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Deep Inelastic Scattering and Jets

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Abstract

An attempt is made to describe some of the interest and fascination of Deep Inelastic Lepton Scattering. The basic kinematics is outlined and various experimental aspects are discussed. The data, both on Structure Functions and on Hadron Production, are discussed first within the framework of the Quark Parton Model and then within that of perturbative QCD.

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I) Introduction

In general the aim of the physicist and especially the high energy physicist is to understand the most fundamental forces in matter. This implies that a study is made of matter in its most particular form. The conventional wisdom that arose from studies of the spectrum of hadrons [1] was that hadrons were made of quarks. This scenario even had the success of incorporating into the scheme the new quark flavour, charm. However searches for free quarks have met with a singular lack of success [2] which in turn has meant that experimental work with quarks has been to a greater or lesser extent indirect.

One of the most direct of these indirect methods has been provided by Deep Inelastic Lepton Scattering where, as we shall see, the data can be extremely well described by assuming that the quarks in whatever nucleon, proton or neutron, or nucleus are completely free and independent of their environment. Measurements of electron scattering and nuclei show the clear signature of quasi-elastic scattering from the individual nucleons. Electron, muon and neutrino scattering from nucleons is described by the incoherent sum of quasi-elastic scatters from the partons. This scenario originally proposed by Bjorken [3] and rapidly supported by experiment [4] has formed the basis of ~ 15 years of experimental and theoretical effort.

II) Kinematics and Cross-sections

The basic deep inelastic lepton scattering process is illustrated in fig. 1 in which are also given the kinematic notation and definitions which will be used later.

The derivation of the expression for the cross-section has been given many times in many different ways [5] and only the results will be recalled here [6]. The cross-section for charged lepton (e or μ) scattering within the 1-photon exchange approximation is given by

$$\frac{d\sigma}{d\Omega dE'} = \frac{4\alpha^2(E'^2)}{Q^4} \left(\cos^2 \frac{\theta}{2} W_2(\nu, Q^2) + 2\sin^2 \frac{\theta}{2} W_1(\nu, Q^2) \right) \quad (1)$$

$$= \Gamma_t (\sigma_T + \epsilon \sigma_S) \quad (2)$$

W_1 and W_2 are the structure functions of the nuclear target defined in a way analogous to the Electromagnetic Form Factors G_E and G_M of the nucleon but in general functions of the two variables Q^2 and ν rather than just Q^2 . The entirely equivalent expression (2) expresses the cross-section in terms of a photon flux Γ_t and the total absorption cross-sections σ_T and σ_S for transverse and scalar photons (since the photon has $Q^2 \neq 0$ it was one extra degree of polarisation compared to the purely transverse real photon with $Q^2 \equiv 0$).

Recently it has become conventional to write the cross-section for both charged lepton and neutrino scattering in a common form so as to emphasise their similarity.

Charged Leptons

$$\frac{d\sigma^{e,\mu}}{dx dy} = \frac{4\pi\alpha^2 ME}{Q^4} [y^2 x F_1(x, Q^2) + (1-y-\frac{Mxy}{2E}) F_2(x, Q^2)] \quad (3)$$

Neutrinos

$$\frac{d\sigma^\nu}{dx dy} = \frac{G^2 ME}{\pi} [xy^2 F_1(x, Q^2) + (1-y-\frac{Mxy}{2E}) F_2(x, Q^2) + y(1-\frac{y}{2}) x F_3(x, Q^2)] \quad (4)$$

Antineutrinos

$$\frac{d\sigma^{\bar{\nu}}}{dx dy} = \frac{G^2 ME}{\pi} [xy^2 F_1(x, Q^2) + (1-y-\frac{Mxy}{2E}) F_2(x, Q^2) - y(1-\frac{y}{2}) x F_3(x, Q^2)] \quad (5)$$

Some remarks are in order.

- 1) The change from electromagnetic to weak interactions involves the simple substitution

$$\frac{4\pi\alpha^2}{Q^2} \leftrightarrow \frac{G^2}{\pi}$$

- 2) Since parity is not conserved one extra structure function $xF_3(x, Q^2)$ is required in the weak case and this changes sign as $\nu \leftrightarrow \bar{\nu}$.
- 3) Although the symbolic functions F_1 , F_2 used are the same in each case, there is no general reason to suppose a physical correspondence, this only comes either from data (a powerful argument) or through specific models such as the Quark Parton Model.

- 4) The expressions are approximations assuming such reasonable things as negligible lepton mass, but also more arguably single boson exchange and for neutrinos an infinite boson mass.

