Tr. J. of Physics
22 (1998) , 595 – 605.

International Workshop on Linac-Ring
Type ep and γp Colliders

Topics on the Physics Potential and Detector Aspects of the LC-HERA *ep* Collider

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Abstract

We present a brief account of some physics topics which could be addressed at a collider consisting of the HERA proton ring and the future e^+e^- Linear Collider. A few experimental aspects are also discussed.

1. Introduction

A breakthrough in the study of deep inelastic lepton-hadron scattering has been achieved by HERA, which provides, for the first time, collisions of electrons and protons in a collider mode, thereby increasing the centre of mass system (CMS) energy of the scattering processes by an order of magnitude compared to the traditional fixed target experiments. Since the maximal reachable energies for electrons in circular colliders are much lower than for protons, at HERA a 820 GeV proton beam collides with a 27.5 GeV electron beam. A large increase in electron beam energy can only be expected from a Linear Collider (LC) type of machine. If a high energy electron-positron LC would be build close to a laboratory site where a high energy proton storage ring already exists, a new frontier in the study of *ep* scattering can be reached. The DESY laboratory in Hamburg is studying the case to built such a LC [1]. Present planning foresees the collider to be tangial to the existing proton ring of the HERA collider (HERAp), thus allowing for collisions of 250 (500) GeV electrons on 820 (1000) GeV protons. This would increase the CMS energy of the *ep* collision by a factor 3-6 compared to HERA. A study on the possible luminosity which could be reached by using HERA in combination with the TESLA LC is given in [2] and amounts to roughly 10^{31} cm^{-2} s^{-1} for a 250 GeV electron beam, assuming proton beam cooling with sufficiently small cooling times. The use of a dynamic focusing scheme could provide a potential luminosity upgrade by a factor 3-4, and further possible improvements are not excluded. However, for the time being we will take the conservative number above as a guideline, which incidently is very close to the present luminosity a HERA. Some aspects of the present physics program at HERA are investigated. An integrated luminosity of 100 pb^{-1} per year is assumed for this study.

Collisions of 820 GeV protons with electrons of 250 GeV can be achieved 'relatively easily' with a TESLA type of LC. If the full capacitance of the LC is used, i.e. both the e^+ and the e^- accelerator, 500 GeV electron beams (giving roughly half of the ep luminosity compared to above) can be provided with the standard LC, and 800 GeV electron beams with a possible future upgrade of the LC. We will mainly study the case for a 250 GeV electron beam in the following, which would represent the 'day one' type of LC-HERAp collider.

2. Kinematics and detector issues

Figures 1 and 2 show the kinematical plane reachable for a collider with 250 GeV electrons and 820 protons. It allows to increase the kinematic range by an order of magnitude at large Q^2 and small x. Thus x values down to almost 10^{-6} can be reached in the deep inelastic scattering region ($Q^2 > 1$ GeV^2). Ultimately, collisions of 800 GeV electrons on 1 TeV beams of protons will lead to an increase of a factor of about 36 of the CMS energy squared, s, compared to HERA. In Fig. 1 also the iso-angular and iso-energy lines are shown for the scattered electron. The angle θ_e is defined in the HERA or LC-HERAp laboratory system to the direction of the proton beam. Electrons from interactions with Q^2 smaller than 100 GeV^2 have a small scattering angle (i.e. θ_e close to 180 degrees). Hence to access the low-x low-Q^2 region detectors at very low angles, integrated with the machine elements, are required. Such compact detectors could be built, based on similar techniques now proposed or used in the H1 [3] and ZEUS [4] experiments at HERA. For H1 small compact detectors, called VLQ [5] detectors, will be installed during the 97-98 machine shutdown. These detectors are based on a GaAs tracker and a compact Tungsten/Scintillator calorimeter.

