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The HERA Physics Programme

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Abstract

The construction of the HERA accelerator and its detectors H1 and ZEUS opens up new physics regimes to explore at high- Q^2 and low- x . The physics interest and methods of exploration are described, starting from the environment provided by the accelerator and the reaction kinematics.

1. Introduction

High energy lepton scattering has been crucial in the development of our understanding of nature. Starting from J.J. Thompson's discovery of the electron [1], and Roentgen's discovery of X-Rays [2], via atomic energy quantisation by Franck and Hertz in 1914 [3], to wave-particle duality in the interference experiments of Davisson and Germer in 1927 [4] and the establishment of quantum mechanics. Increasing the energy of the electrons to 400 MeV, Hofstadter (1956) measured the size of nuclei and showed that there are proton constituents within the helium nucleus [5], and twelve years later experiments at SLAC and DESY showed that there are point-like "parton" constituents within the proton, work which gained the 1990 Nobel Prize for Physics for Friedman, Kendall and Taylor [6,7]. Throughout the last hundred years therefore, lepton scattering has continuously challenged our desire to declare that physics is already complete.

The use of electrons and muons as probes of nucleon structure has had surgical precision because of the point-like nature of the $e\bar{e}\gamma$ and $\mu\bar{\mu}\gamma$ couplings. This was dramatically verified in the extraordinarily accurate measurements of the anomalous magnetic moments of the electron and muon [8,9], and in the absence of any residual effects of substructure in Bhabha Scattering ($e^+e^- \rightarrow e^+e^-$) and $e^+e^- \rightarrow \mu^+\mu^-$, where substructure scales of order 2 TeV are set [10]. ep , μp and νp scattering can therefore be used with confidence as a test of the structure of the hadron vertex and the nature of the exchanged boson.

There is therefore every motivation to proceed to the construction and use of the HERA ep collider. We discuss our current understanding of its exploitation, bearing in mind always that

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we must expect the unexpected, starting with a description of the accelerator and the experimental environment; then, how the physics need dictates the detector form; and the physics reach of the detectors in terms of tests of the Standard Model, and exploration in Q^2 and in $1/x$, where there are both theoretically unknown things within the Standard Model, and theoretical speculations outside it.

2. The HERA Machine and Experimental Environment

The Hadron Electron Ring Anlage is constructed in an underground tunnel some 6.3 km in circumference containing counter-rotating $e^\pm$ and proton beams in separate magnet rings, arranged to intersect at four points around the ring, where experiments can be constructed. Beams of electrons or positrons, with either helicity at up to 35 GeV, collide head on with protons of 820 GeV. The 30 GeV nominal electron energy gives a maximum Q^2 of 98400 GeV^2 , equivalent to an electron beam of 51 TeV incident on a stationary target. The kinetic range accessible is thus increased by more than an order of magnitude over previous facilities. The luminosities expected are such that $e_L p \rightarrow \nu X$ will occur with 100 events per day. Several countries contributed to the design and construction of the accelerator. Installation was completed in 1990, 1991 is occupied with the commissioning of the nine accelerators and their associated transfer lines. In contrast to an e^+e^- or $p\bar{p}$ storage ring, no symmetry principle of nature forces even the periods of rotation in an ep collider to be equal, so that great care over tolerances has to be taken throughout. At the time of writing (May, 1991) all parts of the $e^\pm$ system have operated to design specifications and a proton beam has been injected into HERA and stored with a lifetime of half an hour. When operating for ep collisions 210 e and p bunches are used, providing a new crossing, which has to be tested for possible triggers, every 96 ns. This is approximately 200 times faster than at LEP (to date) and approaches the repetition rate of LHC and SSC (16 ns). The triggering and data-flow techniques pioneered at HERA are a strong basis on which to build systems for high-rate hadron colliders.

The HERA storage ring and the various stages of injection are illustrated in Fig. 1. The beams run in a tunnel 15-20 m below ground and collide at four intersection points - two of which, (North and South Halls) house the H1 and ZEUS experiments.

To fit 820 GeV proton beams into such a small perimeter, high field ($B = 4.65\text{T}$) magnets are required. Well over 1000 superconducting magnets were needed. A new design of superconducting Nb-Ti magnet was devised in which the iron is maintained at liquid He temperatures. Operation (and safety) are simplified in that there is no liquid nitrogen cooling. To obtain the required field uniformity (eg ratio of quadrupole to dipole moment $< 2 \cdot 10^{-4}$)

20 μm precision is required on conductor location, maintained over the 9 m dipole length. Magnets were supplied by BBC (Germany) and Ansaldo (Italy) and every one was extensively tested and measured at DESY before installation. The quality of the magnets is such that the 820 GeV energy could well be exceeded. Operation at 1 TeV/c is not out of the question.

Long straight sections on either side of the interaction regions allow the electron and proton beams to be brought together and in particular allow longitudinally polarised (left or right handed) $e^\pm$ beams to be prepared. Polarisation may be as high as 80%. Transverse electron polarisation builds up, (in the absence of depolarising resonances - a highly non-trivial statement), as $P(t) = P_0 (1 - \exp(-t/t_0))$ where $P_0 = 0.92$ and $t_0 = 98 \rho^2 R E^{-5}$, where t_0 is in s, ρ is the bending radius in m, R the average radius in m, and E in GeV. For $E = 30$ GeV, $t_0 = 25$ min - a time during which the beam has passed around $2 \cdot 10^8$ turns. The polarisation buildup is therefore extraordinarily sensitive to machine imperfections. A 'Siberian Snake' of magnets makes use of the difference between the spin rotation frequency (ω_{Larmor}) and the orbital frequency ($\omega_{cyclotron}$)

$$\omega_{Larmor} - \omega_{cyclotron} = \gamma \frac{g-2}{2} \frac{eB}{m}$$

(where $\gamma = E/m$). This leads to a spin rotation $\theta = 0.0011159 \gamma \phi$, where ϕ is the angle of rotation. Using a carefully designed snake, longitudinal polarisations of up to 80% can be achieved. (See Figure 2). The magnet line must be moved laterally when polarisation is reversed. This opens new possibilities in the study of the chiral structure of gauge interactions, using e^-_L , e^-_R , e^+_L and e^+_R beams in collision with protons. Polarisation can only be undertaken at energies away from depolarising resonances. The main ones occur whenever a simple integer ratio holds between ω_{Larmor} and $\omega_{cyclotron}$, ie every $2m/(g-2) = 440$ MeV in energy. DESY accelerator physicists look forward to early measurements of the buildup of transverse polarisation, to be followed by installation of the first spin-rotators.

In order to achieve the required luminosity of $1.5 \cdot 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$ the electron and proton beams collide head-on. They are brought together (and apart) by bending magnets. Being of lower momentum, the electron beam is bent more, and at 35 GeV, 9 kW of X-rays of critical energy 80 keV are produced. $8 \cdot 10^{17}$ γ 's pass through the intersection region. One can tolerate perhaps 10^8 γ 's into a detector. It is not possible simply to let the X-rays pass through to infinity. After 23 m the "fan" of X-rays strikes a magnet aperture and a fraction is reflected back into the detector. A complex set of collimators must be introduced to prevent any primary or first - or second-scattered X-rays from entering the detector. Since the p-beam is larger at injection energy the collimators must be mobile. The set-up used for ZEUS is shown in Figure 3. All detector elements must be kept outside the zone from -70 to +110 mm. The use of silicon vertex detectors is therefore somewhat constrained, compared to SLC for example.

Further descriptions of the machine (and experiments) are given in references 11,12.

3. Lepton-Parton Kinematics and Measurement

HERA is a lepton-parton collider. Figure 4 defines the basic kinematics of a lepton of four-momentum, k , incident on a proton of four-momentum, p . In the HERA case we are forced from the beginning to work (as we should anyway) in Lorentz invariants. Beware of all substitutes. In particular a massive literature of νN physics that uses formulae expressed in terms of proton rest-frame variables.

Let k' be the outgoing electron four-momentum and θ its angle of deflection. The $q = k - k'$ be the four-momentum of the exchanged boson. Then we write

$$\begin{aligned} s &\equiv (k+p)^2 \\ &= m_e^2 + m_p^2 + 2E_e E_p + 2p_e \cdot p_p \\ &= 4E_e E_p \quad (E_e^2 \gg m_e^2, E_p^2 \gg m_p^2) \\ &= 98400 \text{ GeV}^2 \\ \text{ie } E_{cms} &= 314 \text{ GeV} \end{aligned}$$

$$\text{Define } Q^2 \equiv -q^2 \equiv -(k-k')^2$$

Note that for photoproduction, ($Q^2 = 0$), the outgoing electron is emitted at 0° and is captured and has its energy measured (and hence the photon energy and Q^2 measured,) in the luminosity monitor.

Then $0 < Q^2 < s$.

Define $x \equiv Q^2/(2p \cdot q)$ Then $0 < x < 1$.

$x = 1$ for elastic ep scattering. $x < 1$ looks like elastic scattering from a target of fractional light-cone momentum $x = (E+p)_{parton}/(E+p)_{proton}$

We can introduce

$$y \equiv (p \cdot q)/(p \cdot k) \quad \text{Then } 0 < y < 1$$

y has a ready interpretation when rest masses can be ignored. $y = \sin^2 \theta/2$ in the lepton-parton c.m. frame. Then $Q^2 = sxy$.

Measurement of two independent variables defines the scatter completely. For electromagnetic scattering one traditionally takes (Q^2, x), (since the photon propagator introduces a $1/Q^4$ term in the cross-section) and for charged currents, where the propagator effects are modest but the helicity couplings introduce y -dependent terms, (x, y) are used. In terms of experimental

measurement, the convenient variables turn out to be (Q^2, y) .

The two fundamental processes are neutral current and charged current scattering (see Fig. 5). In the former case, the outgoing electron energy and direction and the outgoing hadrons (except as far as they are lost in the beam pipe) are available for measurement. In the latter case the hadronic information alone must be used. We can reconstruct (Q^2, y) from the outgoing electron as follows:

$$\begin{aligned} Q^2 &= 4 E_e E_e' \sin^2 \theta/2 \\ y &= 1 - E_e'/E_e \cos^2 \theta/2 \end{aligned}$$

(which the reader may verify from the definitions). In order to reconstruct (x, y) when only the outgoing hadrons are observed Jacquet and Blondel devised a method which minimises the effect of losses down the beam pipe [13]. They set

$$\begin{aligned} y &= \sum_h (E_h - p_{zh})/2E_e \\ Q^2 &= \left| \sum_h p_{zh} \right|^2 / (1-y). \end{aligned}$$

For proof see the Appendix. For hadrons lost in the beam pipe, $(E - p_z)$ and $p_\perp$ are both very small, and so they do not contribute. Note however that the sum is intended to be made over all the hadrons and not just those identified as being in a current jet. Missing neutrinos in the hadronic jet provide a bias, as does the finite aperture of the beam hole [14,15]. A much more serious effect at high Q^2 is the energy resolution of the calorimeter.

Figure 6 shows a polar diagram of the electron and current jet momenta as a function of x and Q^2 . One sees how the hadron jet contours crowd together at high Q^2 . The useful Q^2 range for charged current events is directly dependent on the hadron energy resolution (see Figure 7). As this is a fundamental study for HERA, there is therefore a strong motivation to have the best possible hadron calorimeter energy resolution, and both collaborations have addressed this topic energetically.

Before discussing the techniques used to optimise the jet energy resolution we note that at low- x the situation is quite different. Figure 8 shows, for $x \sim 0.01$, outgoing electron and jet directions at different beam energies, superimposed on an outline of the inner part of the ZEUS detector. Here it is the electron momentum which dominates over the parton momentum. Accurate energy (and electron direction) measurements in the rear direction, are important.

The energy of a particle or jet of charged and neutral particles is measured efficiently in a calorimeter with a fractional resolution that improves as $E^{-1/2}$ (because of the increase in shower statistics) and a detector depth that grows only as $\log E$. To obtain sufficient hadronic absorption lengths in a reasonable space one uses dense (and therefore high Z) absorber plates interspersed with active detector layers, usually of lower Z . For an electromagnetic shower in such a sampling calorimeter one expects:

$$\frac{\sigma(E)}{E} = 0.05 \sqrt{\frac{\Delta E (1 + 1/N_{pe})}{E}}$$

for an electron of E GeV, losing ΔE MeV/layer with N_{pe} electrons seen per minimum ionising particle (mip) per layer [12]. For 3 mm DU (depleted uranium) and 2.5 mm scintillator $N_{pe} = 4$, $\sigma/E = 0.14 E^{-1/2}$.

In a detector with high Z absorber/low Z detector, electrons leave a signal less than that of a minimum ionising particle (say a muon) [16]. This is because the energy lost by the electrons is detected downstream and migrates to regions of high Z , as can be seen from the Z -dependence of the energy-detecting processes: ionisation and Compton scattering (Z^1), pair production and bremsstrahlung (Z^2) and, the dominant contribution, photoelectric effect (Z^5). Thus e/mip is about 0.6 for DU/Sci, 0.7 for Pb/liquid argon, 0.85 for Fe/Sci, 0.95 for Cu/liquid argon.

For hadrons the situation is more complicated and the losses are greater. A hadronic shower has, compared to an electromagnetic shower, fewer interactions (each of high multiplicity) and a large unknown loss of energy (the binding energy of the struck nucleon) at each interaction. A variable fraction is lost in neutrinos, and each time a π^0 is made the energy is deposited much more locally (on a scale X_0 (rad) ~ 1 cm, not λ_{int} ~ 15 cm) as an electromagnetic shower. The result is that there is significantly less energy deposited (typically 70% of that from an electron-initiated shower of the same energy), but a widely varying distribution, reaching all the way up to the electron energy for those occasional cases where the shower is dominated by π^0 s (see Figure 9(a)). As a result hadronic energy resolution is much degraded compared to electromagnetic resolution, $\sigma/E = (0.7 \text{ to } 1.0) E^{-1/2}$ typically, and the ratio of energies dumped by an electron and a hadron, $e/h \sim 1.7$.

The hadronic energy resolution is improved by making the energy measurement insensitive to the π^0 content of the shower. In the jargon one 'compensates' for nuclear energy losses to achieve $e/h = 1$. (The jargon is a little unfortunate. Values of e/h greater than or below 1 can be achieved). The two experiments have chosen different routes - hardware compensation in the case of ZEUS, and software compensation for H1.

The ZEUS experiment use of calorimeter mode of depleted uranium and scintillator layers.

In a depleted uranium-scintillator calorimeter, neutron spallation and γ -emission provide an opportunity to compensate for the hadronic energy loss [16-19].

If one adjusts the calorimeter properties to achieve exact compensation, $e/h = 1$, then hadron energy resolutions of $(0.30 \text{ to } 0.35) E^{-1/2}$ are achieved. The following effects determine the response of a DU-scintillator to hadronic showers:

- Ionisation by charged particles (dE/dx).
- Electromagnetic showers from the decay of π^0 , giving $e/mip \sim 0.6$. The low energy component ($E \leq 1\text{MeV}$) is mostly lost into the DU by photoelectric effect.
- Hadron-nucleus collisions. One loses typically 15-20% of the energy to nuclear binding and neutrinos, but gains fissions (4.1/GeV for 300 GeV pions) and spallation neutrons (450 neutrons of $\sim 3 \text{ MeV}$ for 10 GeV protons) over a timescale of order 100 ns (somewhat matched to the HERA inter-crossing time).
- Spallation neutrons give np elastic scatters on the free hydrogen in the scintillator. (For a detector such as liquid argon without free hydrogen this mechanism is negligible, although γ -emission gives some compensation).
- The slow protons ionise the scintillator. $\beta \sim 0.08$ and $dE/dx \sim 1/\beta^2$ so saturation effects are important. The light output follows Birks' law

$$\frac{dL}{dx} = \frac{S \frac{dE}{dx}}{1 + K_B \frac{dE}{dx}}$$

$$(K_B \sim 0.01 \text{ g cm}^{-2} \text{ MeV}^{-1} - \text{ see Figure 10})$$

One sees that electrons give a signal 40% below a mip. Hadrons are suppressed even further, but the compensation mechanism, through np scatters in a hydrogenous detector (such a scintillator or tri-methylpentane), provides an enhancement. By adjusting the detector parameters, one can achieve compensation with 1-2%. The energy resolution will be

$$\frac{\sigma(E)}{E} = \frac{0.22}{\sqrt{E}} \oplus 0.09 \sqrt{\frac{\Delta E (1 + 1/N_{pe})}{E}}$$

for 3 mm DU, 2.5 mm Scintillator, $N_{pe} = 4$, $\sigma/E = 0.33 E^{-1/2}$. Here and below $\oplus$ symbol means the terms are to be added in quadrature. Figure 9(b) shows some results from ZEUS tests. Compensation and improved resolution are seen when DU is used. Since spallation occurs in all heavy elements, compensation can be achieved with Pb/Sci. A resolution of $0.45 E^{-1/2}$ has been achieved, the best seen in a non-uranium calorimeter, but with an electromagnetic resolution degraded to $0.24 E^{-1/2}$ [21].