Contact with the Parton Model

Consider the electromagnetic scattering of leptons on quarks with charge q_i of different helicity

Now the electromagnetic coupling γ_μ can be written

$$\gamma_\mu = \frac{1}{2} [\gamma_\mu(1+\gamma_5) + (\gamma_\mu(1-\gamma_5))].$$

Each of the two terms is equivalent to the spin projections illustrated above so that the overall cross-section for the scattering has the form

$$\frac{d\sigma}{dy} \propto \frac{1}{2} [1 + (1-y)^2],$$

more precisely for a quark i with charge q_i

$$\frac{d\sigma}{dy} = \frac{4\pi\alpha^2}{Q^4} ME q_i^2 \frac{1}{2} [1 + (1-y)^2].$$

Now, considering several quarks i each carrying a momentum fraction x of the proton momentum such that the distribution in x is $f_i(x)$, then

$$\begin{aligned} \frac{d\sigma}{dx dy} &= \frac{4\pi\alpha^2}{Q^4} ME (\sum q_i^2 x f_i(x)) \frac{1}{2} [1 + (1-y)^2] \\ &= \frac{4\pi^2\alpha^2}{Q^4} ME (\sum q_i^2 x f_i(x)) \left[\frac{y^2}{2} + (1-y) \right] \end{aligned} \quad (7)$$

A comparison of terms between equations (3) and (7) then yields the identification

$$2xF_1 \leftrightarrow \sum_i q_i^2 x f(x)$$

ie. the structure functions are directly measures of the momentum distribution of quarks in the target nucleon. This identification made most explicitly ≈ 10 years ago [7] will be the start point for comparison of data with models.

III) Experiments

The results discussed later have the following properties. They come from:

DIFFERENT EXPERIMENTS
with DIFFERENT BEAMS
DIFFERENT APPARATUS
DIFFERENT AIMS
and DIFFERENT CAPABILITIES

Since the audience is composed mainly of young theorists, it is perhaps appropriate to discuss some aspects of the daily work of the experimental physicist [8] in a modest attempt to reduce (in the future) comments of the type:

"We can calculate x , y , α with high precision, but (uncomprehending eyes to heaven) apparently the experimentalists find it hard to measure"

or (tone of outrage)

"the experimentalists must make every effort to understand their errors".
The truth is that often a number for the answer is very quickly obtained, but the experimentalist spends the longer time from that point to publication in understanding the systematic error without which the measurement has no value.

As pointed out in the previous section, the cross-section is a function of three variables (assuming the target to be at rest)

$$\frac{d\sigma}{dx dQ^2} = f(E, E', \theta)$$

therefore experiments measure all three of these or equivalent linear combinations.

In general charged lepton experiments measure the incident and outgoing lepton energies and the scattering angle more or less directly. The neutrino experiments on the other hand cannot measure with any precision the incident neutrino energy and so measure the total hadronic energy E_h . Furthermore the mode of measurement of E_h differs drastically between the electronic neutrino experiments which use calorimetric methods and the bubble chambers which measure and sum all tracks. This situation is summarised in Table I, what needs to be considered is the reflection on the structure functions $F(x, Q^2)$ of

- a) Resolution smearing
- b) Systematic measurement errors

on these quantities. My remarks, for lack of time, will be confined to some aspects of the latter in the hope that an incomplete story nevertheless prompts interest.

1) Electronic Neutrino Experiments, eg. CDHS

The beam used by the CDHS experiment is the narrow band beam at the CERN SPS. The flux in this beam is sketched as a function of neutrino energy in fig. 2, the two visible components arise from decay of pions and kaons respectively. In order to determine the absolute flux at a given energy it is necessary to have detailed knowledge of the π and K production spectra, to measure the relative π , K content in the hadron beam with a Cerenkov counter and also to monitor the muon yields at various points in the shielding. The commonly estimated combined systematic error from these various measurements is $\sim 5\%$ however from the spread of world measurements of $\frac{\sigma}{E}$ [9] this appears to be an underestimate.

Within a narrow band beam there is a well defined relationship between the radius of impact of the neutrino on the detector and its energy. This relationship allows events at a given energy to be separated into "pion" and "kaon" samples, but while it provides a useful check it's precision is low. This difficulty to measure the neutrino energy implies that the experiment has to measure E_h extremely well.