The detector assumed for these studies consists of a central detector, taken to be an existing one, H1 or ZEUS, equipped with small angle electron detectors, as shown in Fig. 3. Such a detector would allow to measure scattered electrons with angles down to 179.7 degrees. Note that for this cost-efficient solution one of the experiments would still need to be moved to the West Hall at the DESY site, tentatively foreseen for the location of the ep interaction point, and e.g. calorimeter electronics needs to be modified for the much larger energies at LC-HERAp. Note also that if the interaction point is in the West Hall the protons need to be accelerated in HERAp in the opposite direction compared to the one presently at HERA. A further potential weakness of re-using existing HERA detectors is their asymmetry: the backward regions (large θ_e region) are much poorer equipped for measuring hadronic final states (charge particles, energy flows, jets...) compared to the forward ones. The impact of this asymmetry will be discussed below. Fig. 2 shows the iso-angle and iso-energy lines for the current quark jet (for QPM events). The down left corner (low-x, low-Q^2 region) shows that there can be a large energy flow in the backward direction.

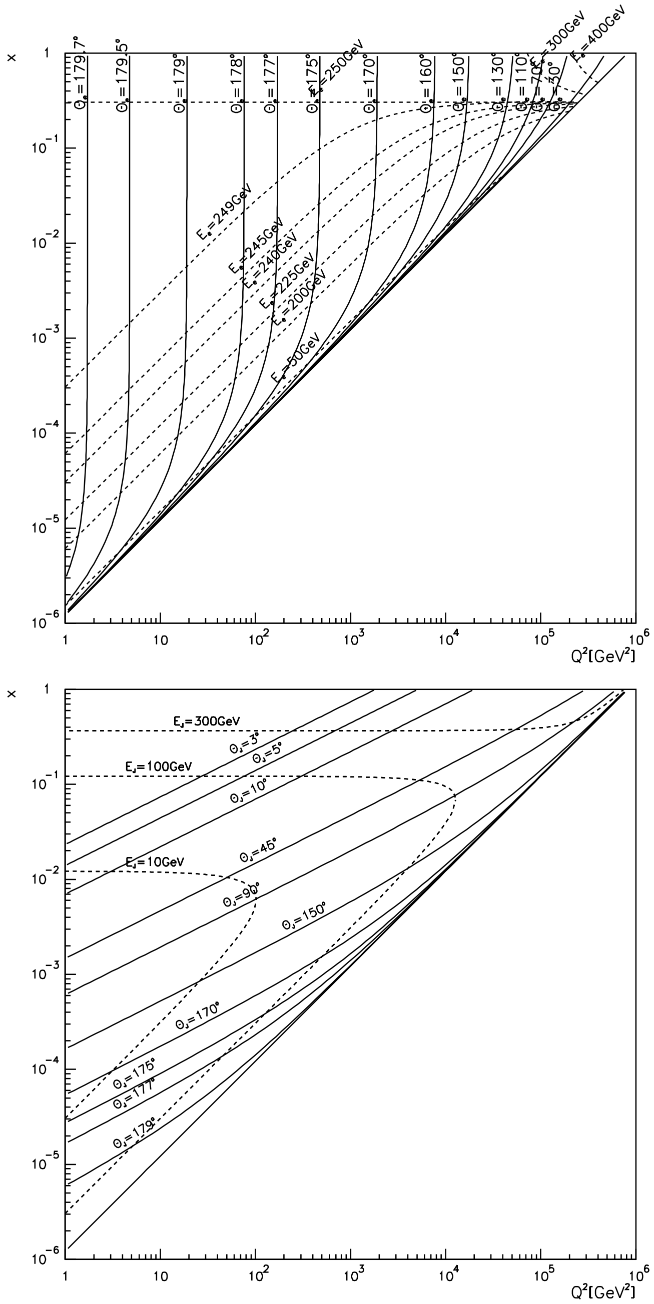

Figure 1. Kinematic plane in x and Q^2 for collisions with $E_e = 250$ GeV and $E_p = 820$ GeV. Iso-angular and iso-energy lines are shown for the current quark in the quark parton model.

