a momentum fraction between x and x+dx

The resulting cross section for electron proton scattering via quark q is;

$$\frac{d^2\sigma^q}{dxdy} = \frac{4\pi\alpha^2}{x^2y^2s}[1-y+\frac{y^2}{2}]e_q^2xq(x) \tag{1.7}$$

The total e-p cross section is obtained by summing over all quark contributions i.e.

$$\frac{d^2\sigma(ep\to eX)}{dxdy} = \frac{4\pi\alpha^2}{x^2y^2s}[1-y+\frac{y^2}{2}]\sum e_q^2xq(x) \tag{1.8}$$

By comparing eq.2 and eq.8 one gets

$$F_2^{NC}(x) = \sum e_q^2xq(x) = x[\frac{4}{9}u(x)+\frac{4}{9}\bar{u}(x)+\frac{1}{9}d(x)+\frac{1}{9}\bar{d}(x)+...] \tag{1.9}$$

Since only pointlike spin 1/2 constituents contribute, therefore

$$F_2^{NC}(x) = 2xF_1^{NC}(x) \tag{1.10}$$

and

$$F_L^{NC}(x) = 0 \tag{1.11}$$

Inclusion of Z^o exchange leads to the following expressions

$$F_2^{NC}(x,Q^2) = \sum A_q(Q^2)x[q(x)+\bar{q}(x)] \tag{1.12}$$

and

$$xF_3^{NC}(x,Q^2) = \sum B_q(Q^2)x[q(x)-\bar{q}(x)] \tag{1.13}$$

where

$$\begin{aligned} A_q(Q^2) \quad &= \quad e_q^2 - 2e_qv_ev_q[Q^2/(Q^2+M_(Z)^2)] \\ &\quad + (v_e^2+a_e^2)(v_q^2+a_q^2)[Q^2/(Q^2+M_(Z)^2)]^2 \end{aligned} \tag{1.14}$$

and

$$\begin{aligned} B_q(Q^2) \quad &= \quad -2e_qa_ea_q[Q^2/(Q^2+M_(Z)^2)] \\ &\quad + 4v_ev_qa_ea_q[Q^2/(Q^2+M_(Z)^2)]^2 \end{aligned} \tag{1.15}$$

The corresponding QPM expressions for the CC case are

$$F_2^{CC}(x) = x\sum\{|V_{u_id_j}||^2u_i(x)+|V_{u_jd_i}||^2\bar{d}_i(x)\} \tag{1.16}$$

and

$$xF_3^{CC}(x) = x\sum\{|V_{u_id_j}||^2u_i(x)-|V_{u_jd_i}||^2\bar{d}_i(x)\} \tag{1.17}$$

where $V_{u_id_j}$ are the elements of the CKM matrix,u_i and d_j denote up-type and down type flavours i.e.

$$\begin{pmatrix} u_i \\ d_i \end{pmatrix} = \begin{pmatrix} u \\ d \end{pmatrix}, \begin{pmatrix} c \\ s \end{pmatrix}, \begin{pmatrix} t \\ b \end{pmatrix} \tag{1.18}$$

At energies well above thresholds we have

$$F_2^{CC}(x) = x[u(x)+c(x)+\bar{d}(x)+\bar{s}(x)+...] \tag{1.19}$$

and

$$xF_3^{CC}(x) = x[u(x) + c(x) - \bar{d}(x) - \bar{s}(x) + ...] \tag{1.20}$$

In QCD, the parton densities become Q^2 dependent, $u(x) \rightarrow u(x, Q^2)$, due to gluon radiation or photon-gluon interactions via an intermediate quark. The Structure functions measurements at a given value of Q^2 can be extrapolated to other Q^2 values by QCD evolution with the help of the GLDAP formalism. In derivation of the evalution eqs., $ln(1/x)$ terms are neglected over lnQ^2 terms. While this is justified for the range $x \geq 10^{-2}$ covered by fixed target experients, it may not be so for x values as small as 10^{-4} accesible at HERA. This approximation is avoided in the BFKL equations.

1.4 Sum Rules

Historically, the algebra underlying the sum rules was the foundation for the developement of QCD. In most cases,these sum rules follow from the requirements of the current algebra though they are more simply and physically viewed as consequences of the quark-parton model.