One can tune the e/h ratio as a function of plate thickness, and is able to pick a precise configuration and predict its performance [22]. Figure 11 shows results up to 100 GeV beam energy. Linearity is better than $\pm 1/2\%$. For hadrons in the energy range 10-100 GeV they find:

$$\sigma/E = 0.34 E^{-1/2} \oplus 0.013.$$

From this experience we proceed to the design of the high resolution calorimeter. Each calorimeter tower consists of repeated units of depleted uranium and scintillator give one sample each radiation length in the hadronic part. Each DU plate is clad in steel to reduce the radioactivity emitted to a level that does not provide a troublesome background to energy measurement, but does provide a ready, universal, absolute stability monitor. Each calorimeter tower has 146 to 186 such layers. The towers are $20 \times 20 \text{ cm}$ with three depth segmentations (EMC, HAC1, HAC2 except at the rear) read out with wavelength shifter bars both sides to photomultipliers at the rear. The front (EMC) section has $5 \times 20 \text{ cm}$ towers. In the barrel region (BEMC, BHAC) the towers have a wedge shaped layout (32 sectors), and a pointing EMC section. In all there are 7612 electromagnetic readout channels and 5228 hadronic channels. There are 499 tons of depleted uranium, and 23 tons of scintillator.

A calorimeter of great statistical precision has an advantage only if its systematic errors (calibration, uniformity, time dependence) can be controlled equally well. Tests have shown almost no change in attenuation length (a) with radiation dose (b) with time, and great uniformity by the use of reflection masks (c) across the scintillator of an EMC tower and (d) in depth down a wavelength shifter bar. The irregularities across cracks are also found to be very small. No cracks point at the vertex.

The hadron energy measurement is completed by the backing calorimeter. This detector has extruded aluminium proportional tubes between 7.5 cm thick layers of iron. It provides measurement of the energy in the tail of a shower to resolution $1.0 E^{-1/2}$, or can be used to define events contained fully in the uranium. Triangular cathode pads provide measurement of a through-going muon trajectory to 2 mm accuracy along the wire.

The H1 collaboration have adopted a different approach [23], using lead or stainless steel absorber plates and a liquid argon sampling medium. This allows very many more readout

channels than in the ZEUS technique, so that the calorimeter is finely segmented both in transverse dimensions and in depth (see Figure 12). The tower size in the forward electromagnetic part of the calorimeter in $3.0 \times 3.0 \text{ cm}^2$, matched to the Molière radius of electromagnetic showers, with four depth segments. Pad sizes in the hadronic section are typically $12 \times 12 \text{ cm}^2$, with typically six depth segments. The electromagnetic section is up to $30 X_0$ deep and the total calorimeter depth varies between 4λ and 8λ with polar angle - the calorimeter being thicker in the forward direction where the most energetic particles are found. As in ZEUS, the calorimeter is completed by a coarse calorimeter (known as the 'tail catcher').

Figure 13 shows the average deposited charge as a function of depth for 170 GeV pions (a) all events (b) events contained in the main calorimeter [24]. Monte Carlo shower calculations resemble the data, but are not quite perfect, reflecting the difficulty of computer modelling of hadronic showers. As expected, they find $e/h \sim 1.7$. The energy resolution for single hadrons is found to be $\sigma/E = 0.58 E^{-1/2} \oplus 0.06$. At this point one takes advantage of the fine segmentation, (60338 readout channels) to identify local clusters of energy at whatever depth in the calorimeter. One declares these to be electromagnetic in origin (from π^0 production, say) and rescales the gain for this cluster [25]. One obtains:

$$\sigma/E = 0.44 E^{-1/2} \oplus 0.01.$$

This energy resolution is obtained together with excellent spatial granularity, that will aid lepton identification, both for electrons and muons. Note however that this spatial granularity will certainly be needed if the energy clusters are to be spotted in a multiparticle hadronic jet.

Compared to a LEP detector, a HERA detector needs much superior hadron calorimetry, and the two HERA experiments have pushed the techniques forward. Other features necessary at HERA are:

Strong forward tracking and lepton detection, using Transition Radiation Detection for electron identification and forward magnetic toroids for muons.

Zero-degree electron-photon detector for luminosity monitoring, for tagging $Q^2 = 0$ photons, and for making radiative connections event by event.

A leading proton spectrometer to identify diffracted hard scatters.

The ability to run at a 10 MHz crossing rate.

HERA experiments offer a technical step on the route to high luminosity hadron colliders (LHC/SSC), where even shorter (15 ns) intercrossing intervals are needed. All devices must have short sensitive times and powerful rejection of out of time particles. This particularly

restricts drift chamber techniques, ruling out slow detectors such as TPCs. One needs to build out of time rejection into the detector geometry (see Figure 14). In addition the readout and trigger have to be built in a 'pipelined' manner, so that a new candidate event can be processed every 96 ns, even though this is less than the maximum drift time. As far as the first-level trigger (5-10 μs) a digital pipeline is used. This trigger reduces the rate to 1 kHz. Events can then be stored in a primary buffer for data reduction and event selection before output at 1-10 Hz.

The H1 and ZEUS detectors are illustrated in Figures 15 and 16. For further information see references [12, 23, 26].

4. The Physics Range

HERA will extend the accessible Q^2 range by a factor ~ 200 , and the x-range by a similar factor. Figure 17(a) shows the cross-sections in $\text{pb} = \text{events/day}$ expected for $ep \rightarrow eX$ in a $\log Q^2 - \log x$ plot. for $Q^2 > 10$, $x > 10^{-4}$ thousands of events/day are expected. The figure also indicates roughly the range explored up to 1991. A huge increase in available range is evident. This opens up new physics in the study of QCD evolution, in high Q^2 , (in the sense that perturbative calculations should be valid,) at very low x . In testing the weak propagators and chiral couplings at the scale $Q^2 \geq m_Z^2$ and in searching for new phenomena at the Fermi scale.

Figure 17(b) shows the region where accurate event reconstruction (in the sense that most events plotted in a $Q^2 - x$ bin arise truly from that bin, with a good calorimeter) is possible, using electron and jet measurements. For CC events only the jet region is accessible. The low Q^2 cuts arise from particle losses down the beam pipe. The high Q^2 limit is set by a demand of ≥ 20 events/year. There is a gap between the measurable region and the 1991 measured region. To link these, for example in structure function evolution, additional running is required at an intermediate energy. One choice is 100 GeV/c protons on 30 GeV/c electrons, giving $s = 12000 \text{ GeV}^2$.

There are three main neutral current QCD processes, illustrated in Figure 18 - deep inelastic scattering, QCD Compton ($\gamma q \rightarrow gq$) and photon gluon fusion ($\gamma g \rightarrow q\bar{q}$). Such $Q^2 \sim 0$ photoproduction processes are the dominant reactions at HERA. Photon-gluon fusion is the main source of heavy flavours (c, b), not present as constituents of the proton. DIS events produce hadrons over a wide range of final state hadronic mass, W . As examples, we illustrate three cases:

$W^2 = s(1-x)y$	1000	10000	50000 GeV ²
$< Q^2 = sxy >$	2500	70	100
$< x >$	0.7	0.007	0.002
$< N_{ch} >$ into det	7.5	13	20
evts/year	6	240K	300K

$W^2 \sim 100$ events, corresponding to PETRA energies, are very rare. Most events are much higher, and made at very low x . Figure 19 illustrates parton-shower calculations of the number of jets into the detector, and jet energies in the laboratory [27]. Note the curious feature that the high W^2 events are slow in the laboratory.

Boson-gluon fusion (where boson = $\gamma, Z^0, W^{\pm}$) produced $10^8 c\bar{c}$ and $10^6 b\bar{b}$ events per year. b -production is the dominant source of muons of $p_T > 4$ GeV and allows HERA to be used as a B -factory, for example in the study of $B^0 - \bar{B}^0$ oscillations. In the angular range $30^\circ < \theta < 100^\circ$ one day at full luminosity gives 250,000 charm and 3000 beauty events (see Figure 20). We discuss below the use of these in measuring the gluon structure function.

Figure 21(a) shows the number of events per year (200 pb^{-1}) for $Q^2 > Q_0^2$ by $e^- \text{ NC}$ and CC events. For $Q^2 > M_Z^2$ all processes fall roughly as Q^{-4} and the CC rates are roughly equal to (actually exceeding) the NC rates. Based on statistical limits, we expect to probe NC and CC events beyond $Q^2 = 30000$ and 40000 GeV^2 respectively. Figure 21(b) shows the mean Q^2 for $e^- p \rightarrow \nu X$ events as a function of $\sqrt{s}$. In 1991 $\langle Q^2 \rangle = 30 \text{ GeV}^2$. At HERA $\langle Q^2 \rangle = 4000 \text{ GeV}^2$, but the increase is much slower beyond here, as the W-propagator limits the rates for $Q^2 > M_W^2$. HERA has gone much of the way to asymptopia [28].

The massive increase in Q^2 -range at HERA opens up the weak-boson propagators to study for the first time. We pass right through the region where γZ^0 interference operates into a unified electroweak regime (see Figure 22(a)). Figure 22(b) illustrates the dramatic effects on the y -distributions, and the importance of polarised beams. For $x = 0.25, y = 0.8$ the ratio $\sigma(\gamma + Z^0)/\sigma(\gamma)$ varies between 2.5 (for e^-_L incident), and 0.3 (for e^-_R). There is ample room to check out detailed predictions of the standard model, or to look for variations around it.

Here for the first time we see the importance of making measurements with different beam helicities.

5. Quark Structure Functions

In lowest order, including the effects of γ, Z^0 and W exchange the differential cross-sections for deep inelastic neutral and charged current events are given by

For $e^\pm p \rightarrow e^\pm X$

$$\frac{d^2\sigma}{dx dy} = \frac{4\pi\alpha^2}{s^2 y^2} \left[xy^2 F_1(x, Q^2) + (1-y) F_2 \pm (y - y^2/2) x F_3 \right] \quad (1)$$

where $F_2 = 2 x F_1 = \sum_f A_f(Q^2) x [q_f(x, Q^2) + \bar{q}_f(x, Q^2)]$

$$x F_3 = \sum_f B_f(Q^2) x [q_f(x, Q^2) - \bar{q}_f(x, Q^2)] \quad (2)$$

the sum running over all flavours. Here

$$A_f(Q^2) = e_f^2 - 2 e_f y \gamma_e Q^2 / (Q^2 + M_Z^2) + (v_e^2 + a_e^2)(v_f^2 + a_f^2) (Q^2 / (Q^2 + M_Z^2))^2 \quad (3)$$

$$B_f(Q^2) = 0 - 2 e_f a_f a_e Q^2 / (Q^2 + M_Z^2) + 4 v_e v_f a_e a_f (Q^2 / (Q^2 + M_Z^2))^2 \quad (4)$$

where e_f, a_f, v_f are the quark charge and weak axial and vector couplings. The first term in A_f and B_f is purely electromagnetic, the second represents γZ interference, and the third is purely weak.

For $e^- p \rightarrow \nu X$

$$\frac{d^2\sigma}{dx dy} = \frac{\pi \alpha^2 s}{4 \sin^2 \theta_w (Q^2 + M_W^2)^2} \left[\sum_{u,c} x q_f(x, Q^2) + (1-y)^2 \sum_{d,s} x \bar{q}_f \right]$$

For $e^+p \rightarrow \bar{\nu} X$

$$\frac{d^2\sigma}{dx dy} = \frac{\pi \alpha_s^2 s}{4 \sin^2 \theta_w (Q^2 + M_w^2)^2} \left[\sum_{u,c} x \bar{q}_f + (1-y)^2 \sum_{d,s} x q_f \right]$$

In this case for d,s one understands the Cabibbo-rotated weak flavours

$$d_c = d \cos \theta_c + s \sin \theta_c, \quad s_c = s \cos \theta_c - d \sin \theta_c.$$

With four sets of measurements from $e^-_L p, e^-_R p, e^+_L p, e^+_R p$, one can unfold the $u, \bar{u}, d, \bar{d}$ distributions.

Approximate and exact unfolding procedures to establish the evolution of each structure function as a function of Q^2 have been given by Ingelman and Ruckl [29]. Figure 23(a) shows predictions for the change with Q^2 of F_2^{em} as a function of x , and Figure 24(b) plots the expected result as a function of Q^2 for runs of 100 pb^{-1} at 12000 and 98400 GeV^2 together with existing measurement at lower x .

The Q^2 -evolution of the proton-structure function arises because of the radiation of gluons from accelerated quarks, and the splitting of gluons into $q\bar{q}$ and gg pairs. As Q^2 increases the number of partons increases and hence the energy ($-x$) of each decreases. There is no *a priori* prediction of the distributions, but the change in the distribution with Q^2 is described by the Altarelli-Parisi equations [30].

$$Q^2 \frac{\partial}{\partial Q^2} \begin{pmatrix} q(x, Q^2) \\ \bar{q}(x, Q^2) \\ G(x, Q^2) \end{pmatrix} = \frac{\alpha_s(Q^2)}{2\pi} \int_0^1 \frac{dy}{y} P(y) \begin{pmatrix} q(x/y, Q^2) \\ \bar{q}(x/y, Q^2) \\ G(x/y, Q^2) \end{pmatrix}$$

where the 3×3 matrix P describes the splitting function for an elementary process such as $g \rightarrow q\bar{q}$. Thus, in analogy with an electromagnetic shower

$$P_{q\bar{q}}(z) = \frac{1}{2} \left[z^2 + (1-z)^2 \right]$$

$$P_{Gq}(z) = \frac{4}{3} \left[\frac{1 + (1-z)^2}{z} \right]$$

$$P_{q\bar{q}}(z) = \frac{4}{3} \left[\frac{1+z^2}{1+z} + \frac{3}{2} \delta(1-z) \right]$$

$$\text{and } P_{GG}(z) = 6 \left[-\frac{z}{1-z} + \frac{1-z}{z} + z(1-z) + \left(\frac{11}{12} - \frac{f}{18} \right) \delta(1-z) \right]$$

where f is the number of active flavours.

(The handling of the singularities is a little subtle, see for example Buras [31]; Dokshitzer, Dyakonov and Troyan [32].)

Experimentally, one has to solve these integro-differential equations to fit the measured structure functions as a function of Q^2 . The scale of the Q^2 variation is given by the strong-coupling constant, where to leading order

$$\alpha_s = \frac{12\pi}{(33-2f) \ln(Q^2/\Lambda^2)}$$

Modern analyses try to solve the equations directly, most recently by Harriman, Martin, Roberts and Stirling [33]. Acceptable fits are obtained to a wide range of data in νN , μN and μp scattering and the Q^2 evolution of F_2 and xF_3 is described well. The ability to extract the unknown Λ and gluon structure function $G(x, Q_0^2)$ at fixed Q_0 is more limited. The uncertainty in Λ is understandable as for most data $Q^2 \gg \Lambda^2$. Also as Q^2 approaches Λ^2 , α_s blows up and the theory, usually carried out to 2nd order in α_s (so that terms such as $P_{q\bar{q}}(z)$ are needed) becomes inapplicable. One finds solutions for Λ in the range 100 to 300 MeV, giving $\alpha_s \sim 0.2$. The gluon distribution at low Q^2 is not well determined. The gluon distribution is best tied down by WA70 data on inverse QCD Compton scattering ($pp \rightarrow \text{high } p_T \gamma \gamma$ via $qg \rightarrow q\gamma\gamma$). HMRS find $xG(x) = (1-x)^n$ where $n = 4.4$ or 5.1 depending on whether EMC or BCDMS data are preferred. We return later to the question of the Gluon Structure Function at very low- x .

HERA-derived structure functions can be used to test the running of α_s with energy. Figure 24 illustrates the anticipated accuracy [34].

6. W-boson Production

Intermediate vector bosons can be produced by processes such as $e^- p \rightarrow e^- W^\pm X$, $e^- p \rightarrow \nu W^- X$, $e^- p \rightarrow e^- Z^0 X$, $e^- p \rightarrow \nu Z^0 X$. ($e^- p \rightarrow \nu W^+ X$ is forbidden in leading order). From 200 pb^{-1} we expect about 100 W^- , 80 W^+ and 50 Z^0 events. These modest rates provide however a severe test of the standard model, as they test directly the triple-gauge boson vertex [36]. Figure 25 gives the leading Feynman diagrams. The leptonic and triple-boson processes individually give a cross section of 10^{-35} cm^2 , but the sum of the two is two orders of magnitude lower. Thus any anomalous process affecting this cancellation could produce a massive increase in the rate (see Figure 26).