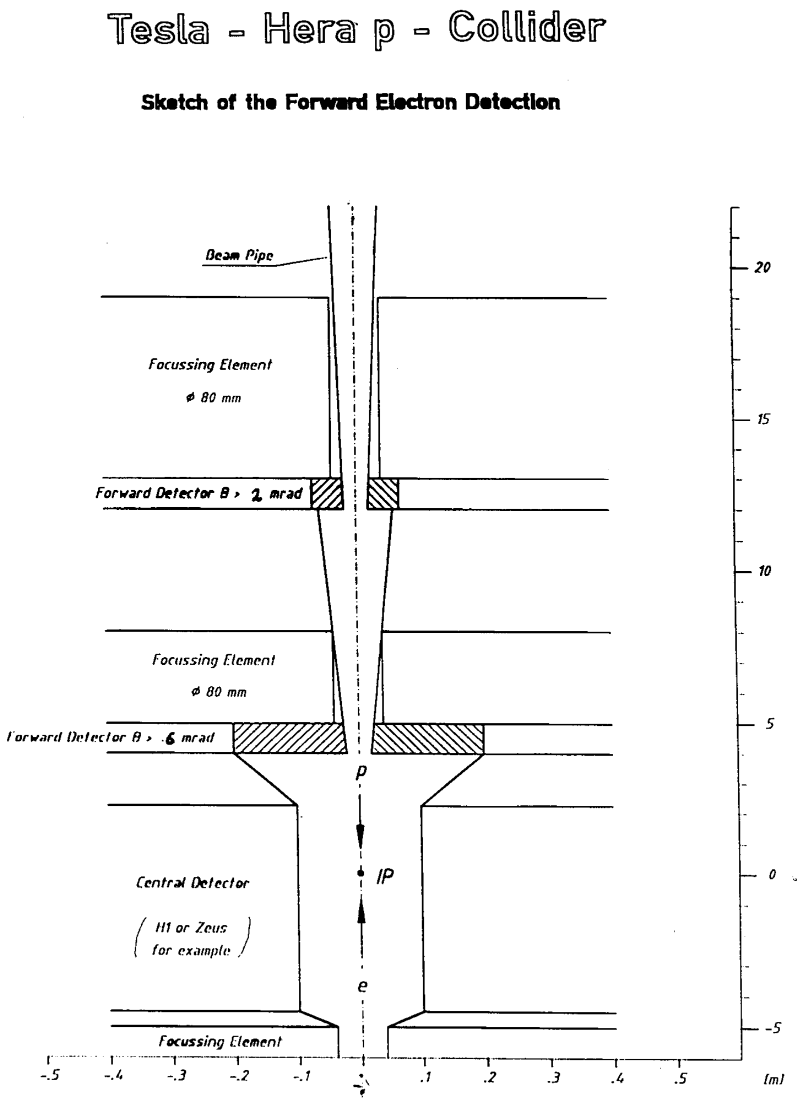

Figure 2. A possible layout of a detector at LC-HERAp, consisting of a central detector and several compact detectors close to the beampipe, taking into account the (preliminary) requirements of the machine. In this picture the proton direction is from top to bottom.

3. Structure functions

One of the flagship measurements at HERA is the measurement of structure functions in a large kinematic region. An important issue here is, apart from event statistics, the quality of the reconstruction of the kinematics of the scattering process. The event kinematics