- At the level of photon exchange

$$\int_0^1 dx F_3^{NC}(x) = \frac{4}{9}N_U + \frac{1}{9}N_D = 1 \tag{1.21}$$

where N_U is the total number of u,c and t valence quarks inside the proton and N_D is the total number of d ,s and b valence quarks inside the proton. And

-

$$\int_0^1 dx F_2^{NC}(x) = \frac{4}{9}U + \frac{1}{9}D \tag{1.22}$$

where U is the total momentum fraction of proton carried by u,c and t valence quarks and D is the total momentum fraction of proton carried by d,s and b valence quarks.

- Bjorken sum rule

$$S_{Bj} = \int_0^1 dx(g_1^n(x) - g_1^p(x)) = \frac{1}{6}[\frac{g_A}{g_V}] \tag{1.23}$$

combining this with the result from HERA for $\int_0^1 dx(g_1^p(x)$ one can find $\int_0^1 dx(g_1^n(x)$.

So in summary, the results from HERA extend and will clear more with increasing data, the experimental knowledge about QCD and the standard model. One can see the importance of expressing structure functions in terms of x and Q^2 and cross sections in terms of x ,y and Q^2. So one notices the importance of correct reconstruction of x, y and Q^2 as vital step. A wider kinematical range both in Q^2 and in x can be reached for the determination of structure functions and valence quark, sea quark and gluon densities within the proton. Over the whole Q^2 range, the strong coupling constant $\alpha_s(Q^2)$ decreases by a factor of two, and it is possible to test quantum chromodynamics where non-perturbative effects become negligible. The transition into non-perturbative regime occurs at moderate Q^2 and low x, where parton wave functions may overlap and shadowing and saturation effects could manifest themselves. In contrast to the previous experiments the unique kinematics at HERA makes it easy to observe the hadronic recoil. HERA also makes it possible to study the weak charged current at high momentum transfer. The strange, charm as well as the bottom quark momentum distributions can be measured via the photon-gluon fusion process. At HERA the study of rare and forbidden decays is feasible because of the high cross section rate for producing charmed quark-antiquark pairs which makes HERA a nice source of D-mesons with much cleaner background condition than obtained with the hadron beams. Photoproduction also benefits from the extention to higher energies and larger transverse momenta, where remnants of the hadronic components of the photon may be directely obsservable as jets leading to a measurement of the photon structure function. Along with the studies of neutrino, muon and photon interactions the HERA physics program also covers the search for new physics at the Fermi scale of about 300 GeV. If the quarks and electrons have any structure, it is possible to observe this through the scattering cross sections and polarisation asymmetries, provided the mass scale does not exceed 5 TeV. This is favored by observing the excited leptons or the the formation of leptoquarks. Leptoquarks could be easily identified by their decay into leptons and quarks. If there exist new gauge bosons with masses upto .5TeV they will modify the cross section at high Q^2. HERA's polarized beams of electrons and positrons should be particularly useful tool for these studies.

Chapter 2

Experimental aspects

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Experimental aspects

2.1 The HERA collider

The HERA (Hadron Electron Ring Analog) at DESY, Hamburg is the first lepton-nucleon collider ever constructed. It has the circumference of 6.3 km. HERA started its operation in 1992 with two large detectors H1 and ZEUS at two different interaction points (figure 2.1). This collider accelerate the electrons to 27.5 GeV and protons to 820 GeV, giving centre of mass energy of $\sqrt{s} = 300.3GeV$, which is equivalent to the electron energy of 50 TeV at fixed-target experiments. HERA is different from conventional e^+e^-, $p\bar{p}$ collider, mainly in two ways; first there is an imbalance in the energy of the colliding beams which requires an asymmetric detector and secondly there is high background, as proton induced background arises from beamline vacuum conditions. The HERA project is not limited to the electron-proton collider. One can replace electron beam by positron beam. Similarly proton beam can be replaced by deuteron or more heavy ions like Fe. Study of electron-deuteron collision will give the neutron structure functions. Another experiment at HERMES will produce polarised electron beams for the study of spin structure functions g_1 and g_2. These structure functions give information of quark spin distributions.

2.2 General about H1 detector

For the physics study one has to observe the products of the collision. At HERA there are two detectors which observe the same type of events. In H1, the fine granularity of a calorimeter allows the observation and precise measurement of final electron produced. While ZEUS is special in measuring the energy of final hadrons with high resolution which is necessary for the study of charged currents. An ideal detector should detect all the particles produced at the interaction point over the full solid angle of 4π. In reality one tries to construct the detector as near to the beam as possible. Also one tries to reduce the cracks due to dead material in the detector, mechanical supports and electric wires. Like in all the detectors of colliders two subdetectors make the heart of H1.