If HERA is so sensitive to the triple gauge boson vertex, is it a good place to discover the Standard Model Higgs? the answer is, "No". HERA has a light quark-light lepton initial state, and Higgs production rates are very small. Depending on the mass, rates of order 1/year are predicted.

7. Exploration at High Q^2

The standard model of quarks, leptons and bosons has had widespread success, and prompted many theoretical attempts to explain or extend it. Tests for these in ep collisions have been studied in detail previously [37, 38], and we outline quickly some of them here. We shall see that for the production of new particles, the mass reach is comparable to, and sometimes above, that to be reached at LEP II. In some channels, such as coloured leptons, HERA has a clear advantage. The sensitivity is extended beyond the kinematic limit by a factor more than ten in mass, by the use of interference measurements. One sees in figure 22(a) and equations (3.4) that interference terms become effective at lower Q^2 than the pure intensity terms. The low energy limit of equation (4) is

$$B = -2e q_f q_e Q^2/M_z^2 + 4 \nu_e \nu_f q_e q_f Q^4/M_z^4$$

and the first term dominates for $Q^2 \ll M_z^2$. One measures this term by looking at electron-positron asymmetries (equations 1,2). The exploration of e^+ , e^- asymmetries, and particularly asymmetries between left- and right-handed beams, extends the mass range of our sensitivity.

Thus the introduction of new electroweak gauge groups, (for example extending $SU(2)_L \otimes U(1)$ to $SU(2)_L \otimes SU(2)_R \otimes U(1)$), alters figure 22(b) significantly.

Depending on the chiral structure of one's preferred mode, new bosons (eg right-handed W' or axial Z' etc) one or other of the six asymmetries that can be made from $\sigma(e^-_L)$, $\sigma(e^-_R)$, $\sigma(e^+_L)$, $\sigma(e^+_R)$ is the most sensitive. For new weak bosons mass ranges up to 0.5 TeV are

accessible [39].

If leptons and quarks are composites with common components then new interactions are possible. We know from QED tests in $e^+e^- \rightarrow e^+e^-$ for example, that the scale of any such interaction is of order 1 TeV. Recent measurements by CDF and UA2, comparing jet p_T spectra with QCD expectations out to 150 GeV/c, set lower limits on quark compositeness scales at 0.95 and 0.825 TeV [40]. However, this by no means excludes it from study at HERA. In addition to the exchanges of γ , W , Z we will see an effective 4-fermion interaction (see Figure 27). This is analogous to Fermi theory of beta decay obtained by setting

$|Q^2| \ll M_W^2$ and thus suppressing the W -propagator. The structure function will be modified, but it is the interference of the residual interaction with the standard model that extends the sensitivity to well beyond the kinematic limit [41,42]. (Compare the measurement of electroweak asymmetries at PETRA [43]). One has for the Lagrangian

$$L_{eff} = L_{SM} \pm g^2/\Lambda^2 \Sigma C(e\Gamma e)(\bar{q}\Gamma q)$$

where the Γ matrices may have various chiral structures. ($g^2/4\pi$ is set equal to 1 conventionally for these superstrong interactions). Large polarisation asymmetries results. In Figure 28 we show an asymmetry comparing $\sigma(e^-_L)$ and $\sigma(e^-_R)$ that probes couplings where the leptons and quarks have the same chiral structure for $\Lambda \equiv 5 \text{ TeV}$ (ie. LL , RR , VV , AA couplings to leptons and quarks). Comparing e^+_L and e^+_R combinations such as (LR, RL) are tested [43].

If the analysis of asymmetries is extended not just to $F_2(x, Q^2)$ but to the structure functions $u(x, Q^2)$, $d(x, Q^2)$ the nature of any new interactions can be further investigated. Different models for new Z' can give similar or radically different handednesses for u and d quarks. Different leptoquark s -channel exchange bosons may affect only one flavour, or may affect u and d flavours with opposite handedness. In general comparing e^-_L , e^-_R tests for cases where the chiral couplings to leptons and quarks are the same. Comparing e^-_L , e^+_L tests for cases where the chiral couplings to leptons and quarks are opposite.

Another extension of the standard model to be considered is that there may be new fermion states. At present each generation of fermions is classified into left-handed weak isodoublets and right-handed singlets

$$\begin{pmatrix} \nu \\ e \end{pmatrix}_L, \begin{pmatrix} u \\ d \end{pmatrix}_L, e_R, u_R, d_R.$$

There may be additional states, such as

$$\begin{pmatrix} L^0 \\ e \end{pmatrix}, \begin{pmatrix} u \\ D \end{pmatrix}_R \text{ or } \begin{pmatrix} \bar{u} \\ d \end{pmatrix}_R,$$

coupling via right handed W, Z . W_R have been excluded up to 300 GeV for massless L_R^0 from studies of μ -decay [44]. For massive L_R^0 the situation remains open.

Present data set $m_{U,D,L} > 20$ GeV [45, 46, 47]. New Q, L can be produced by the exchange of existing or new W and Z 's. LEP limits depend on couplings to the Z^0 [48]. Spectacular final states are produced. For example the reaction $eq \rightarrow L^0 Q$ with $M_Q > M_L$ gives

$e^+ e^- \rightarrow e^+ e^- \ell^+ \ell^- q, e^+ e^- \ell^+ \ell^- q \bar{q}, e^+ e^- \ell^+ \ell^- q \bar{q} q \bar{q}$ with branching ratios of $\frac{1}{9}, \frac{4}{9}$ and $\frac{4}{9}$. Each quark is to be understood as a high p_T jet. Placing a limit of one event per ten days one finds one can access $(M_L + M_Q)$ up to 220 GeV if produced by W exchange, or $(M_L + M_Q)$ up to 175 GeV if a W_{2L} of mass 200 GeV is exchanged [37].

Alternatively there may be excited states of quarks and leptons, which can decay as $\ell^* \rightarrow e\gamma$ or $\nu W^*, q^* \rightarrow qg$ or $q^* \rightarrow qW^\pm$. Present limits on excited states are at relatively low masses. One can reconstruct invariant mass peaks and suppress backgrounds with kinematic cuts. The accessible mass range is limited by the beam energy to $m \leq 250$ GeV [37].

Supersymmetry has been proposed an explanation for the hierarchy problem, and naturally produces SUSY partners of quarks and leptons on the W and Z mass scale. The reactions with the greatest sensitivity are $eq \rightarrow \tilde{e}\tilde{q}$ by $\tilde{\gamma}$ exchange [49] and $eq \rightarrow eq$ followed by SUSY bremsstrahlung $e \rightarrow \tilde{e}\tilde{\gamma}$ [50]. A cross-section of one 0.1 pb allows one to access $M(\tilde{e}) + M(\tilde{q})$ up to 180 GeV. The event signatures are spectacular - high p_T lepton + high p_T jet + missing p_T + discrepancy in y as calculated from the lepton and from the jet. This allows great sensitivity and background suppression [37, 51] (See Figure 29).

Lastly we address the question of generations in another way. Why is the electron charge exactly equal and opposite to the proton? Theories that attack this question - be they grand unification, technicolour or SUSY produce leptoquark or leptoquark bound states, often with masses in the Fermi-scale, as the same naturalness question that fixes the W and Z masses so far below the Grand-Unified scale pushes the leptoquark states into this region [52-55]. Such states give strong signatures and peaks in the lepton-jet mass spectrum [37, 56]. A leptoquark produced by eq fusion shows as a sharp peak in the x distribution, whether it decays to eq or νq . An isotropic decay distribution shows up as a flat y distribution. Such events stand out very strikingly in an x - y plot over the background of normal DIS events. Leptoquarks which

are simulating the Higgs mechanism (as in Technicolour) couple preferentially to heavy quarks, and are produced from gluons in the proton making a $Q\bar{Q}$ pair, one of which fuses with the electron. These do not make a peak in the x -distribution, but one can still reconstruct a narrow mass peak, even if the preferred decay is via τ , with missing neutrinos [37, 57].

Production rates (often mediated by unknown mixing angles) can be large, so that the mass range explored extends almost up to the kinematic limit. The discovery of such an object would be a prize to crown the field of lepton-hadron physics and an answer to the riddle: if leptons and quarks are so similar in properties and arranged so neatly in generation multiplets, where is the underlying dynamics that enforces this pattern?

8. Low- x . A new Regime

For the region $x < 0.01$ the structure function is largely undetermined by existing data or fits, even within QCD fits, as shown in Figure 30, where a variety of different fits are extrapolated into this region. The gluon structure function is equally undetermined. The Altarelli-Parisi equation relates the Q^2 -evolution of the gluon distribution to the quark and gluon distributions at higher- x .

When making measurements at low x , and particularly also at high- y , one has to take careful account of radiative corrections. One writes

$$\frac{d^2\sigma}{dx dy} = \frac{d^2\sigma}{dx dy} \Big|_{\text{Born}} (1 + \delta).$$

Calculations of δ due to initial and final state γ -radiation from the electron, (we discuss only neutral current processes,) are shown in Figure 31(a) [58]. $\delta = 1.0$ means the observed rate will be a factor 2 above the Born calculations. However, these corrections can be tamed experimentally. Using the 0° luminosity monitor one can tag or veto forward γ 's, subject to backgrounds, and can veto or tag wide angle γ 's in the main detector. One can also cut out events where the outgoing electron and jets give incompatible (x, y) . This makes the radiative corrections modest, slowly varying with y , and experimentally verifiable (see Figure 31(b)).

The work of Harriman *et al.* [33] suggests a Gluon Structure function $xG(x) \sim (1-x)\eta$ at $Q^2 = 4$ where $\eta = 4.4$ or 5.1, based on fits to existing data. Kwiecinski *et al.* have pointed out that a flat $xG(x)$ distribution is not stable as Q^2 increases at $x < 10^{-1}$ [59] (see Figure 32). There is presently considerable theoretical interest in the possible forms of $xG(x)$ at low- x [60, 61].

Consider the photon-gluon fusion diagram shown in Figure 33(a). As Q^2 is increased the

gluon will radiate others, as in 33(b). Altarelli-Parisi evolution assumes strong ordering in Q^2 ($Q^2 \gg k_{t1}^2 \gg k_{t2}^2 \gg \dots \gg k_{tn}^2 \gg Q_0^2$) and in x ($x \ll x_n \ll x_{n-1} < 1$). As $x \rightarrow 0$ this is no longer sufficient and instead we need the Gribov, Levin, Ryskin equation (see Figure 34 taken from ref. [62]).

The gluon distribution valid to leading order in $\ln(1/x)$ found by Kwiecinski *et al.* [59] is

$$\lim_{x \rightarrow 0} xG(x, Q^2) = h(Q^2) x^{-\lambda}$$

where $\lambda \sim 12/\pi \alpha_s(k_0^2) \sim 0.5$

Thus approximately $xG(x, Q^2) \sim h(Q^2) x^{-1/2}$ [60].

To find the cross-section one needs the modulus-squared of the amplitude (in Figure 33(b)), i.e. the diagram of 33(c). One sees that we have generated a ladder-diagram. We have Reggeised the gluon to make a 'Pomeron'. The intercept of the Pomeron-Regge trajectory

$\alpha_R^0 = 1 + \lambda \sim 1.5$, giving a σ (semihard) which rises with energy as s^{α_R-1} . This grows with energy and would eventually exceed the total cross-section. This, of course, will not occur. The mean free path of a photon on the proton becomes small compared to the proton diameter, so that a photon beam is rapidly attenuated. This parton "shadowing" or "saturation" is analogous to the dip seen at $x = 0$ in the EMC effect. As a result the rise as $x \rightarrow 0$ may be significantly slower than $1/\sqrt{x}$. $G(x)$ can be measured in a number of ways, for example by measuring σ_L/σ_T at fixed x and Q^2 - the photon polarisation can be varied by varying the centre of mass energy [63], or by measuring inclusive J/ψ production. The reaction $\gamma g \rightarrow (J/\psi)g$ proceeds via a c -quark loop. High rates are obtained at $Q^2(\gamma) = 0$. If the photon energy is tagged in the zero-degree luminosity monitor, we demand $E_\psi/E_\gamma < 0.8$ and $p_T^2(\psi) > 0.1 M_\psi^2$. The perturbative calculation can be relied on and good statistical accuracies can be obtained. Figure 35 shows the power to discriminate different current models of $xG(x)$ [64].

Parton saturation can be investigated in another way by looking at diffracted hard scattering, see Figure 36 [65]. Diffracted events are tagged in the ZEUS detector by a high-momentum forward proton ($x_F > 0.9$). Depending on one's point of view on the parton structure of the Pomeron, widely different predictions are made of, for example, high p_T jet production angular distributions and the mass spectrum in b -production events.

The gluon structure function of the photon may be investigated in deep inelastic scattering. One distinguishes 'direct' photon reactions, in which the point-like γ explores the gluon structure of the proton, from the 'resolved' photon, in which the photon is broken into partons

and one of these undergoes the hard scatter (see Figure 37). The Altarelli-Parisi distributions for the photon generate a quark component even for $\alpha_s = 0$, and a gluon component arises from the $\alpha_s \neq 0$ evolution of this. (It comes from the particular integral of the inhomogeneous equation.) Fletcher *et al.* [66] point out methods for tagging resolved-photon events using an electron-tag in the luminosity monitor to get the energy of $Q^2 = 0$ photons. Event reconstruction from the outgoing hadrons will show a lower energy for the participating parton. In high p_T inclusive J/ψ production the direct photon events go backwards and resolved events forwards relative to the proton direction.

The whole question of parton saturation and low- x structure is in a state of great theoretical interest. Cross-sections are high and events simple. If suitably understood triggers can be operated and the tagging of forward electrons, gammas and protons mastered, a productive period is expected.

9. Where is the Proton Spin?

The first (pre-natal) success of the quark model, was to explain the proton magnetic moment in 1933 [67]. We end the discussion of hadron structure with a failure, or at least a problem, in accounting for the proton spin. By scattering longitudinally polarised muons from a longitudinally polarised proton target, EMC measure the spin structure of the proton [68]. They measure the polarisation asymmetry,

$$A = \frac{d\sigma_{\uparrow\downarrow} - d\sigma_{\uparrow\uparrow}}{d\sigma_{\uparrow\downarrow} + d\sigma_{\uparrow\uparrow}}$$

Correcting for photon depolarisation they obtain the photon-nucleon asymmetry A , shown in Figure 37. The results are consistent with earlier work, but not with the extrapolation to low- x made previously. From this asymmetry they extract the polarised structure function

$$g_1(x) = \frac{1}{2} \sum_{i=u,d} e_i^2 \left[q_i^+(x) + \bar{q}_i^+(x) - \bar{q}_i(x) - \bar{q}_i(x) \right]$$

where the $\pm$ sign shows the quark spin alignment relative to the proton. The result is shown in Figure 37. The integral $\int_0^1 g_1(x) dx$ appears to settle at $0.114 \pm 0.012 \pm 0.026$.

The Bjorken sum rule gives [69,70]

$$\int_0^1 dx [g_1^p(x) - g_1^n(x)] = \frac{1}{6} \left| \frac{G_A}{G_V} \right| (1 - \alpha_s/\pi) = 0.191 \pm 0.002$$

This is a fundamental parton model sum rule. With extra assumptions, Ellis and Jaffe (1974) gave

$$\int_0^1 g_1^p(x) dx = \frac{1}{12} \left| \frac{G_A}{G_V} \right| \left[\left(1 + \frac{5}{3} \frac{F(D-1)}{F(D+1)} \right) \right] = 0.189 \pm 0.005$$

in strong disagreement with the EMC measurement. Hence one deduces that only $(14 \pm 9 \pm 21)\%$ of the proton spin is due to u and d quarks.

Various escapes are proposed - disbelieve the analysis, polarise the strange quark sea, or settle for an unexpectedly dominant gluon contribution to the spin [71,72]. The lesson for experimenters is that the measurement at low- x should be repeated, and also done with polarised neutrons. Such an experiment is proposed for HERA by the HERMES collaboration, using a beam of polarised electrons incident on a polarised gas jet target, either hydrogen (protons), helium-3 (all spin from neutrons), or deuterium [73]. Target polarisations either along or perpendicular to the beam can be used. Expected precisions of $\int g_1^p(x) dx$ are four times better than for EMC, and first measurements will be made of $\int g_1^n(x) dx$, and of other spin structure functions $g_2^p(x)$, $g_2^n(x)$ and tensor structure functions of the deuteron. Running times are not long. The detector (Figure 38) is simply an electron spectrometer and is proposed for installation in HERA Hall East. Approval will be considered when electron beam polarisation has been established.