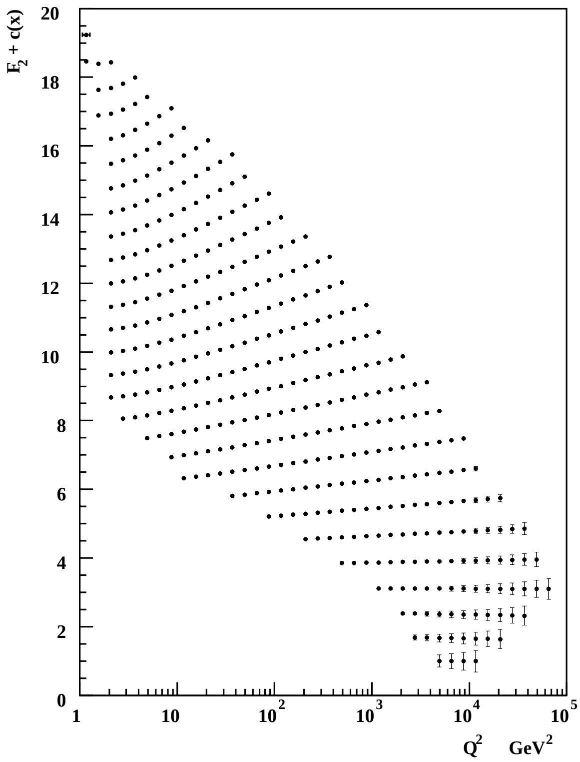

Figure 3. Projected measurements of the structure function F_2 for 100 pb^{-1}, assuming $\theta_e <$ 179.7, and $y_e < 0.9$, and at least 10 events/bin. The errors are the squared sum of the statistical errors (assuming 100% efficiency for the event detection) and a 2% systematical error. The values of F_2 plotted are $F_2 + c(x)$, where $c(x)$ is $0.6 \cdot (J + 0.6)$. J is the bin number in x, with $J = 1, 2, 3, 4, 5$ corresponding to $x = 0.52, 0.32, 0.20, 0.13, 0.082$ etc. The smallest x value is 2.10^{-6}.

can be reconstructed using the energy of the scattered lepton E'_e and the polar angle θ_e according to the relations:

$$y_e = 1 - \frac{E'_e}{E_e} \sin^2 \frac{\theta_e}{2} \qquad\qquad Q^2_e = 4E'_e E_e \cos^2 \frac{\theta_e}{2} = \frac{E'^2_e \sin^2 \theta_e}{1 - y_e}. \tag{1}$$

where E_e is the electron beam energy. The variable x is then calculated as $x = Q^2/sy$. This reconstruction method, based on the scattered lepton, is called the electron method. It is best applicable at large values of y, and found to give a good resolution for $y > 0.1$ at HERA energies. As $\Delta x/x \sim \Delta E_e/(yE_e) \sim 1/(y\sqrt{E_e})$ the higher electron energy of the LC-HERAp collider allows to cover a range of a factor 3 lower in y compared to HERA.

The kinematics can also be calculated from hadronic final states. An example is the Σ method [6] which is used by H1 to determine F_2 at low y. This method combines the electron and the hadronic measurements by defining:

$$y_\Sigma = \frac{\Sigma}{\Sigma + E'_e(1 - \cos\theta_e)} \qquad\qquad Q^2_\Sigma = \frac{E'^2_e \sin^2\theta_e}{1 - y_\Sigma}, \tag{2}$$

with

$$\Sigma = \sum_h (E_h - P_{z,h}). \tag{3}$$

Here E_h and $P_{z,h}$ are the energy and longitudinal momentum component of a particle h, the summation is over all hadronic final state particles, and masses are neglected. The denominator of y_Σ is equal to twice the energy of the true incident beam energy, which differs from the nominal beam energy if real photons are emitted by the incident electron. LC-HERAp is also favourable for the hadronic measurement of the kinematics, as noise contributions at low y get suppressed by an additional factor of 10 compared to HERA, due to the higher energy of the scattered electron. The real limitation comes from beampipe losses (see Fig. 2): when the current jet angle θ_{jet} becomes smaller than 5-10 degrees, the jet will be partially lost in the beampipe, preventing a reliable calculation of the event kinematics. However, the kinematics allows to cover the region down to $y = 0.001$ at low Q^2 and to about $y = 0.01$ at $Q^2 \sim 1000$ GeV^2. A potential problem is the loss of hadrons in the electron direction: the jet angle is close to the beampipe at very small x. Monte Carlo studies show however that only large y ($y > 0.3$), low-Q^2 points are seriously affected. This is a region which is well measured by the electron method, hence no extra hadronic calorimetry in the electron direction is required for structure function measurements. Note that the measurements will also have a large overlap with the present HERA measurements in the $x - Q^2$ plane, due to the low y reach at LC-HERAp

An integrated luminosity of 100 pb^{-1} would lead to more than 10^7 events/bin around $Q^2 \sim$ few GeV^2 at low x, more than sufficient for precision measurements of structure functions. Above $Q^2 = 10,000$ GeV^2 only a few thousand events are expected. Fig. 4 shows a projection of the structure function measurements for an integrated luminosity of 100 pb^{-1} with error bars including the statistical errors and a systematical error of 2%, added quadratically. Data points are shown for which at least 10 events/bin are expected. The H1 F_2 parametrization as given in [7] is used for the extrapolation. In Q^2 8 bins per decade are taken, while in x 5 bins per decade are assumed. With 100 pb^{-1}, the structure function F_2 can be measured up to $Q^2 = 10^5$ GeV^2, and beyond if a coarser bin size is chosen.