- Tracking chamber: To find the trajectories of charged particles, there are tracking chambers just around the beam pipe at the interaction point. In the presence of the magnetic field $\vec{B}$, radius of curvature R allows to determine the sign of charge of the particle and then its momentum p by $p = qRB$. To measure p correctely one needs to measure R precisely.

- Calorimeters: Tracking chambers are surrounded by calorimeters which measure the energy of the particles. They absorb the energy of the particle and transform into the signals which can be read.

One also finds the tracking chambers around the calorimeters for the detection of the particles which escape almost all the calorimeters like muons.

2.3 General about the detectors

In this section some general features of the detectors are discussed. The different types of the detectors are described in brief.

2.3.1 Principle of electronic detection

Most of the electronic detectors use the fact that the charge particles of sufficient high energy leave a trace more or less fine because they ionise the matter through which they pass. An electric field is applied to gather these electrons on electrodes. If the field is sufficiently high, the primary ions excite the electrons by colliding with the adjacent atoms of the matter. Thus initial number of ions produced is multiplied although the velocity of the propagation of ions remains constant. Thus electric signal of charges collected at the electrodes is amplified. The ionizing material is either a rare gas or a liquid or in some cases a semiconductor material. The amplification of charges under the external electric field and the energy lost by the particle par unit its distance covered in the matter is charactrised by the gas.

2.3.2 Proportional chambers

The first detector using the above idea was the proportional counter, which consisted basically of a cylindrical tube filled with gas and maintained at negative potential, and a fine central anode wire ($D = 20\mu m$) at a positive potential. Away from the wire the electric intensity is very strong ($E \propto 1/r$), and electrons gain sufficient energies to cause secondary ionization and a chain of such processes leads to an avalanche of secondary electrons which can be collected as a pulse on the wire. The number of electrons which reach the wire is *proportional* to the number of primary ion pairs. Subsequently, the resolution of proportional counters was greately improved as a result of the discovery that, if many anode wires are arranged in a plane between a common pair of cathode plates each wire acts as an independent detector. This device is called a multiwire proportional chamber (MWPC), and has been a major ingradient since its introduction in 1968.

The precision of the wire chambers is limited by the distance between the wires which should not be less than the 2mm. If one needs high prewcision then one should have a large number of electronic circuits (amplifiers). This makes MWPCs expensive.

2.3.3 Drift chambers

Drift chambers are special kind of MWPCs. They use less number of anode wires and they give also the better spatial resolutions ($40\mu m$). These use the fact that the liberated electrons take time to drift from the point of production to anode.

2.3.4 Scintillation counters

One of the old methods used for the detection of isolated articles is of scintillation. When a particle passes through suitable material, called scintillator, it losses its energy by exciting the atoms on its path. A part of this lost energy re-emerges as visible light during de-excitation. Very sensitive photo detectors convert this light into electric signals.

2.3.5 Principle of calorimeters

Calorimeters are important class of detectors used for measuring the energy and position of a particle by its total absorption. They differ from most other detectors in that the nature of the particle is changed by the detector, and in that they detect neutral as well as charged particles. In H1 shower counters are used. In a shower counter type calorimeter, there is a sandwich construction with separates layers of absorbers (e.g a materiel such as lead) and detectors. During the absorption process the particles will interact with the material of the absorber, generating secondary particles which will themselves generate further particles, and so on, so that a cascade or shower will develop. The energy is transfered into secondary particles by following ways:

- Bremstrahlung, for electrons
- Pair production , for photons
- Nuclear reactions with atomic nuclei of the absorbers, for hadrons

2.4 Particle identification

Although two main classes of detectors have certain distinct fuctions (tracking chambers find the tracks with out changing the particle which leaves the track and calorimeters measure different quantities of the particles accurately) one needs further secondary information for identification of particles. In reaction $e + p \rightarrow e + X$ one has to distinguish between the the final electron and pion in the hadronic jet for example. Moreover in the charge current events the neutrino escapes the detection. Its energy and momentum are estimated by the four momentum conservation. So the precision in the measurements of neutrino depends upon the precision with which one measures the momentum and energy of all other particles. In the particle zoo most of the particles have life duration of less than 10^{-10}s. Therefore mostly, in a detector, one detects the products the decay. In H1 detector the particles which have chance to be directly detected are $e^{\pm}, p, \bar{p}, n, \mu^{\pm}, K^{\pm}, \pi^{\pm}, \gamma$.