10. Summary

A varied and exciting programme of physics is foreseen at HERA. It makes new demands on accelerator and experiment techniques particularly in the areas of beam polarisation, hadron calorimeter resolution and crossing-rate. The reward is a new window on physics.

In the Quark and Boson sector we foresee structure function measurements up to $Q^2 \sim 40000$ GeV^2 , tests of QCD and the triple gauge boson vertex, measurement of parton growth and saturation, and comprehensive measurements of the nucleon spin structure.

There is a wide range of new physics possibilities to explore on the Fermi Scale - looking for new fermions, new bosons, new interactions and substructure. Accessible mass ranges are

estimated as

New Z	up to 800	GeV
New W	800	
New W_R, L_R^0	500, 250	
New quarks	120	
Excited q, l	250	
New Q, L	200	
Leptoquarks	180	
Substructure	4000-7000	
SUSY $\tilde{q}, \tilde{l}$	160-180	GeV

Beam Helicity has a major role in tests Z^0 and W phenomena, in measuring structure functions, in searching for new currents and substructure, and in tying down the nucleon spin. The next years are full of promise.

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Figure Captions

1. Layout of HERA.
2. Layout of spin-rotation snakes and zero-crossing angle geometry for $e^+_{LR}p$ collisions.
3. Arrangement of magnets and collimators ($C_1 - C_5$) and synchrotron radiation absorbers (A_1, A_2) close to the interaction region.
4. Kinematics of ep scattering.
5. Neutral Current and Charged Current scattering.
6. Polar diagram of the kinematics for the final lepton (upper part) and the current jet (lower part) at HERA. The laboratory energy and angle are found by connecting a given (x, Q^2) point with the origin.
7. x and y error ellipses obtained from calorimeter measurements (a) Electron measurement in NC interactions (b) Hadron measurement in CC interactions, showing two different energy resolutions.
8. Outgoing electron and jet directions at $Q^2 = 100$, $x = 0.002$ for different c.m. energies superimposed on the inner part of the ZEUS detector. CTD, RTD, FTD = tracking detectors. REMC, BEMC, FEMC = electromagnetic calorimeters, RHAC, BHAC, FHAC = hadronic calorimeters.
9. Pulse height distributions for 5 GeV, e, μ , hadrons with (a) Pb-scintillator (5 + 5 mm), (b) depleted uranium + scintillator (3.2 + 5 mm).
10. The ionisation loss and light output (arbitrary units) for protons.
11. ZEUS calorimeter tests - response to e, μ at energies of 10-100 GeV.
12. H1 calorimeter longitudinal and transverse tower segmentation. Rectangles represent the series of pads ganged together to form pseudo-projective towers shown in five places. Thicker lines in the e.m. part correspond to longitudinal segments.
13. Longitudinal shower shape for pions (MC and data) of 170 GeV. (H1 test) (a) all events, (b) events without large longitudinal leakage.

14. Electron drift lines and isochrones (constant drift-time contours, 50 ns intervals), in a unit cell of the ZEUS CTD (9 superlayers with 576 such cells in all). The points associated with a track, out of time by one crossing, are illustrated.
15. The H1 detector.
16. The ZEUS detector.
17. The accessible (Q^2, x) range. (a) Differential cross-sections $\Delta\sigma$ for each (Q^2, x) bin, together with the range explored to 1991, (b) area over which accurate (Q^2, x) reconstruction is possible with a good calorimeter using electron and jet measurements.
18. The main neutral current QCD processes.
19. Parton-shower calculations of the number of jets into the detector and of jet energies for $W^2 = 10^3, 10^4, 5 \cdot 10^4 \text{ GeV}^2$.
20. NC heavy flavour events cross-sections (pb/degree) for (a) charmed (b) beauty mesons.
21. (a) Events/year (200 pb^{-1}) at $Q^2 > Q_0^2$ for e^+p NC and CC events
(b) $< Q^2 > \sqrt{s}$ for CC events.
22. (a) Cross-section ratios, normalised to γ -exchange, as a function of Q^2 .
(b) Changes to NC reaction rates due to the presence of Z^0 exchange.
23. (a) Expected variation of F_2^{em} with Q^2 , (b) Anticipated results with errors shown for runs of 100 pb^{-1} at HERA nominal and reduced energies together with existing data. (From [35]).
24. Anticipated accuracy of determinations of $\alpha_s(Q^2)$ from scaling violations of F_2^{em} based on 200 pb^{-1} of data at 314 GeV and 100 pb^{-1} at 134 GeV.
25. Leading diagrams for $e^+p \rightarrow \nu W^+ X$ (a) leptonic, (b) triple gauge-boson, (c) hadronic.
26. Calculation of cross-section $d\sigma/dy$ for leptonic alone, triple boson alone, hadronic, and total.
27. Lepton-quark scattering by exchange of known and unknown bosons.

28. The left-handed right-handed electron cross-section asymmetry at $x = 0.5$ plotted against Q^2 for LL , RR interactions. Curves show effects of different scales Λ_H (TeV). $\Lambda_H = \infty$ gives the standard model.

29. Search for pair-production of SUSY particles. (a) Feynman graphs for $eq \rightarrow eq$ and $eq \rightarrow \tilde{e}\tilde{q}$. (b,c) Scatter plots of $\Delta\phi = (\pi - \text{angle between } e \text{ and jet directions in plane perpendicular to beam})$, against $\Delta y = (\text{difference in reconstructed } y \text{ using lepton and jet variables})$ for SUSY and standard processes without radiative corrections. Suppression factors of 10^{-4} to 10^{-6} are asserted.

30. Extrapolation of NC cross-sections to very low x showing a variety of fits to existing data.

31. Radiative corrections for NC events (a) calculations, (b) effect of cuts (solid line becomes dotted line) as described in text.

32. Evolution with Q^2 of $xG(x)$ which gives flat x distribution at $Q^2 = 4$ [59].

33. Photon-gluon fusion (a) lowest order, (b) multiple gluon emission, (c) intensity calculation for process (b).

34. QCD expansion formulae regions of validity.

35. Statistical and systematic errors on measurements of $xG(x)$ at $x \sim 0.001$ by inclusive J/ψ production.

36. Diffracted hard scattering (a) mechanism, (b) high p_T jet angular distribution for different models of the Pomeron structure function. (c) Hadronic mass for diffractive beauty production.

37. (a) Spin asymmetry measured by EMC, together with earlier results and a fit to earlier work.

(b) Spin structure function and its integral, showing statistical and systematic errors.

38. (a) Schematic view of the proposed HERMES electron-spectrometer.

(b) Components needed to produce and analyse the polarised deuterium gas fed into the target cell.

APPENDIX

The Jacquet-Blondel method for CC event reconstruction

m_e^2, m_p^2 are ignored throughout. A 4-vector is written as (E, p_x, p_y, p_z) .

Then

$$k = (E_e, 0, 0, -E_e)$$

$$p = (E_p, 0, 0, E_p)$$

$$p' = (E_H, p_T, p_z)$$

$$q = p' - p$$

$$W^2 = p'^2$$

$$Q^2 = -q^2$$

$$s = 4E_e E_p$$

Final state hadronic mass²

Mom. transfer

cm energy²

Now

$$x = Q^2/(2p \cdot q)$$

$$x = Q^2/(Q^2 + W^2)$$

$$y = (p \cdot q)/(p \cdot k)$$

$$y = (W^2 + Q^2)/s$$

$$p \cdot p' = E_p (E_H - p_z)$$

$$k \cdot p' = E_e (E_H - p_z)$$

$$-Q^2 = p'^2 - 2p \cdot p'$$

$$= W^2 - 2E_p (E_H - p_z)$$

$$y = (E_H - p_z)/2E_e \text{ as required}$$

Therefore

Now

$$s + t + u = W^2$$

where

$$t = -Q^2 \text{ and } u = (k \cdot p')^2$$

$$u = -2k \cdot p + W^2$$

$$s - Q^2 - 2k \cdot p + W^2 = W^2$$

$$2k \cdot p' = s - Q^2$$

$$2E_e (E_H + p_z) = s(1 - xy)$$

$$E_H + p_z = 2E_p(1 - xy)$$

$$E_H + p_z = 2E_e y$$

$$E_H^2 - p_z^2 = 4E_e E_p y(1 - xy)$$

$$E_H^2 - p_z^2 = sy(1 - xy)$$

$$W^2 = E_H^2 - p_T^2 - p_z^2$$

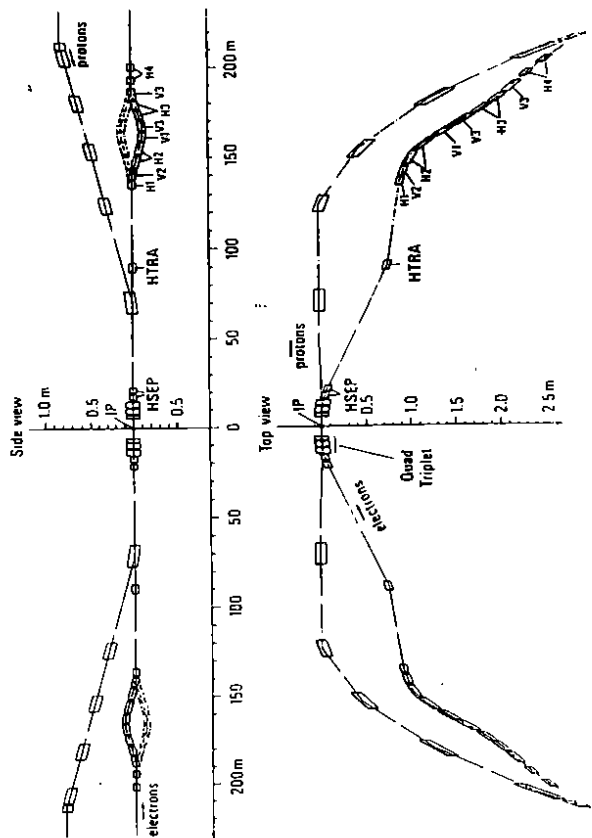
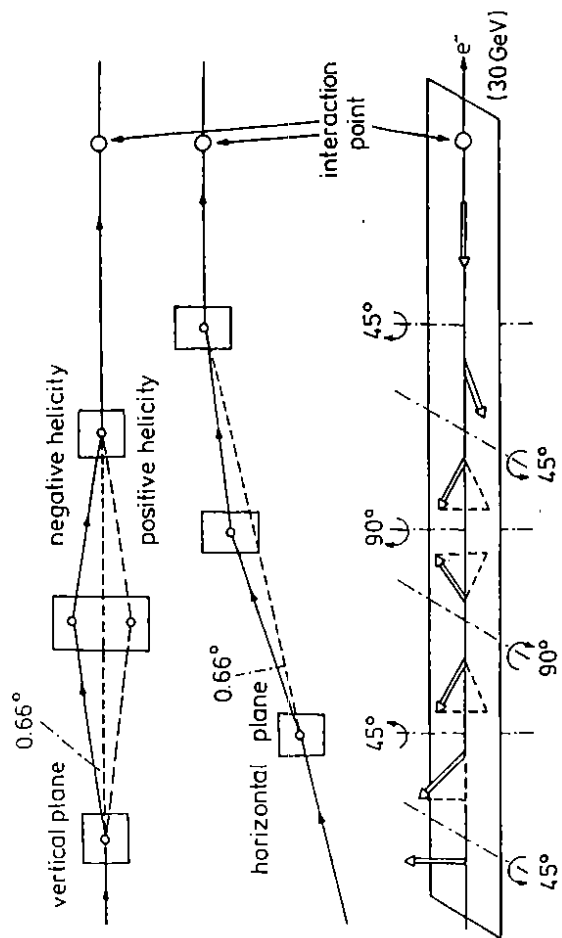
$$W^2 + p_T^2 = sy(1 - xy)$$

$$p_T^2 = sy(1 - xy) - sy(1 - x)$$

$$= sxy(1 - y)$$

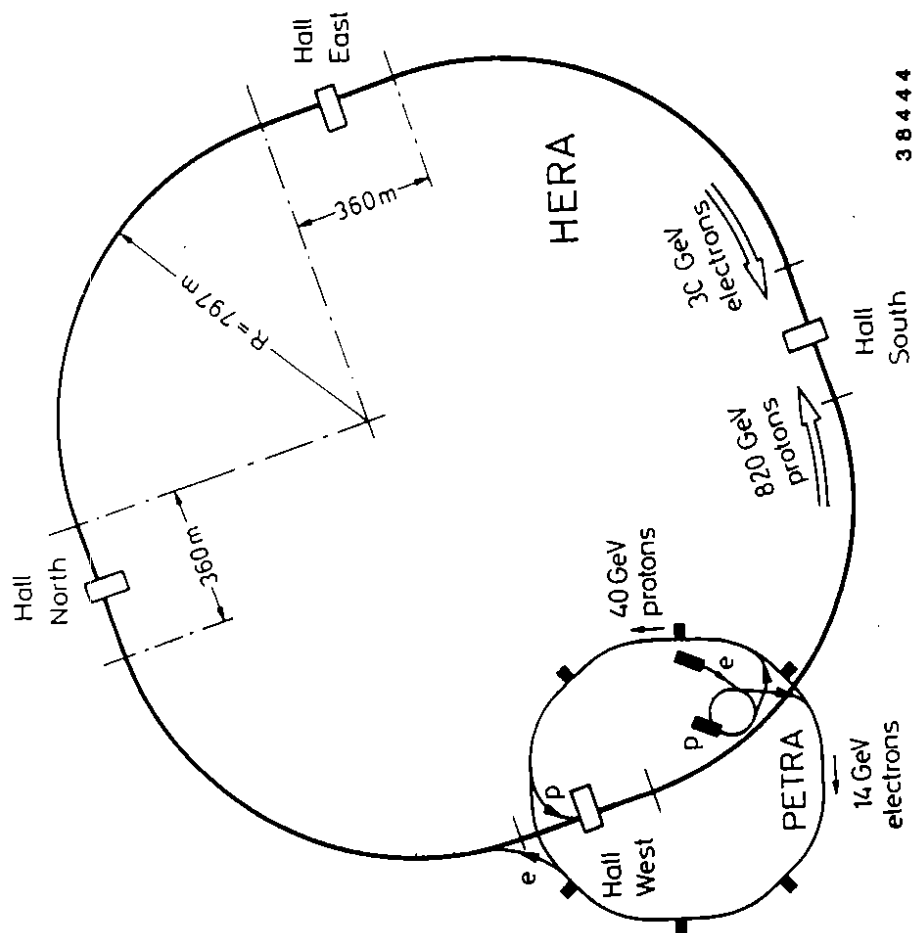
$$Q^2 = p_T^2/(1 - y) \text{ as required}$$

Therefore



39822

Figure 2.



38444

Figure 1.

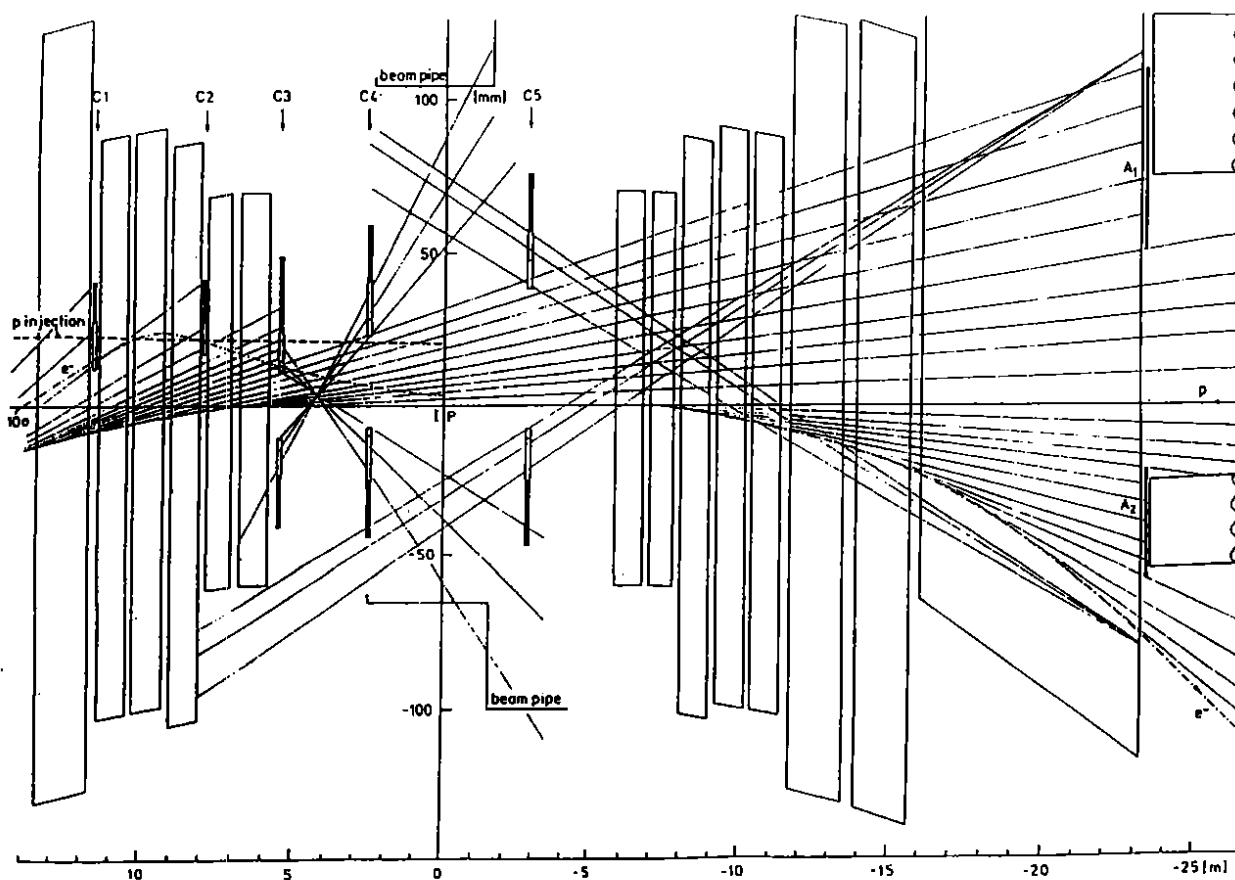


Figure 3.