The extended range will allow further QCD studies of the structure function and the extraction of the gluon density $xg(x)$ from scaling violations. Hence the gluon density for

x values down to 10^{-5}–10^{-6} will be extracted. This will extend considerably the program of studies on low-x parton dynamics, in particular studies of BFKL effects in the parton densities and search for saturation effects. To that end it is of interest to consider the naive saturation limit, given by Mueller in [8], where from geometrical arguments one finds that the full available (transverse) space in the proton is filled when the limit $xg(x) \simeq 6Q^2$ is reached. Hence for a Q^2 value of 5 GeV^2 the saturation limit would be reached for the value $xg(x) = 30$. HERA measures presently $xg(x) \sim 15$ at $x = 10^{-4}$, suggesting that the limit would be reached in the region $x \sim 10^{-5} - 10^{-6}$, within the reach of the LC-HERAp.

4. Hadronic final states and photoproduction

Due to the large coverage of the final state phase space by the detectors, detailed analyses can be performed. These analyses of final states have been an important contribution to the success of the present HERA physics program. Fig. 5 show the energy and particle flow for HERA and LC-HERAp as predicted by the Monte Carlo program LEPTO [9], as function of pseudo-rapidity $\eta = -\log\tan\theta/2$. Positive values are in the proton direction. The events are selected with $Q^2 > 5$ GeV^2. Fig. 5 shows that in order to obtain a full detection of the hadronic final state in the current quark region, hadronic coverage will be necessary down to small angles. For events with $Q^2 > 100$ GeV^2 it suffices to detect hadrons down to $\eta = -5$ to have full current quark hemisphere coverage.

A hot topic presently at HERA is the study of large rapidity gap events, generally identified with diffractive events, constituting approximately 10% of the total deep inelastic scattering cross section [10]. If the system M_x, i.e. the dissociated hadronic system at the photon side of the phase space, can be detected with the future detectors (with the same requirement as above, namely detecting the full current quark region), the increased W^2 (= the $\gamma^* p$ invariant mass squared) of interactions at LC-HERAp, compared to HERA, allows to reach a larger M_x and β region, when applying the present selection of $x_{I\!P}$ for a diffractive sample (e.g. $x_{I\!P} < 0.01$). Here:

$$x_{I\!P} = \frac{Q^2 + M_x^2}{Q^2 + W^2} \qquad \beta = \frac{Q^2}{Q^2 + M_x^2}.$$

where in the infinite momentum frame β acquires the interpretation of the Bjorken-x scaling variable of the parton probed in the diffractive exchange. E.g. for $y = 0.33$ and $Q^2 = 10$ GeV^2 we have $M_x^{max} = 15$ GeV and $\beta^{min} = 0.03$ at HERA while $M_x^{max} = 50$ GeV and $\beta^{min} = 0.003$ at LC-HERAp. The larger M_x region covered yields more phase space for e.g studies of jets with large transverse momentum E_T in diffractive systems. The region at low β is unexplored at present. Does the diffractive structure function rise at low β, similarly to the proton structure function at low x? Questions of this sort can be addressed at the LC-HERAp.

Heavy flavour studies will benefit from the energy increase. Charm and bottom cross sections increase with a factor of about 3 to 4, compared to HERA[12]. Heavy flavours