2.5 Subdetectors of H1 detector

The main parts of the H1 detector are shown in figure 2.2 and are discussed below. For more detail study of H1, the reader can refer to [2]

2.5.1 Inner tracking chamber:

Inner tracking chamber of H1 gives simultaneous triggering, reconstruction and particle identification. Its design features are so that it reconstructs jets with high densities. The precision in the measurements of momentum and energy of the scattered isolated charged particles is of $\sigma_p/p^2 \sim 3.10^{-3}GeV^{-1}$ and $\sigma_\theta \sim 1mr$ respectively. Due to asymmetry between electron and proton momentum, many charged particles are produced at small angle θ. One divides the tracking detector into two mechanically distinct detectors:

- CTD: central tracking detector
- FTD: forward tracking detector

Each is independent of tracking and triggering in its angular region. CTD has two large concentric drift chambers CJC1 and CJC2, which have wires strung parallel to the beam axis (z direction) Here one measures the space point resolution of $170\mu m$ in drift coordinates (rϕ plane) and by comparing the signal read out at both wire ends one achieves a resolution of one percent of wire length in z. From the signals recorded in these chambers the transverse track-momentum is determined and in adition the specific energy loss dE/dx is used to to improve particle identification. Two thin drift chambers, the central inner(CIZ) and central outer (COZ) z-chambers complement the measurement of charged track momenta in the central chambers. Triggering over the full solid angle is based on mulwire proportional chambers with pad readout in the central and the forward regionsand wire readout in the backward direction. They provide a fast first level (L1) trigger decision. The detector walls are thin to reduce the photon conversion and in particular its effects on identification of primary electrons. In forward direction there are three identical supermodules to provide accurate θ measurements, fast triggering, accurate rϕ measurement, moderate radius of curvature measurementsand a limited particle identification.

2.5.2 Calorimetry

For clear identification and precise measurement of e, μ, penetrating neutral particles and high density jets, two types of calorimetrs are implemented inside a large coil. One can divide the calorimetry into following main parts:

- Liquid Argon Calorimeter(LAC)covers polar angle between $\theta = 4^o$ to $\theta = 153^o$.
- PLUG calorimeter covers the region between the beam pipe and LAC with $\theta \leq 4^o$.
- Lead scintillator backward electromagnetic calorimeter (BEMC) covers the polar region $151^o \leq \theta \leq 177^o$.
- Tail-catcher system(TC)

The main reason for choosing the liquid argon techniques was good stability and ease in caliberation, fine granularity for e/π separation and energy flow measurements as well as homogeneity of response.

2.5.2.1 Liquid argon calorimeter

The large central shower calorimeter of H1 consists of two parts : electromagnetic shower calorimeter surrounded by hadronic shower calorimeter. The difference between the two is due to to the absorbing material.

- In electromagnetic calorimeter one uses lead plates as absorbers. This permits to detect electrons and photons. The energy resolution is $\sigma/E = 12\%/\sqrt{E} \oplus 1\%$(E is in GeV and $\oplus$ means quadratic addition)
- The material used as absorber in the outer large hadronic calorimeter is stainless steel plates.This has the energy resolution of $\sigma = 50\%/\sqrt{E} \oplus 2\%$. For electrons and photons one gets tracks in electromagnetic part, for hadrons there are tracks both in electromagnetic and hadronic calorimeters while muons leave vague information inside the calorimeters.

2.5.2.2 PLUG calorimeter

This calorimeter has been designed to close the gap of acceptance for the energy flow measurements between the beam pipe $\theta \sim .6^o$ and the forward part of the LAC $\theta \sim 4^o$. It minimizes the missing part of the total transverse momentum due hadrons emitted close to beam pipe. In adition the energy emitted into a narrow cone arround the beam pipe can be used to separate the proton jet as well as to veto beam gas and beam wall backgrounds. The energy resolution is $100\%/\sqrt{E_h}$.

2.5.2.3 Backward electromagnetic ealorimeter (BEMC)

The backward (-z) region of H1 detector is instrumented with a conventional electromagnetic lead scintillator sandwich calorimeter. This is installed in order to measure energies and directions of electrons scattered under small anglesfrom DIS. Further BEMC has to measure the hadron emerging from photoproduction and medium to low x, high y hadronic final states. The kinematics of DIS accessible with this calorimeter is characterised by moderate four momentum transfers $Q^2 \leq 100 GeV^2$. Such processes are dominant by far the DIS cross section observed in the H1 detector and provide the only access to the low x-part of the proton ($x \sim 10^{-4}$). Energy resolution for electron is $\sigma/E = 13\%/\sqrt{E_e}$.