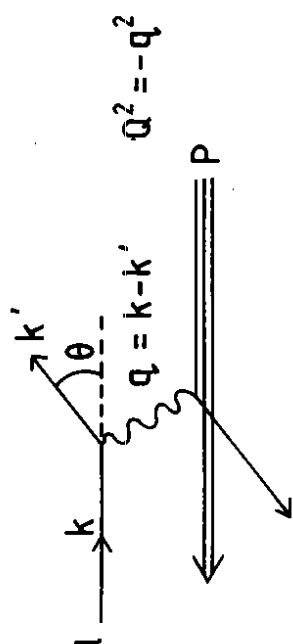


Figure 4.

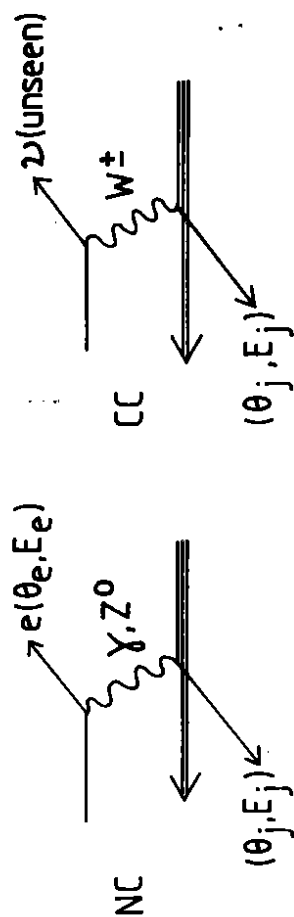
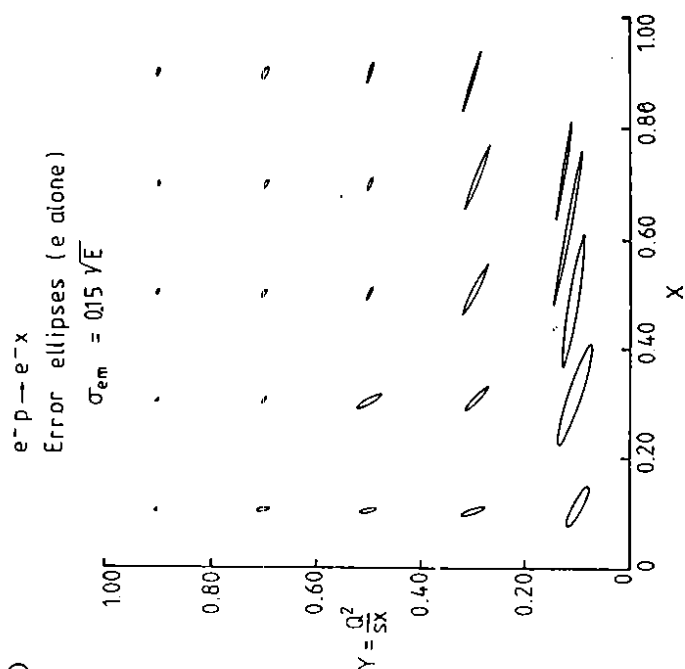


Figure 5.

(a)



(b)

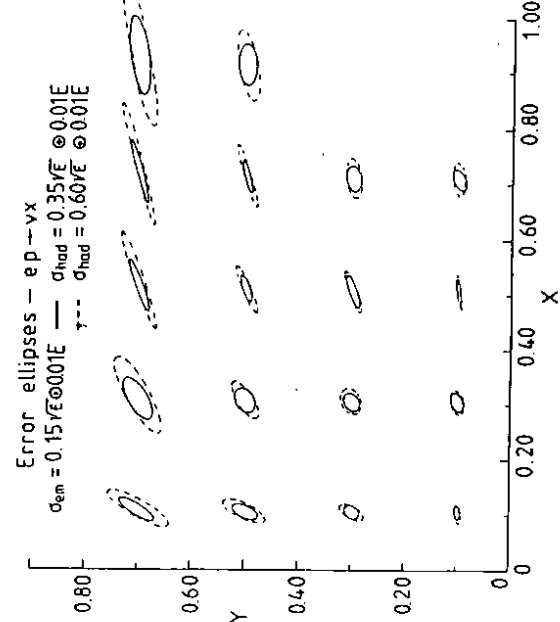
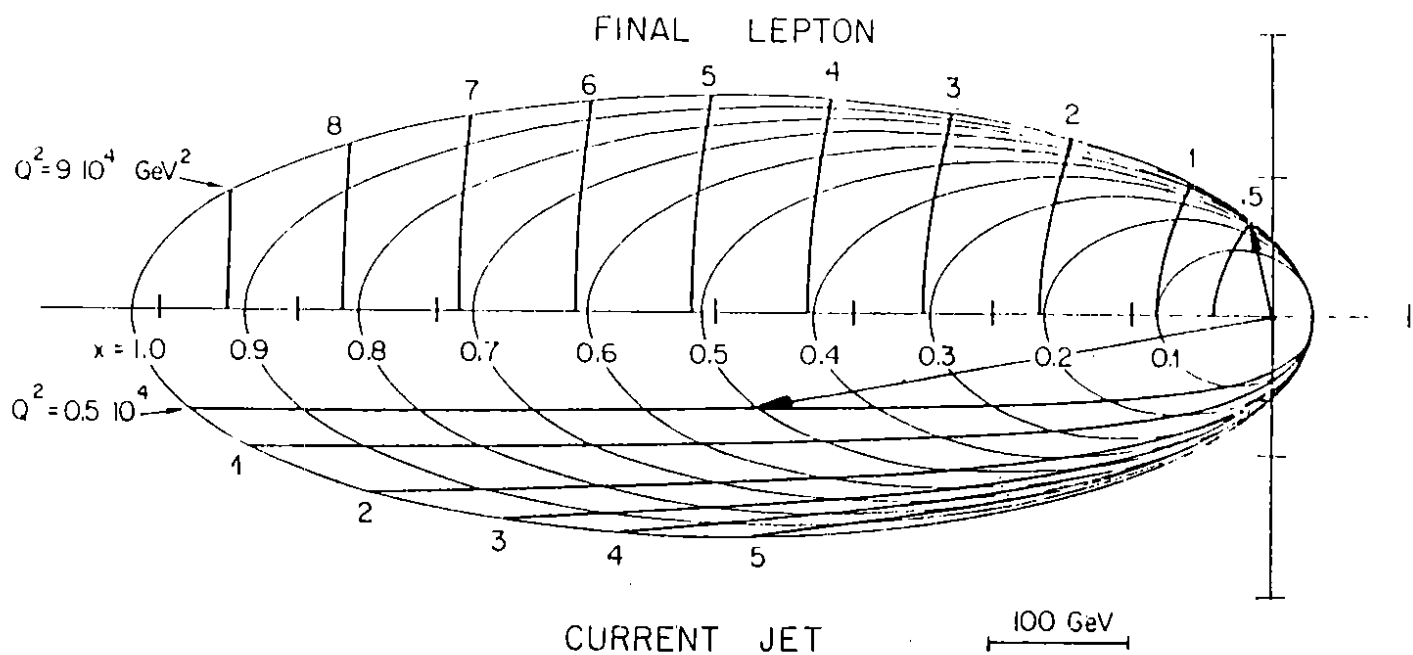


Figure 7.

Figure 8.



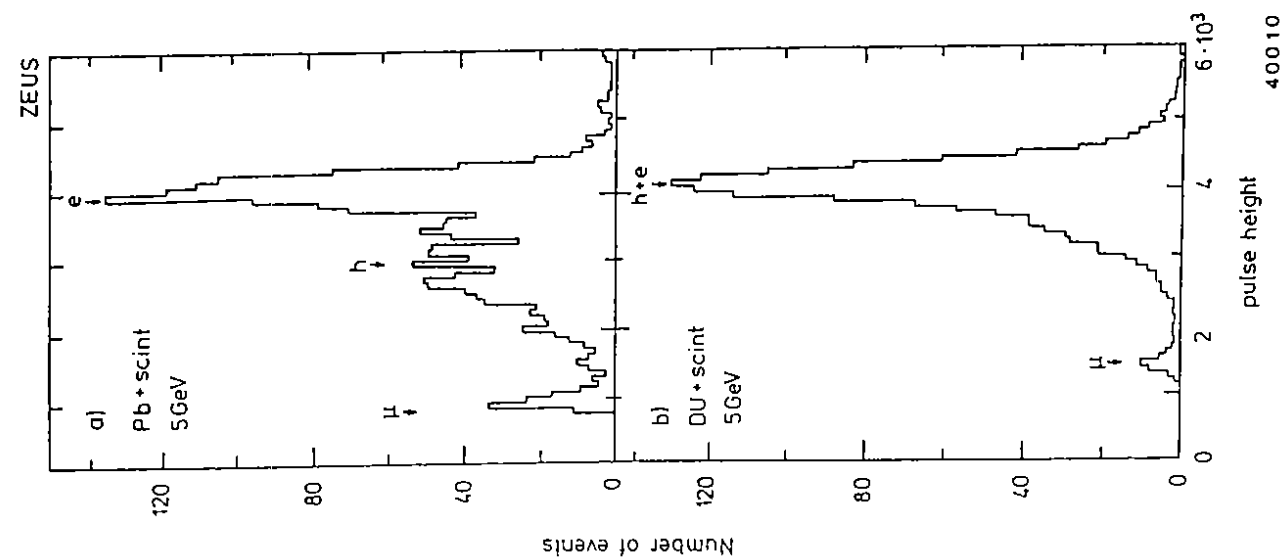


Figure 9.

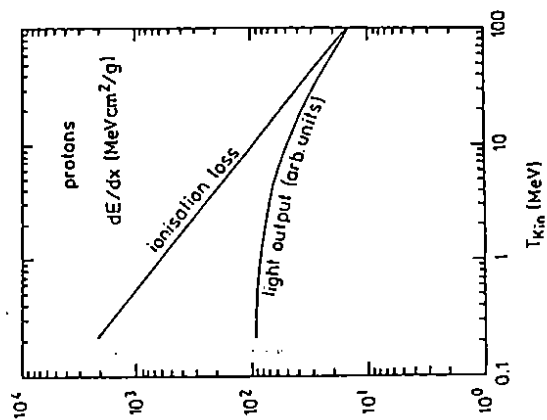


Figure 10.

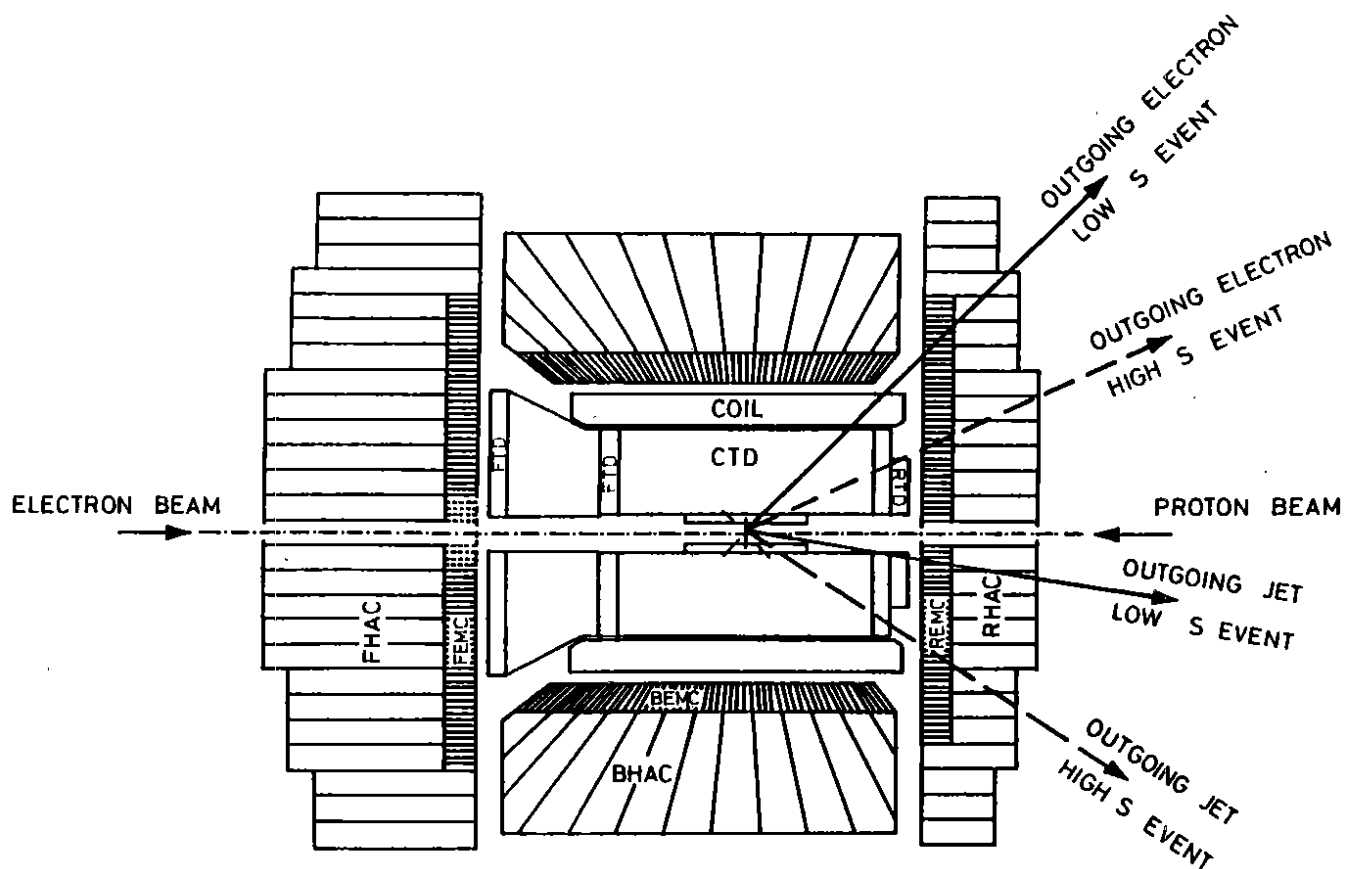


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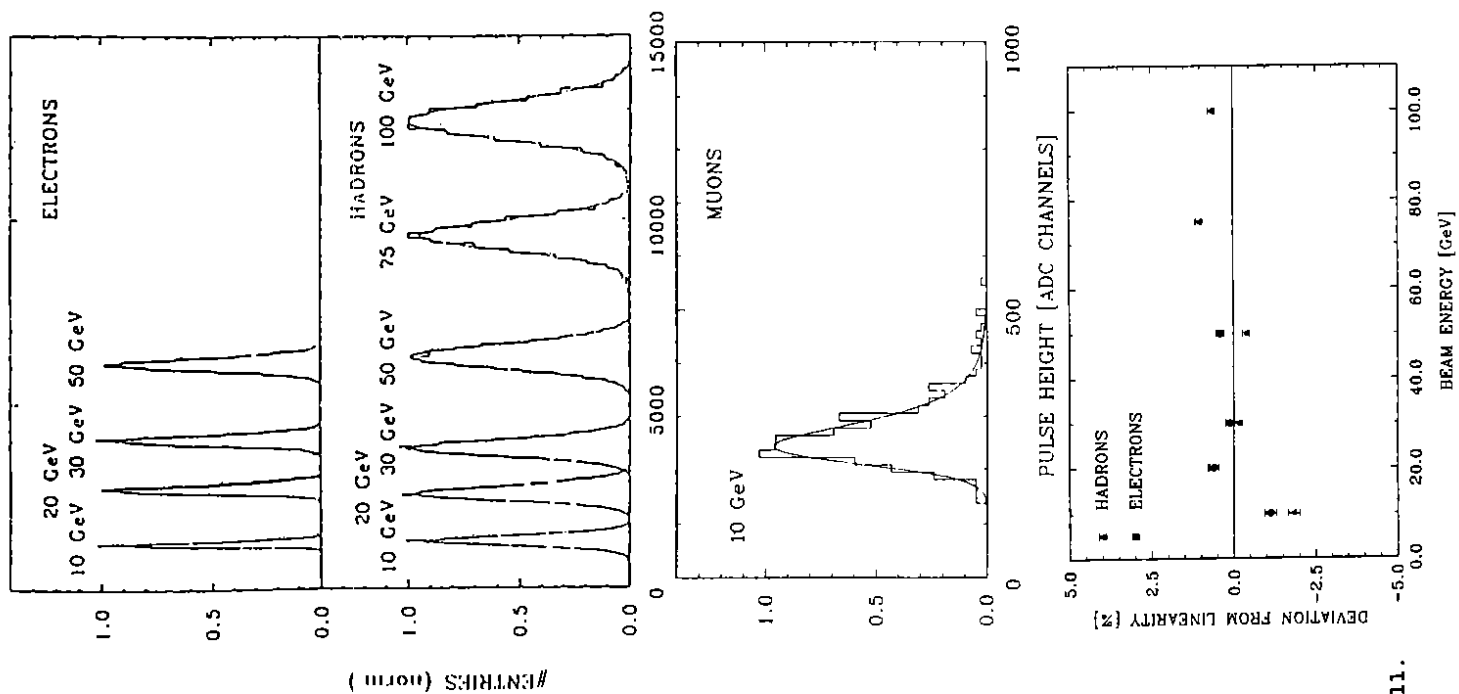