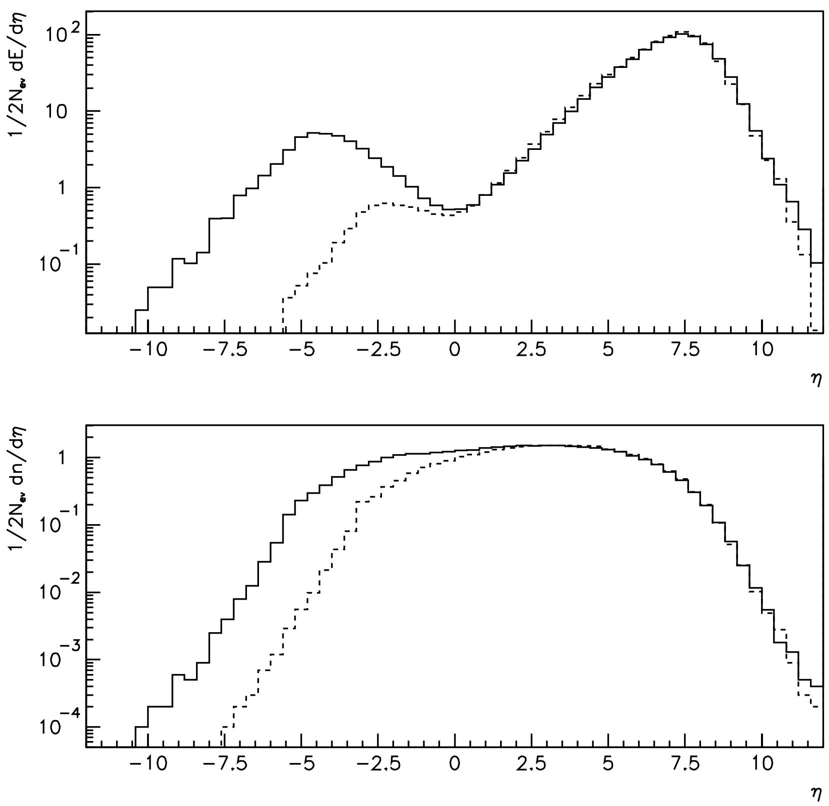

Figure 4. Energy (top) and particle (bottom) flow as function of pseudo-rapidity, for DIS events with $Q^2 > 5$ GeV^2 at HERA (dashed lines) and LC-HERAp (full lines), in the laboratory frame. Negative pseudo-rapidities correspond to the current quark (or virtual photon) direction.

are dominantly produced via the boson-gluon fusion diagram in photoproduction. Hence the cross section is directly proportional to the gluon density in the proton. The extended kinematical range of the LC-HERAp allows to cover x values down to 10^{-4}. The low-x charmed mesons (e.g D^*) are however produced in the electron direction, at pseudo-rapidities of typically -2 to -4. Hence to exploit the sensitivity to the gluon at the lowest x values, charm detection in the backward region must be foreseen for the detectors. LC-HERAp will however not become a machine to study top quarks. The expected number of top quarks produced will be of the order of a few tens per year, even at the highest energies. Clearly the e^+e^- LC itself is the machine to study this topic.

Finally, the presence of electron taggers for electrons with a very small scattering angle, similar to the ones currently used by the HERA experiments, will allow a measurement of the real photoproduction cross sections at $W_{\gamma p} \sim 600$ GeV. Together with the present HERA data this gives a substantial lever arm for studies of the energy dependence of total, inclusive and exclusive photoproduction cross sections, and studies of the interesting questions related to the transition from soft to hard physics, a topic presently explored at HERA.