2.5.2.4 Tail catcher (TC)

This is the system to measure the hadronic energy leaking out of the LAC.

Chapter 3

Event analysis and results

Chapter 3

Event analysis and results

3.1 Introduction

The importance of the reconstruction of the DIS kinematical variables x (the fraction of the proton momentum carried by the struck quark (Bjorken scaling variable)), y (the fractional energy loss of the electron in the proton rest frame) and Q^2 (the square of 4-momentum transfer) was pointed out in the first chapter. The differential cross-sections, the structure functions and the quark distributions give clear physical interpretation, if we express them in terms of x, y and Q^2. The accuracy of the determination of these quantities will depend on the accuracy in the reconstruction of the kinematical variables, thus, on the accuracy of the measurement of the energy and angle of the electron and the hadronic system. Only two of the kinematic variables are independent and only two of the four measured quantities are necessary. Therefore in principle different methods of reconstructing x, y and Q^2 are possible. The resolution in reconstructing them is not uniform over their entire range and varies from method to method.

Some aspects of the x, y and Q^2 reconstruction will be discussed in the following using data of the H1 experiment taken during the e^+p running period of 1994

3.2 The data samples

For the analysis two types of the data was used, the experimental data and generated Monte Carlo (MC) data.

3.2.1 The experimental data

Out of the whole H1 data sample recorded to tape events with high Q^2 were selected by requiring a scattered electron in the final state being measured in the LAr calorimeter. Two events are shown in the figures from the data of 1994. In figure 3.1, a high Q^2 NC event is shown while in figure 3.2, a DIS NC event with hard photon is shown. One can distinguish different particles by looking at their tracks and the energy deposition in the different subdetectors of H1.

3.2.2 The Event Generator DJANGO 2.1

The event generator DJANGO 2.1 is a combination of the program packages HERACLES 4.2 , ARIADNE 4.0 and JETSET 7.3 simulating deep inelastic neutral and charged current ep interactions at HERA energies. HERACLES generates deep inelastic ep processes including leptonic corrections, radiation from the quark line, interference of leptonic and quarkonic radiation and the complete one-loop virtual corrections. ARIADNE is implementing the Color Dipole Model for QCD cascades. JETSET 7.3 performs the jet fragmentation processes. Details and descriptions of the packages can be found in [3].

3.2.3 Monte Carlo data

The Monte Carlo event sample which is refered to in the following was generated with DJANGO 2.1 using QCD dipole parton shower and the structure function parametrization MRSH. Q^2 was greater than 60.0 GeV and theta of the e was less than 155 degress. In order to simulate the detector response the detector simulation of the H1 experiment was applied. After this step the MC data was treated by the same reconstruction process as the real data in order to give the measured MC quantities.

3.3 Reconstruction of DIS kinematical variables

For the reconstruction of x, y and Q^2 the measured quantities are the event vertex, the final state electron energy E', the electron scattering angle θ, the energy of the final state hadronic system E_h and angle of the hadronic system γ. The event vertex is obtained by fitting the tracks measured with the tracking chamber. The electron energy is measured in the electromagnetic section of the LAr calorimeter, while the energy of the hadronic system is measured by the electromagnetic and hadronic section of the LAr calorimeter, the instrumented iron tail catcher and the backward electromagnetic calorimeter. The electron angle is determined from the track parameters measured with the tracking chamber. The angular information of the hadronic system is determined using the calorimeter systems. One reconsructs the variables Q^2 and y, while x is obtained by using the relation,

$$x = Q^2/sy \tag{3.1}$$

This is because it is easier at HERA to determine Q^2 and y and then using the above relation to measure x. In the naive quark-parton model where the electron is scatters elastically against a quark, the two body final state is completly determined by using two variables, if the electron and the proton beam energies are known. Using the enrgies and the the angles of the scattered electron and the struck quark we can combine any two of them to get y and Q^2. This leaves 6 combinations out of which two are of no interest at low x, so we are left with four methods [4, 5] which will be described below.

3.3.1 Electron-only method

The kinematical variables are defined by using the scattered electron information:

$$Q^2_e = 4EE'cos^2(\theta/2) \tag{3.2}$$

$$y = 1 - \frac{E}{E'} sin^2(\theta/2) \quad (3.3)$$

For this method we get the electron energy from the electromagnetic calorimeter while the angle is determined by the tracking system. For the determination of the vertex and the energy-momentum constraint $\sum(E_h - P_{zh}) = 2A$ one refers to the hadronic system. In case of the H1 experiment one expects the electron method to be very precise due to a good energy resolution of the calorimeters for electrons.