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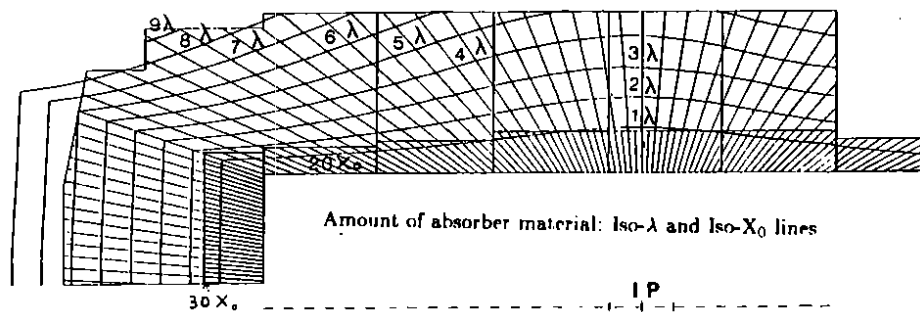
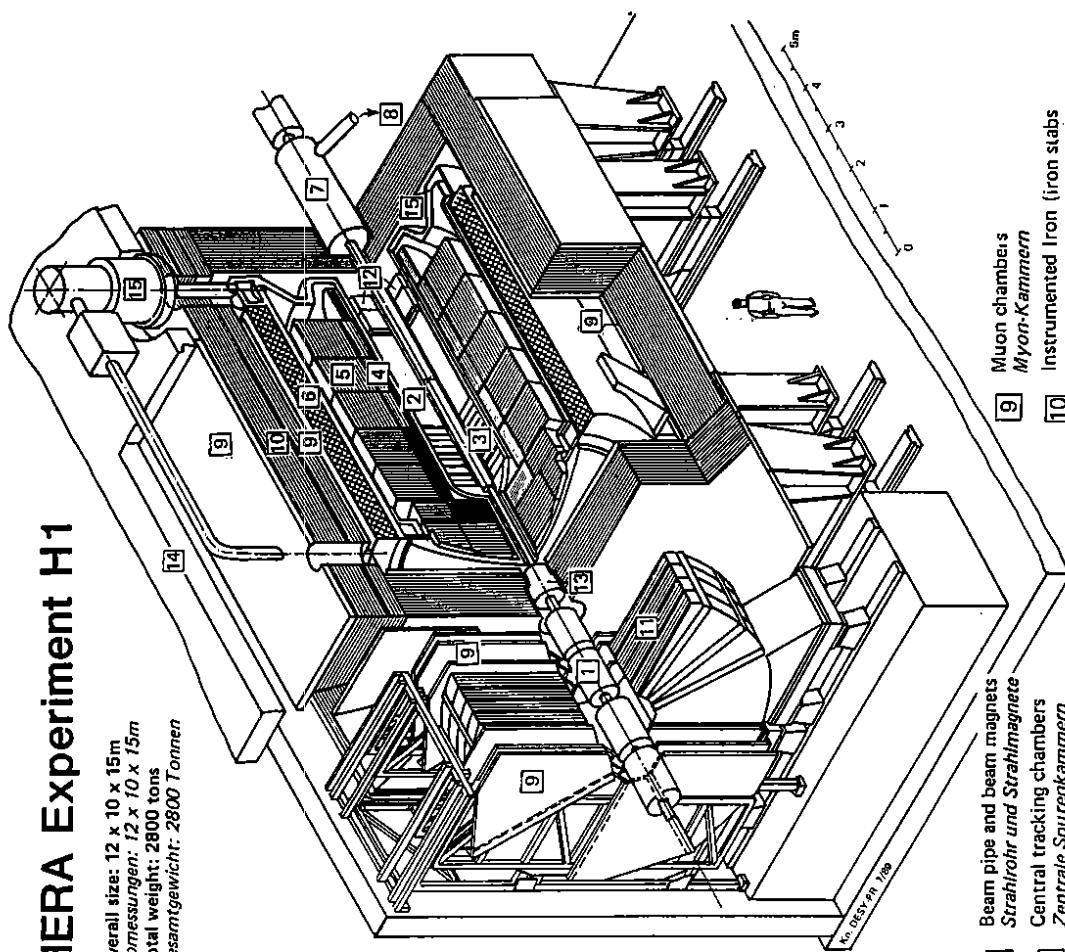


Figure 12.

HERA Experiment H1

Overall size: 12 x 10 x 15m
 Abmessungen: 12 x 10 x 15m
 Total weight: 2800 tons
 Gesamtgewicht: 2800 Tonnen



- | | | | |
|---|---|----|---|
| 1 | Beam pipe and beam magnets
Strahlrohr und Strahlmagnete | 9 | Muon chambers
Myon-Kammern |
| 2 | Central tracking chambers
Zentrale Spurenkammern | 10 | Instrumented Iron (iron slabs + streamer tube detectors)
Instrumentiertes Eisen (Eisenplatten + Streamerrohren-Detektoren) |
| 3 | Forward tracking chambers and Transition radiators
Vorwärtspurkammern und Übergangsstrahlungsmodul | 11 | Muon toroid magnet
Myon-Toroid-Magnet |
| 4 | Electromagnetic Calorimeter (lead)
Elektromagnetisches Kalorimeter (Blei) | 12 | Warm electromagnetic calorimeter
warmes elektromagnetisches Kalorimeter |
| 5 | Hadronic Calorimeter (stainless steel)
Hadronisches Kalorimeter (Edelstahl) | 13 | Plug calorimeter (Cu, Si)
Vorwärts-Kalorimeter |
| 6 | Superconducting coil (1.2 T)
Supraleitende Spule (1,2 T) | 14 | Concrete shielding
Betonabschirmung |
| 7 | Compensating magnet
Kompensationsmagnet | 15 | Liquid Argon cryostat
Flüssig Argon Kryostat |
| 8 | Helium cryogenics
Helium Kälteanlage | | |

Figure 13.

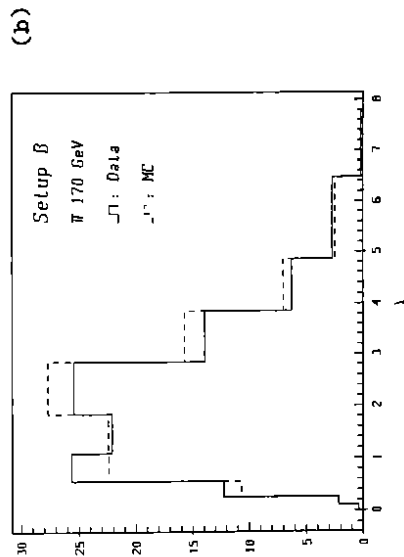
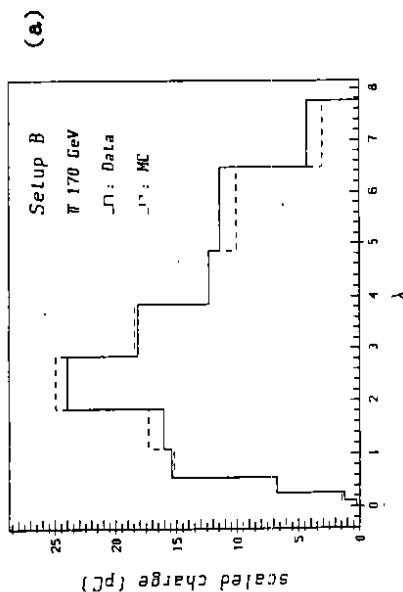


Figure 13.

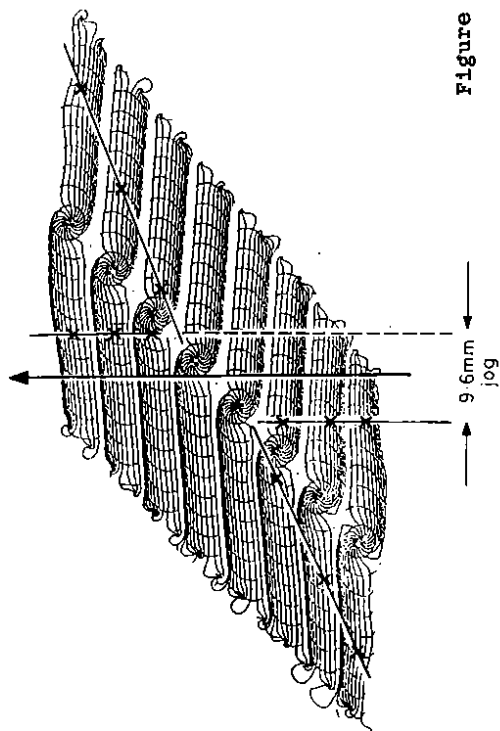


Figure 14.

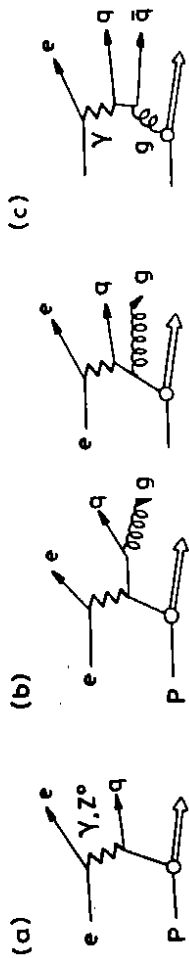


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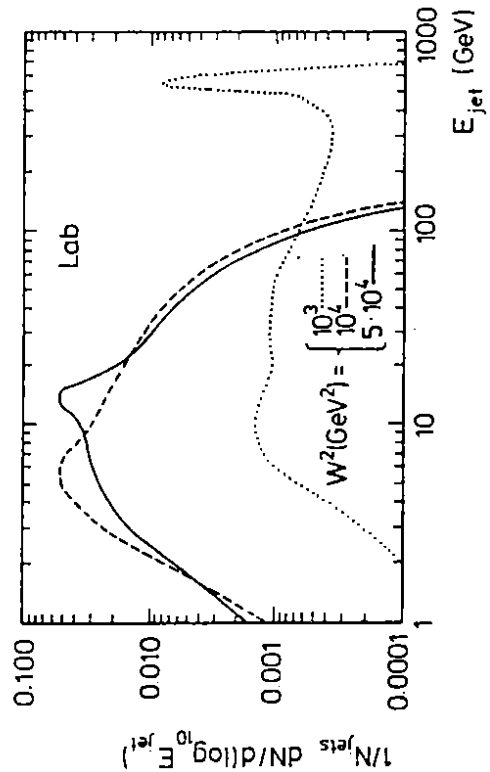
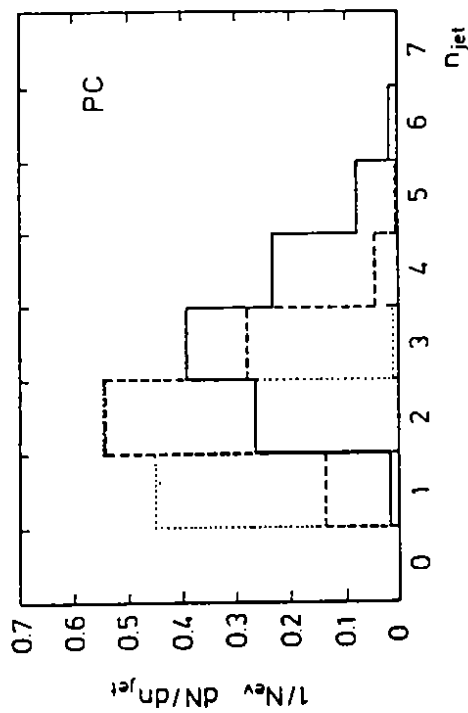


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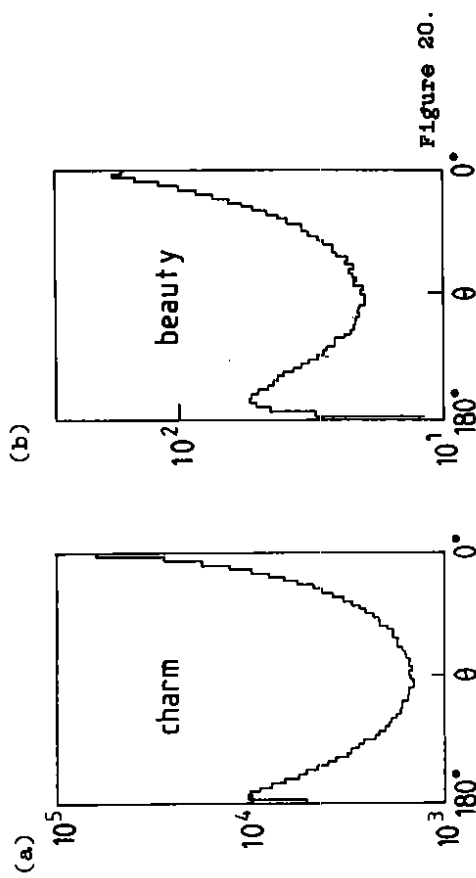


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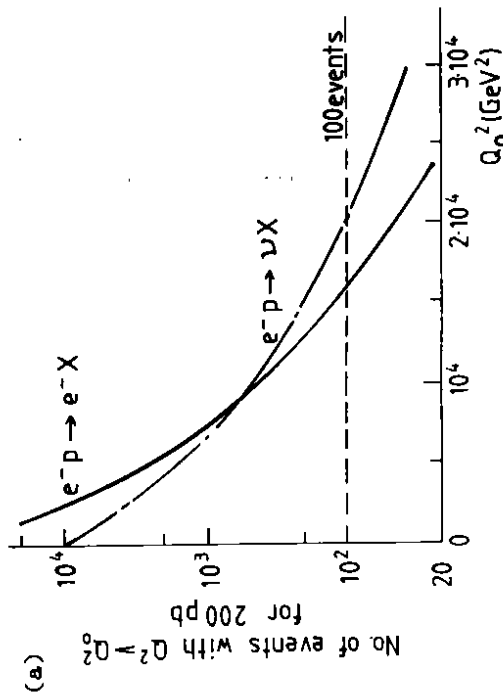
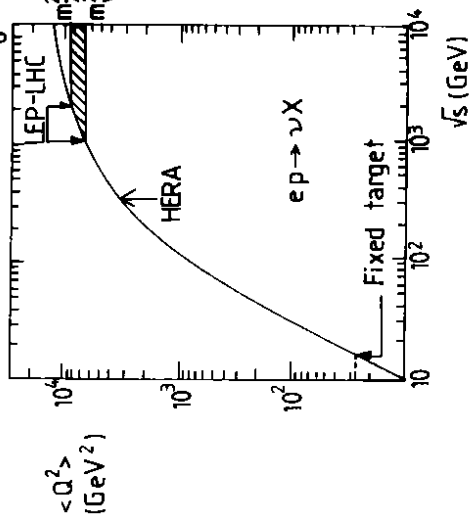


Figure 21.