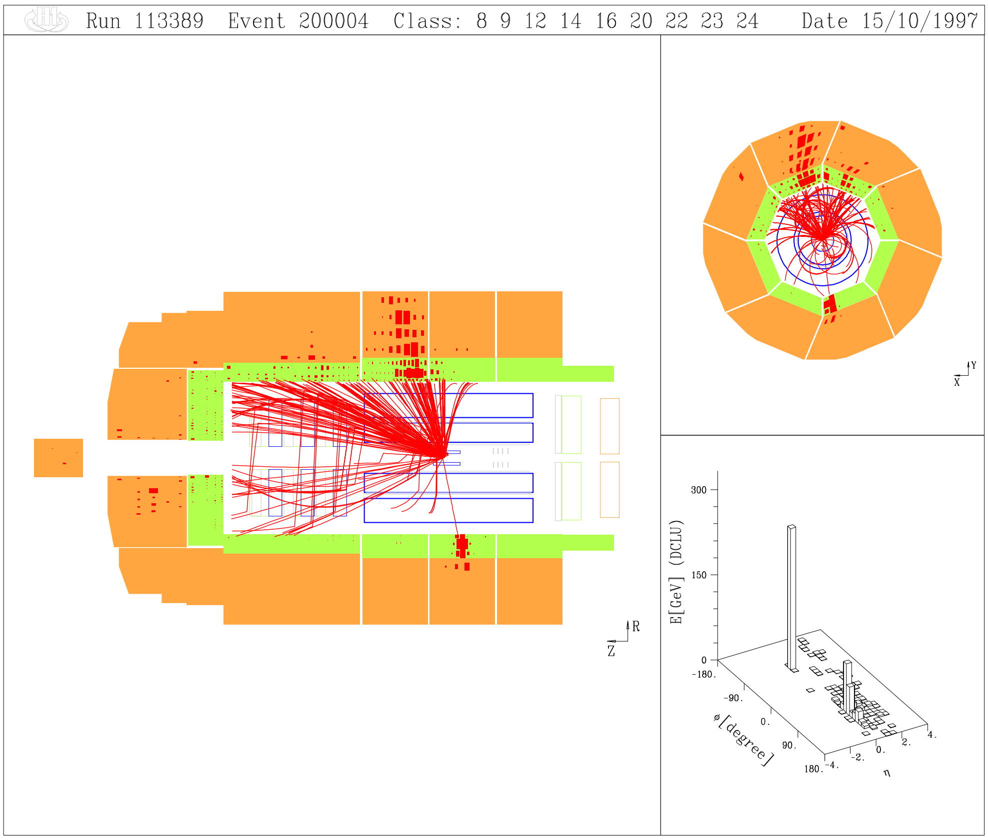

Figure 5. A fully simulated and reconstructed event in the H1 detector for LC-HERAp (E_e = 250 GeV and E_p = 820 GeV), with $x = 0.3$ and $Q^2 = 10^5$ GeV^2. Protons enter from the right, electrons from the left. The scattered electron (bottom) is well isolated from the scattered quark jet (top). The pictures on the right show the transverse view of the central region of the detector and a lego plot of the energy deposits in the calorimeter.

5. High Q^2 region

The recently reported excess of events at high Q^2 at HERA [11] is a clear physics case which strongly supports the road for ep collisions at higher energies. For the same (Q^2, y) region the cross sections rise substantially with increasing collision energy, since the proton is probed at relatively lower x values. Threshold effects are overcome and e.g. in case of contact interactions, the larger Q^2 phase space available allows for more pronounced effects to be observed. Hence increasing the energy of the ep collision will provide vital information on the nature of the high-Q^2 anomaly, if it exists.

The present H1 and ZEUS detectors are very well tailored to measure and analyse high-Q^2 events in the LC-HERAp environment, as is shown in Fig. 6. Here the simulation result of an LC-HERAp event with $x = 0.3$ and $Q^2 = 100,000$ GeV^2 is shown for the H1 detector. The electron is scattered in the central part of the detector (bottom) and quite isolated from the hadronic final state, hence well measurable.

Table 1 gives the cross section for $Q^2 > Q^2_{min}$ values. For $Q^2 > 10^5$ GeV^2, 20 to 50 events per 100 pb^{-1} are expected, according to the Standard Model cross sections (using the GRV [13] structure function and the DJANGO event generator [14]). New effects may dramatically change these numbers, but the table shows that it would be clearly advantageous to have at least a luminosity which is ten times larger than assumed here, in order to study the high Q^2 region in detail.

$Q^2 > Q^2_{min}$ (GeV^2)	10^4	2.10^4	5.10^4	10^5
$\sigma(e^+p \to e^+X)$	29	9	1.3	0.2
$\sigma(e^-p \to e^-X)$	36	12	2.3	0.5

Table 1. Integrated cross sections for $Q^2 > Q^2_{min}$ for e^+p and e^-p neutral current events, in picobarn.

6. Summary

We have discussed some of the physics topics which could be addressed at LC-HERAp. Already in its most conservative mode ($E_e = 250$ GeV, luminosity of the same order as presently at HERA) a rich physics program can emerge at relatively 'low cost', assuming the re-use of one of the present detectors, equipped with detectors for scattered electrons with low angles. Structure functions can be measured at lower x, re-opening search for novel low-x phenomena and saturation, and at higher Q^2. To exploit maximally the continuation of the presently successful analysis program on final states, an improved hadronic coverage in the backward direction is mandatory. The new high-Q^2 region can be studied rather easily with a central detector, but higher luminosities would be desirable.

Acknowledgments

I thank the organizers for providing a well organized and very stimulating workshop in Ankara. I would like to thank for R. Brinkmann and R. Felst for useful discussions.

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