3.3.2 Hadrons-only method

This method uses the energy and the angular information from the hadronic system. The variables are defined as:

$$y_h = F(1 - cos\gamma)/2E \quad (3.4)$$

$$Q_h^2 = \frac{F^2 sin^2\gamma}{1 - y_h} \quad (3.5)$$

The energy and angle are determined by the LAr calorimeter, the instrumented iron tail catcher and the backward electromagnetic calorimeter. A good knowledge of the hadronic energy scale is required.

3.3.3 Double-angle method

Here one uses the angle of the electron θ and angle of the hadronic system (angle of the scattered quark) γ.

$$Q_{da}^2 = 4E^2 \frac{sin\gamma(1 + cos\theta)}{sin\gamma + sin\theta - sin(\theta + \gamma)} \quad (3.6)$$

$$y_{da} = \frac{sin\theta(1 - cos\gamma)}{sin\gamma + sin\theta - sin(\theta + \gamma)} \quad (3.7)$$

One obtaines the kinematic variables which are insensitive to any energy scale used for measuring final state electron and hadrons.

3.3.4 Double-energy method

The kinematical variables are defined as

$$y_{de}^2 = \frac{E' - E}{E' + F - 2E} \quad (3.8)$$

$$Q_{de}^2 = 4E^2(y_{de} - 1) + 4EE' \quad (3.9)$$

This method uses the energy measurements from the electron and the hadron.

I will concentrate on the electron-only method and the hadron-only method while I will use the double-angle method to calibrate the energies. In the following section 3.4 I use the Monte Carlo to compare the generated energy distribution and angular distribution and the corresponding measured energy and angular distributions by MC data. In the same section I will compare the energy distribution using MC data and the real data. This will help in section to understand the errors in the kinematical variables in the electron only method comparing the generated and measured variables by MC. and then MC data and real data. In section 3.5 I will repeat the same procedure in hadron-only method. In section 3.6, a conclusive comparison between the electron-only and the hadron-only methods will be done. The real data and MC data will be compared by using electron and hadron methods separately in section 3.7. In the end in section 3.8 double-angle will be used to calibrate the electron energy (In the following part where I will use "electron energy" this will mean the scattered electron energy)

3.4 Reconstruction of DIS kinematical variables using electron-only method

The reconstruction depends upon the measurements of Eánd θ. Figure 3.3 and 3.4 show the measured energy and the angular distributions of the scattered electron. In the energy distribution, the kinematic peak appears at the beam energy. Comparing the results of experimental data and MC, there are deviations near the peak and at lower energy. The comparison of the angular distributions shows a nice agreement except at very large θ. In order to understand the deviations, the measured energy and angular distributions can be compared to true ones using MC (figures 3.5, 3.6). One finds a small shift in the measured spectrum and the number of events shifted from the higher energy peak to the lower energy values. Moreover at the higher electron energies, the measured energy is underestimated. The long tail with $\theta \sim 153^o$ gives large mismeasurements of the angle in this region which is due to wrong e identification. Otherwise the θ measured distribution agrees well with that of the generator. Other sources of errors are energy losses. These are from the cracks like z-cracks and ϕ-cracks and from the electronic materiel which consists of wires in general. There are also the possibilities of the scattered electron to emerge at large θ which happens at low values of Q^2. In this case the photon energy or the pion energy (these particles come from the backgrounds) or the superposition of both the photon and the pion energies are misidentified as the electron energy. After that one can think of these as the radiation effects or the miscalibration. The electron has probability to emit a real photon. The initial state photon radiation (ISR) and the final state photon radiation (FSR) can cause errors in the measurements. By switching off the radiation and by looking at the particular events with initial state radiation only or with final state radiation only one can see the variations in the energy spectrum. There is no appreciable change in the pattern of both energy and angular distribution by selecting the events without ISR and FSR. So one should think of the remaining sources of errors discussed above. Normally one expects the measured energy less than the actual one due to energy losses. There are cracks between the BEMC and LAr calorimeter,BBE and CB1 and CB1 and CB2. If an electron with an energy of about 29 GeV passes this crack it will be seen at small energy values in the energy spectrum near 10 GeV. This can be the one source of the shifts in energies as discussed above.