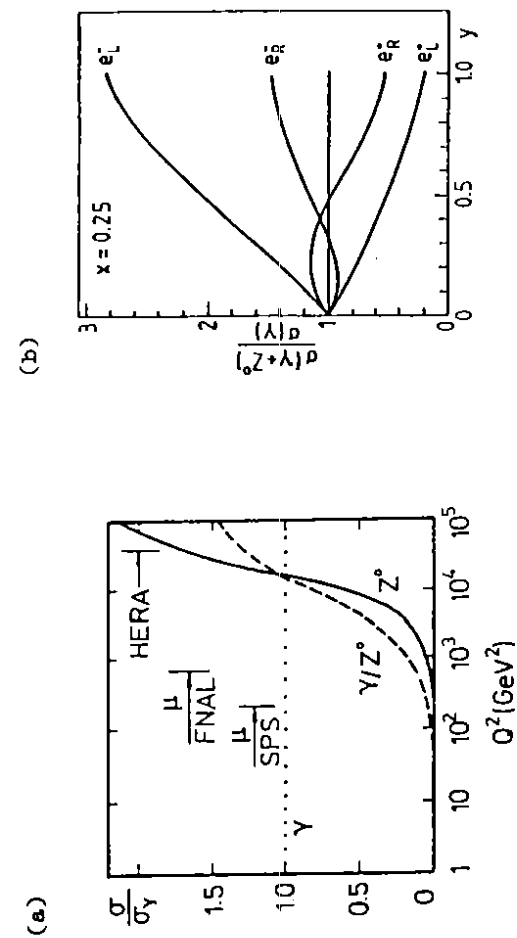


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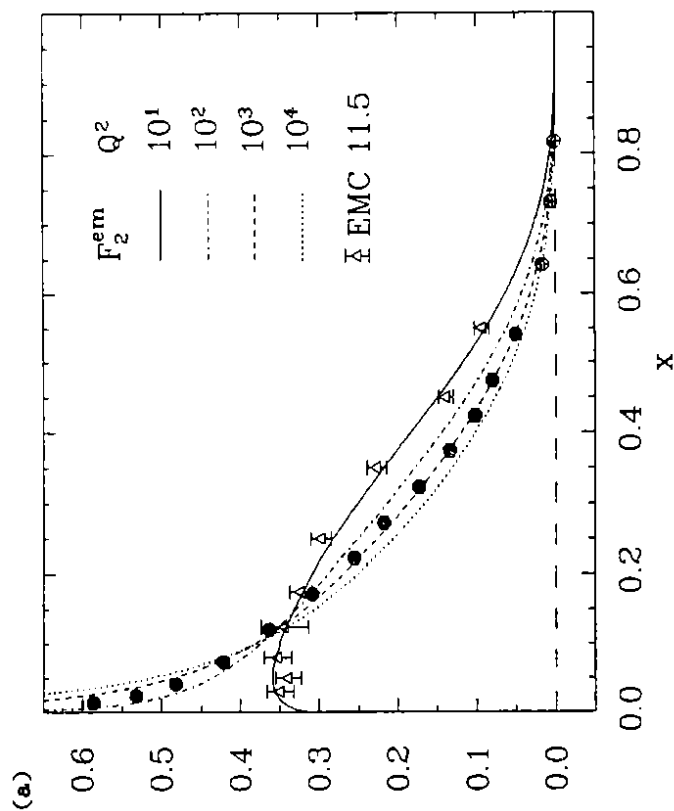


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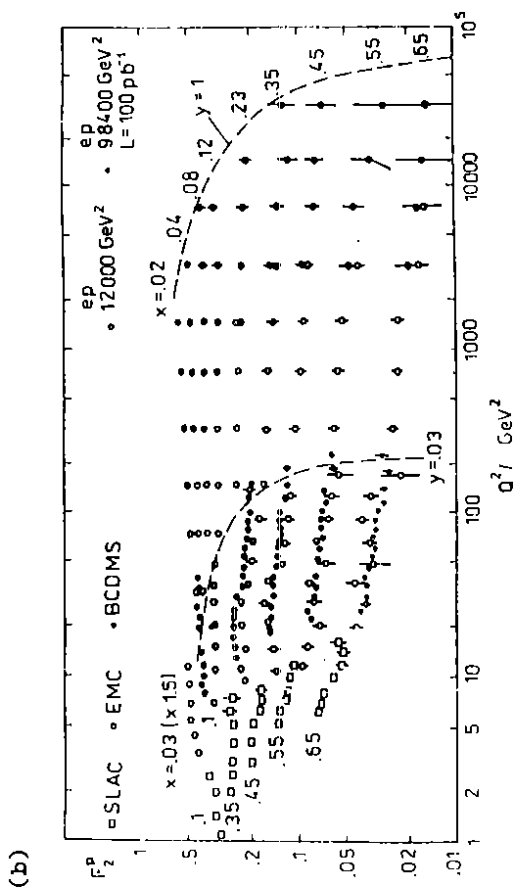


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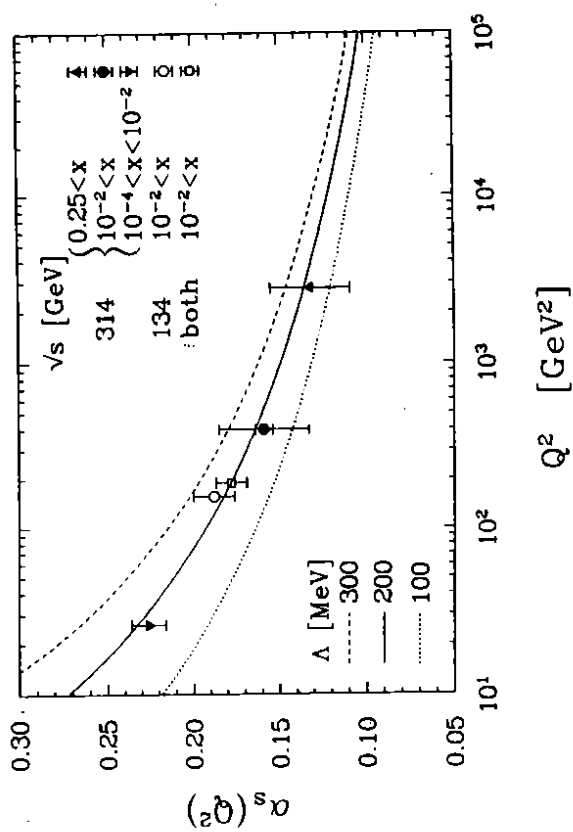


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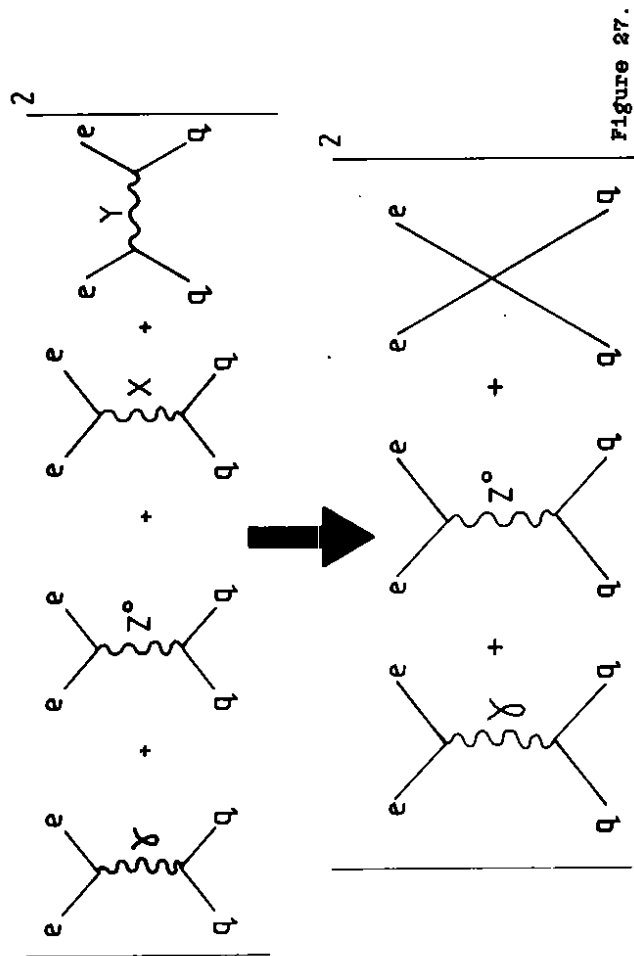


Figure 27.

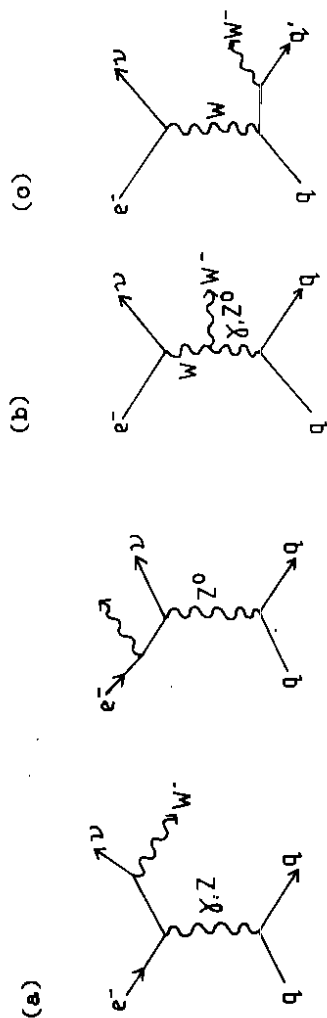


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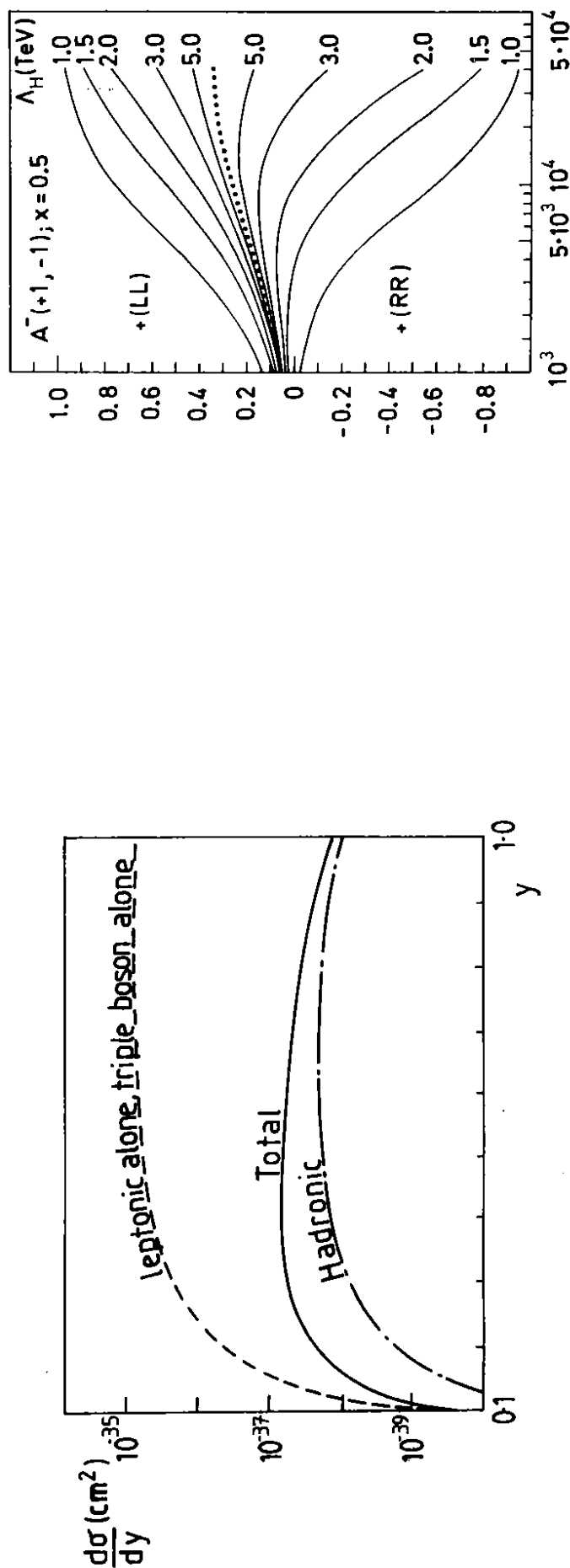


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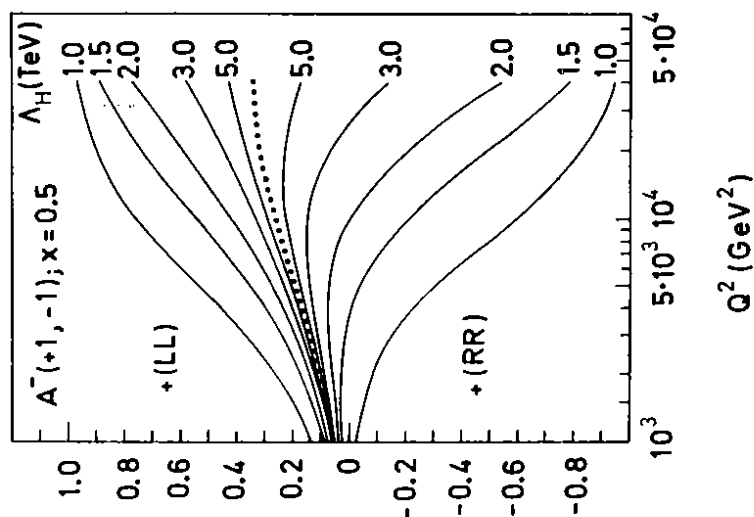


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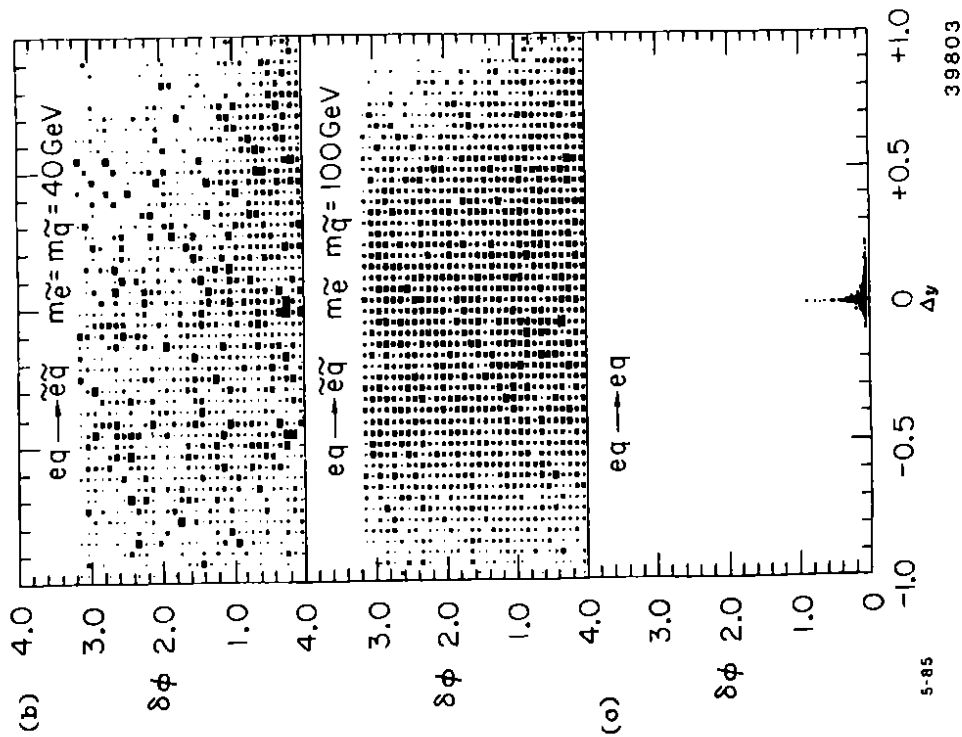
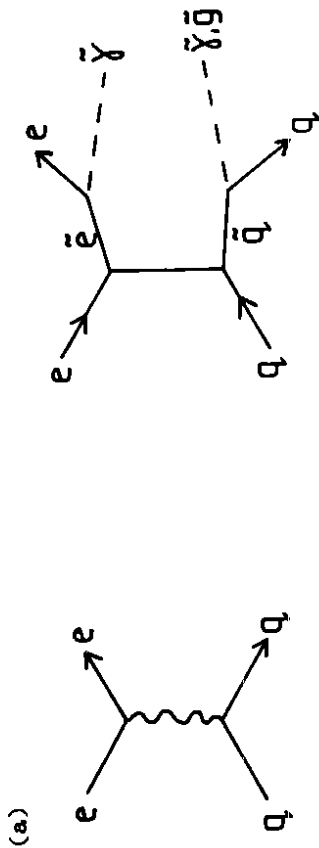