Looking at the Q_e^2 for the electron method one can see the influence of the energy and angular resolution of the measurements by simply taking the partial derivatives of Q^2,

$$\frac{\delta Q^2}{Q^2} = \frac{\delta E'}{E'} - tan(\theta/2)\delta\theta \tag{3.10}$$

The resolution in Q^2 has a dominant contribution from the energy resolution except at very small scattering angles where the angular resolution plays the dominant role ($\theta \rightarrow \pi \Rightarrow tan(\theta/2) \rightarrow \infty$). For the distribution in MC data, a peak at $Q_e^2/Q^2 < 1$ is observed which is mainly due to uncerrected losses in the measurement. Looking at the Q_e^2/Q^2 distribution (figures 3.7 ,3.8), this is evident that at small Q^2 values there is a tail for $Q_e^2/Q^2 < 1$. This can be due to the crack between BBE and CB1 and energy scale problems in the LAr of a few percents. If an electron with an energy of about 30 GeV passes this crack, it will correspond to this tail. At small Q^2 values there is a long tail for $Q_e^2/Q^2 > 1$. One source of this tail can be the misidentification of the electrons which results in large errors in θ and some errors even in the E' measurements.

One can notice that this region gets sizable contribution from FSR and some contribution from ISR. In case of the final state radiation, in most of the cases, the final electron and the final radiated photon have large angles. Their distributions have almost the same shape (figure 3.9), so one expects a small angle between these two. They can superpose their energies in the same cluster of the electromagnetic calorimeter which will give compensate the expected losses. The electron beam energy is 27.5 GeV with very small deviations. If one does include the initial state photon radiation, this brings the large uncertainties in the energy measurements of the incident electron. One can see from the photon angular distribution (figure 3.10) that the photon is almost collinear with the electron beam and is not identified by any detector. Which means that the initial energy of the electron is too large and the kinematic relations for Q_e^2 becomes wrong. This effect is normally included in MC corrections. However, it can be shown that a cut in the quantity $\sum(E_i - P_{zi})$ removes most of the events with initial state radiation.

Now coming to y, the partial differentiation of y with respect to θ and E gives the resolution in y as

$$\frac{\delta y}{y} = \frac{1-y}{y}\left(\frac{\delta E'}{E'} + \frac{\delta\theta}{tan(\theta/2)}\right) \tag{3.11}$$

The second term seems to be dangerous for θ approaching zero but actually it is compensated by 1 - y term outside the brackets which also tends to zero when θ approaches zero. The errors in y are the worst near y tending to zero (i.e. $E \leq E'$). A small error in energy or angle can give extremly large errors in y. The more we go to the region near y = 1, the poorer the resolution will be in y.

Figure 3.11 shows the y_e/y as function of y generated. A long tail near y equals zero for which $y_e/y > 1$ is due to the large miscalibration of energy near $\theta \sim 153^o$ corresponding to $E \leq E'$. This also gets contribution from the radiation. The final state radiation corresponds to $y_e/y < 1$ which is uniformly populated. In this area a part comes from the nonradiative processes also. By switching off the radiation one is left with events with large y values. As we have seen above, the region y $\rightarrow$1 is sensitive to the θ, there are no many events in this part because at the same time it corresponds to the hadron backward scattering. There is a regular shaped line $y_e/y \propto 1/y$ which is due to the misidentified electrons discovered in the θ-distribution comparison.

Turning now to x, the resolution in x in terms of the resolutions in Eánd in θ one needs to differenciate the expression for x, partially i.e.,

$$\frac{\delta x}{x} = \frac{1}{y}\frac{\delta E'}{E'} + tan(\theta/2)(x\frac{E_p}{E} - 1)\delta\theta \tag{3.12}$$

One immediate result from this formula is that at low y, the x resolution is quite poor. It is very hard to measure x in this region by the samples of the electromagnetic calorimeters. This can be seen by looking at figure 3.12. Also the resolution in x is quite sensitive to the resolution in θ at high scattering angles except near $x = E/\mathrm{E}_p$. The energy distribution part ($E' < E$) of the scattered electron corresponds to $x < E/E_p$ while the remaining part $E' \geq E$ corresponds to $x \geq E/E_p$. Looking at figure 3.12, one can find the tail of $x_e/x < 1$ near x$\sim$ 0 due to the cracks already discussed. The other part of this region is contributed by the remaining losses especially due to the crack near $\theta \sim 153^o$. There is also a tail near $x \sim 0$ (i.e. E´is low) of $x_e/x > 1$ which implies that $E'_{mes} > E'_{true}$ occurs at low E' values which we have already seen from the electron energy spectrum. The other contribution to this tail of $x_e/x > 1$ comes from the radiation.