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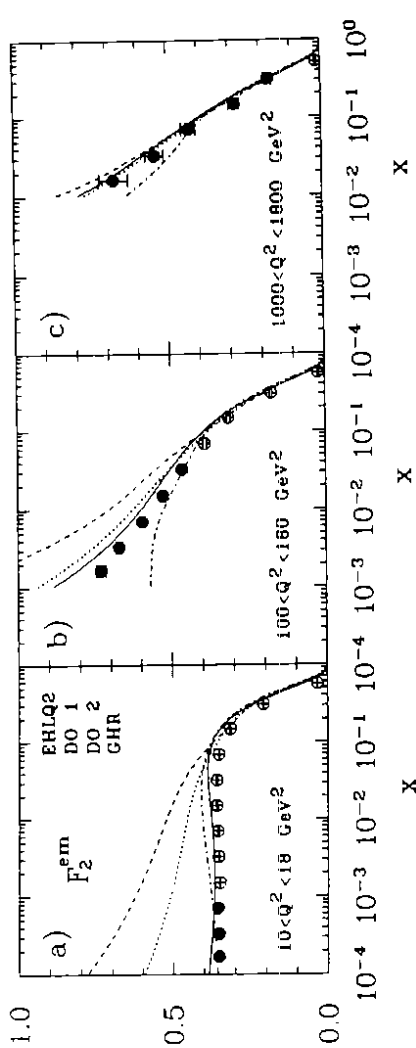


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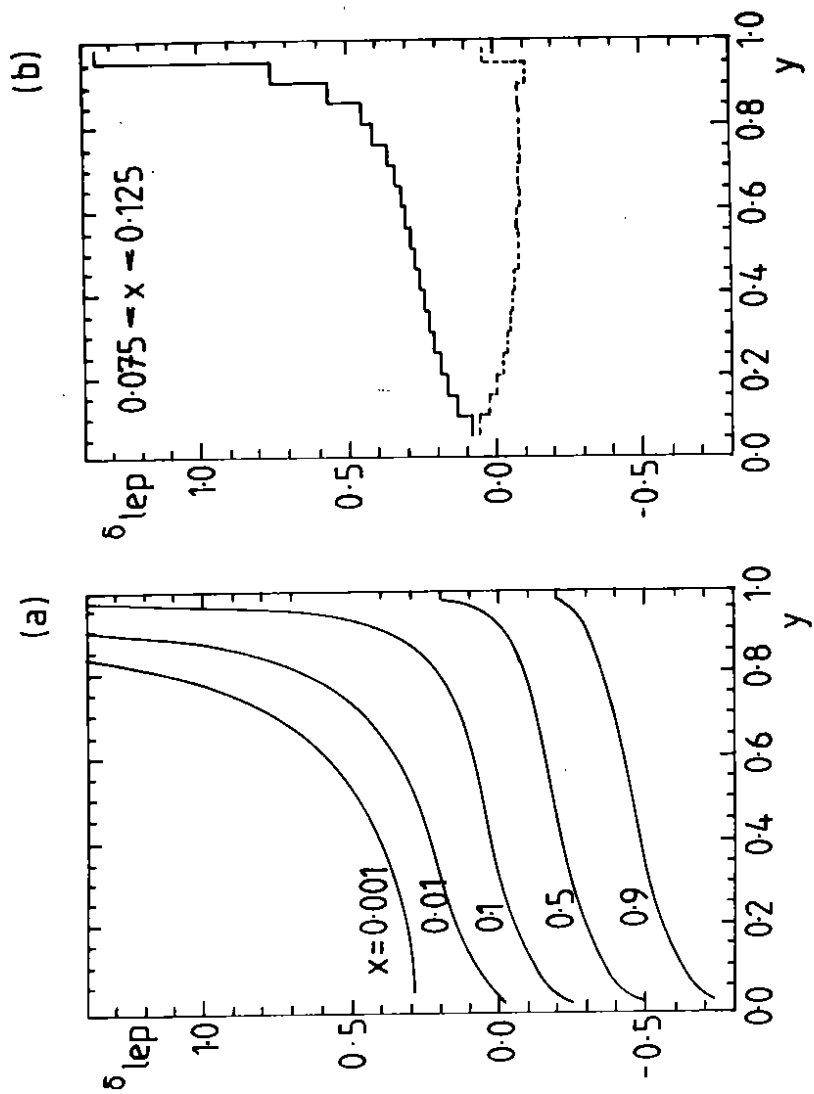


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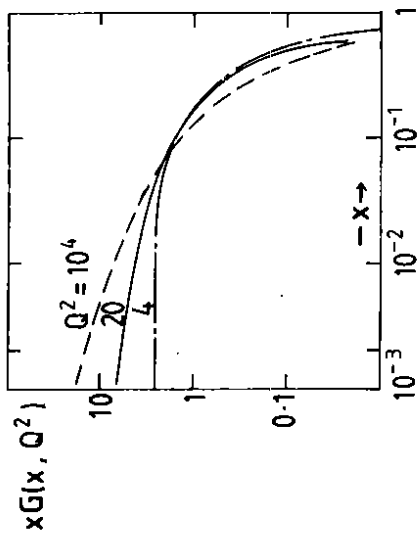
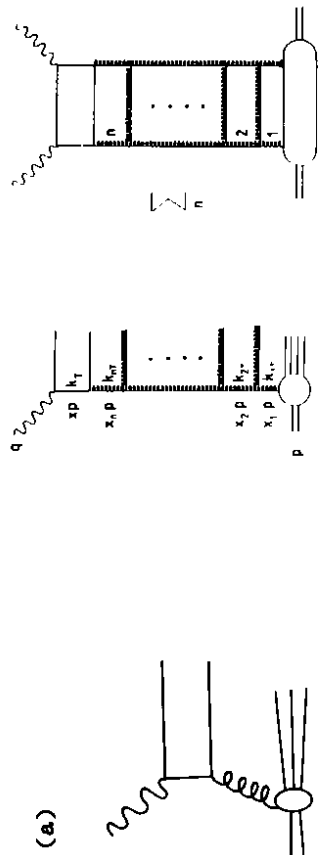


Figure 32.

Figure 33.



(a)

$$\sum_n$$

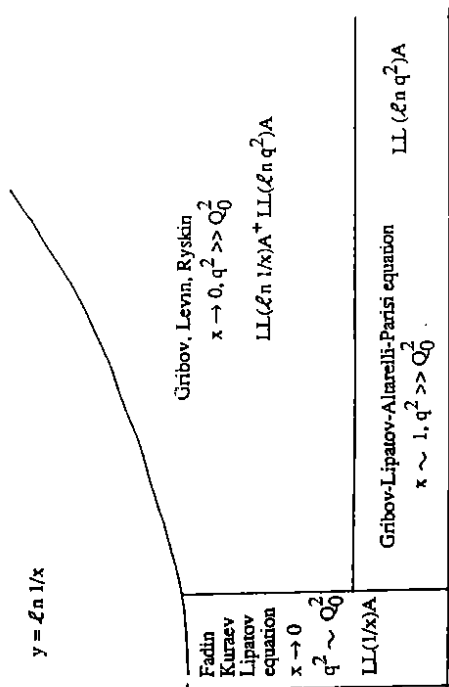


Figure 34.

$$\Gamma = \ln q^2 / \Lambda^2$$

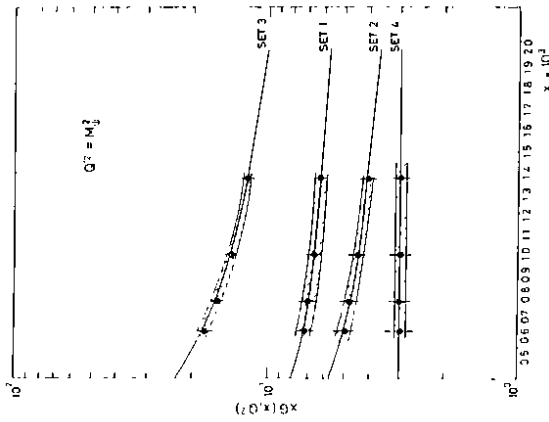


Figure 35.

(b)

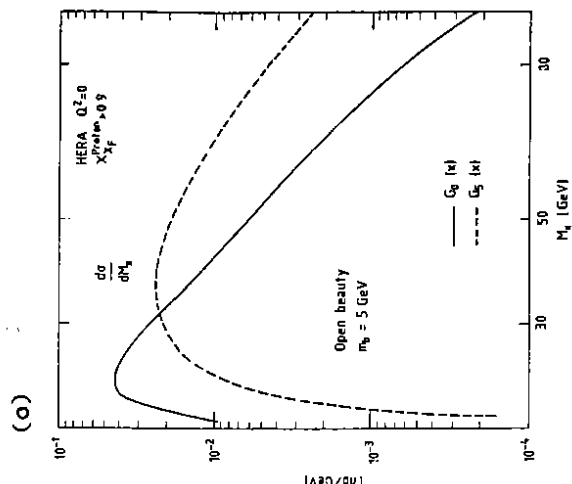


Figure 36.

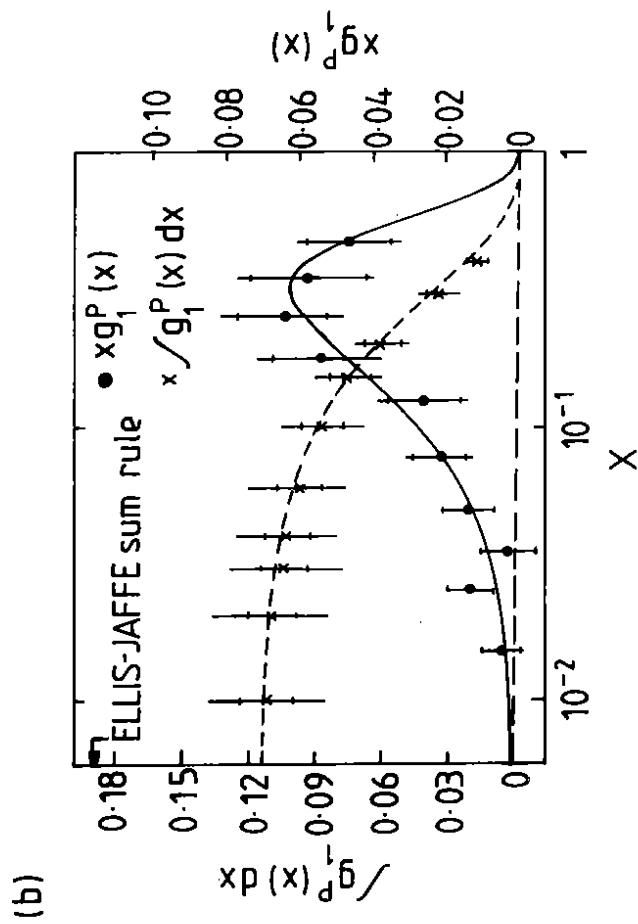
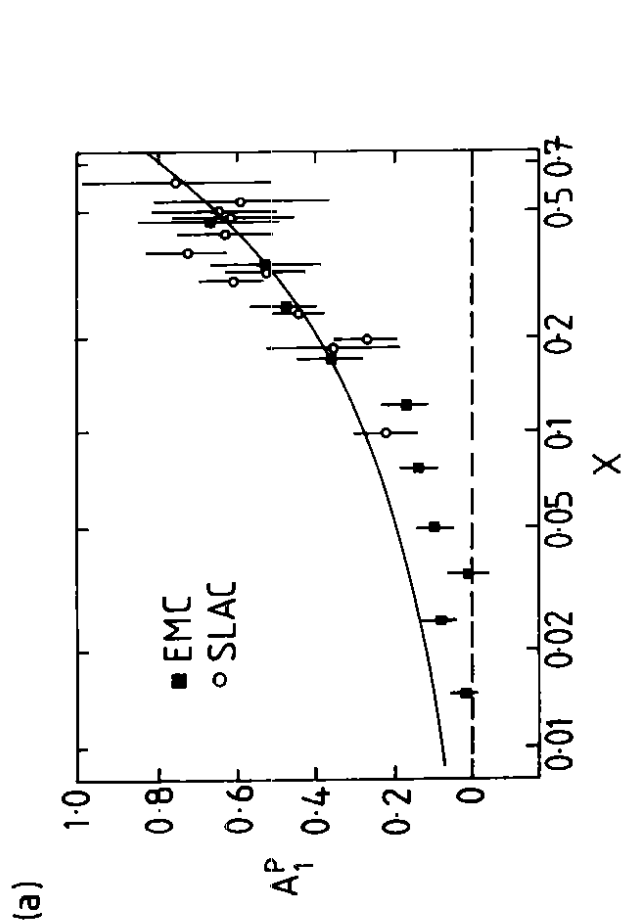


Figure 37.

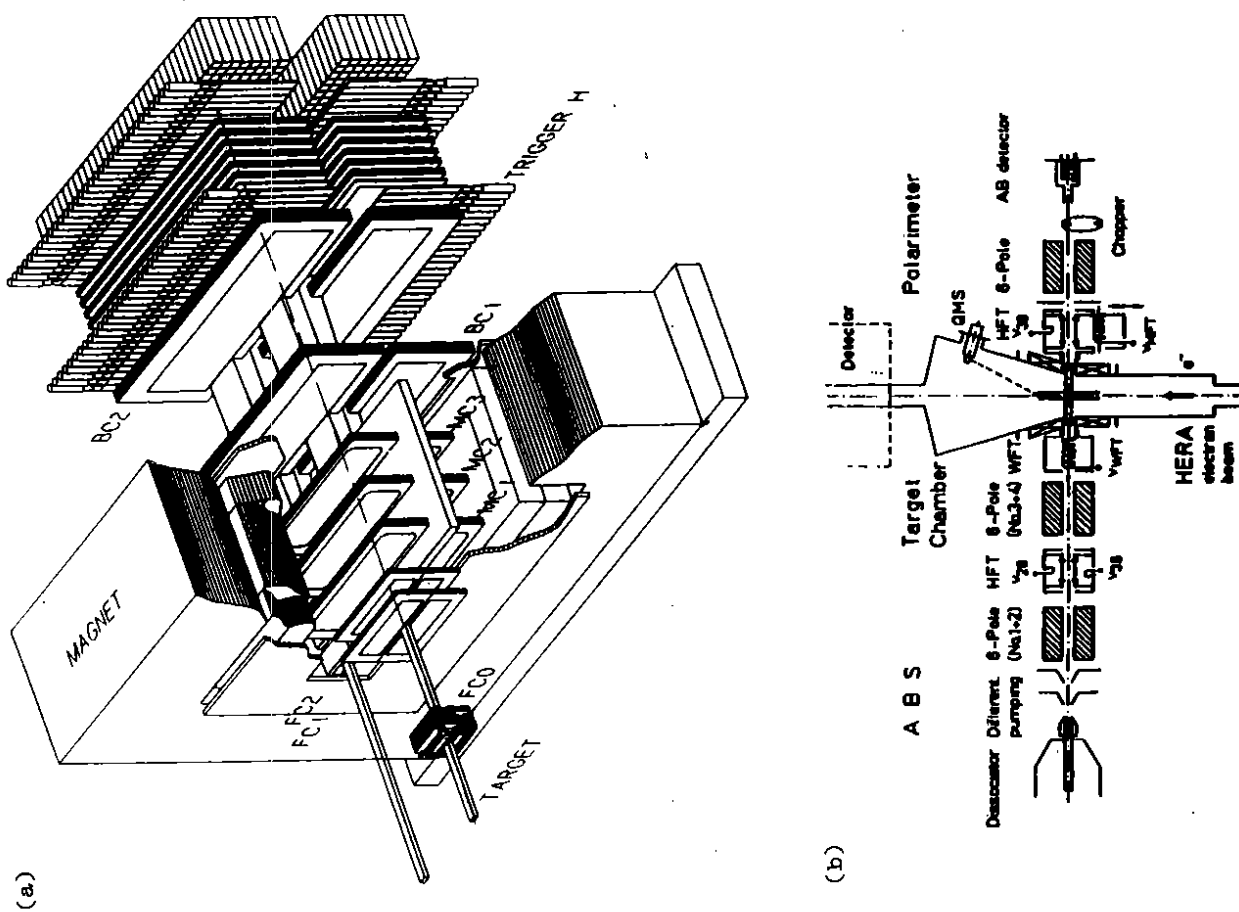


Figure 38.