3.5 Reconstruction of the kinematical variables using hadron-only method

The hadronic method implicitly uses the Jacquet-Blondel method. It is possible to measure the kinematical variables by using only the outgoing hadronic flow without even using any identification of jets and without using any model on the proton structure. As the hadrons emerging in the forward direction contribute little to the x,y and Q^2, the unavoidable dead areas along the beam pipe have only a minor influence. It is the total hadronic flow that enters in the expressions and so no assumption about the internal structure of the proton has to be made. Energies and angles are measured in the electromagnetic and hadronic calorimeters. Reconstruction errors depend on the size of the beam hole, the errors on the angles and energies of the final hadrons. The errors in the measurement are larger as compared to the electron case. The energy stored in the clusters has wider spread.

Starting from y, as the precision in the hadronic energy measurements is less than in the electron case, one has the wider y_h/y distribution having a peak near 1. The tail near y$\rightarrow$ 0 (figure 3.13) is due to the overestimation of energy. Some part of it is contributed by the radiations while the tail for $y_h/y \rightarrow 0$ has the contribution almost entirely from the radiation. As y increases, one has poor resolution in y, so y_h/y has the more width. In the forward region there is the better resolution in hadron measurements than those in the central part, because of the higher energy involved in case of forward going hadrons. In the backward direction there are almost no measurements in the energy of hadrons. Also the high energy photons go in the backward direction. Some part of the region $y_h/y < 1$ is contributed by the final state radiation and some by the initial state radiation (for smaller y) while the remaining (for high y) due to different types of energy losses.

Turning to the Q^2 reconstruction, higher Q^2 values correspond to the higher y-values. As most of the events are near low y, Q^2 is vertically distributed around 300 GeV^2. (See figure 3.14.)

3.6 Comparison of the Electron Method and the Hadron Method

After the above discussion at high Q^2, I conclude the following:

The general behaviour of the electron method and the the hadron method is similar.

The electron method is precise in the higher y ($y > .2$) region. Its resolution becomes rapidly poor with decreasing y.

The hadron method gives a rather precise measurements at low and medium y ($y < .2$) which degrades at higher y. Due to the hadron losses in the beam pipe it gives a poor resolution in Q^2, but this is the only method for charged current events.

3.7 Comparison between the Monte Carlo and data using electron-only and hadron-only methods

The purpose of the above study was to understand the factors which are responsible for the degradation in reconstructing the kinematical variables and to get rid of them. Starting from the electron method if one looks at the figure 3.15. , the variations between the distribution by using mc and data at low Q^2 is cut off by requiring the cuts of $(E_i - P_{zi}) > 45GeV$ and $E_{BEMC} < .1$. Similarly if one look at at figure 3.16 ,the large discrepencies at high y especially and at low y is removed by applying these cuts. Comparison of x distributions (figure 3.17) also gives a nice agreement after applying these cuts. Comparison of y_h and Q_h^2 distributions by using mc and data repeat themselves the same pattern (figure 3.18). By applying the cuts the discrepencies are removed and mc and data look like similar (figure 3.19).

Further,by applying these cuts on the generated Q^2, y and x; one finds that their effect is not limited to some particular part of the range of these variables but is uniformly distributed.

3.8 The energy calibration by using double angle method

As we know that the double angle method do not contain any final state energy information, one can equate Q^2 from the electron method to that from the double angle method and can write the energy of the scattered electron in terms of θ and γ. One can easily see that the distribution is favoured to the peak at $E' \sim 29GeV$ (figure 3.20). One can apply the cut of $\sum(E_i - P_{zi})$ which will remove the most of the initial state radiation which is at the small angles to the beam line and some part of the final state radiation also. After that one finds within a few percent, agreement between the generated energy and the double angle measured energy (figure 3.21). Still there is discrepency in the measurements at the peak even without the radiation and also in the final state radiation. This is due to the miscalibration of energy. From these kind of studies one can fix the energy scale for electron.

Conclusions

Conclusions

I have presented the prescription for the DIS kinematic reconstruction adapted to study the high Q^2 physics in the full y range ($y < .2$ for hadron only method and $y > .2$ for electron only method). I have also made the detailed analysis of initial state photon radiation (ISR) and the final state photon radiation (FSR) by looking at their effects on the reconstruction. I conclude that their effects are large. Also there are large number of events involving these radiations. Probability for the ISR is about 32% and for the FSR it is about 23%. Finally, the energy calibration using the double-angle method proved to be useful.

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