The CDHS apparatus [10] sketched in fig. 3 is a magnetised iron toroid with calorimeters which had (for the measurements discussed later) scintillators interleaved between 5 cm iron plates for a part of the detector and 15 cm iron in the major part. With 5 cm Fe spacing the resolution is given by $\frac{\Delta E}{E} \sim \frac{100\%}{\sqrt{E}}$ which clearly gives important smearing corrections at low v . The absolute calibration which determines the resultant systematic error depends on five separate operations.

- i) The response of a small (baby) calorimeter with the same characteristics as a large module is measured in a hadron test beam. This gives the response in terms of GeV/peak of muon pulse height. It also permits the development of an algorithm for taking proper account of the electromagnetic component of the shower.
- ii) The response of a few full size modules is measured in a hadron beam with respect to a distributed laser pulse height (GeV/LASER).
- iii) Cosmic muons are measured in all modules between SPS spills giving a measure of LASER/COSMIC MEAN.
- iv) A combination of ii) and iii) gives GeV/COSMIC MEAN.
- v) The energy deposition in the neutrino beam is checked to be the same in all modules.

The final systematic error quoted is of the order of 1%! The importance is demonstrated in fig. 4 where, for a series of discrete neutrino beam energies, the ratio $F_2^{\text{True}}/F_2^{\text{Meas}}$ for two different supposed systematic errors. The error is assumed to lead to a non linearity and even when, as in fig. 4, the deviation is 0.00025/GeV, it generates a non scaling of $\sim 5\%$.

2. Muon Scattering Experiments, eg. BCDMS, EMC.

Sketches of the apparatus for these experiments are shown in fig. 5. In the SPS muon beam the transmitted momentum bite is $\sim \pm 10\%$ and typical beam fluxes are $5 \cdot 10^6 - 5 \cdot 10^7$ muons/SPS pulse (1.5-2.5 secs).

Since muons are charged particles the situation is vastly different from the neutrino case, the incident flux is in general measured in one of two ways:

- i) The incident beam is counted directly and corrections for counter and electronics dead time are made. Corrections have also to be applied to account for the extra beam requirements which may be made in the physics analysis.
- ii) A random trigger [11] is used to take beam data in a well defined time window. These data are then passed through exactly the same analysis as physics events and a measure of the useful flux (with whatever analysis requirements) is directly obtained. The typical normalisation error estimated for a given data set is $\lesssim 3\%$

The momentum for individual beam tracks is also measured and the systematic error on this measurement is controlled by:

- i) The absolute field measurement and surveying of the beam spectrometer;
- ii) A cross-check of the beam spectrometer with the experiment's scattered muon spectrometer. The absolute error obtained is $\sim 0.3-0.4\%$.

The scattered muon energy similarly depends on the absolute measurement of the experiment's spectrometer magnetic field and detector survey. A good check is provided by the absolute mass obtained for known resonances K^0 , ψ . An example dimuon spectrum showing the J/ψ in EMC liquid target data is shown in fig. 6. Again the precision is $\sim 0.3-0.4\%$.

The effect on the measurement of F_2 is shown in fig. 7 where we have exaggerated the effect by considering a 1% error on incident beam momentum and we show only a single muon energy, in general the systematic errors from different beam energies are large in a different regions of phase space. It

can also be shown [12] that if the relative error between incident and scattered muon can be reduced then the sensitivity to the absolute scale is much diminished at least for a measurement of the slopes with Q^2 of F_2 .

Taking into account the systematic errors discussed above and all others and combining their separate effects on F_2 yields the representation of the final systematic errors on F_2 shown in fig. 8 which refers to EMC iron data [13].

3. Neutrino Bubble Chamber Experiments

Because of their lack of statistics bubble chamber measurements of scale breaking of F_2 are of little significance however they are still used to make measurements of the final state hadrons and for this aim there are no competitive neutrino experiments. However the weakness engendered by the lack of knowledge of the neutrino energy still appears, and is perhaps increased, because often the wide band neutrino beam is used for which there is no relationship between impact radius and energy.

The total hadronic energy is obtained by adding up the momenta of all event associated tracks observed. For a hydrogen filling this implies charged hadron tracks, but for a neon fill can also include e^+e^- pairs from the photons of π^0 decay (i.e. the systematic errors are different in the two cases).

The techniques used are ways to make the transition from the transverse momentum conservation constraint

$$P_T^\mu = \sum P_T^{CH} + \sum P_T^{Neutral}$$

to the determination

$$E_H = \sum E_{CH} + \sum E_{Neutral}.$$

This jump is made using different models and the reliability is studied using Monte Carlo data with some physics models included. The kind of variation possible is illustrated in fig. 9 which shows the estimated bias from three different methods, the figure is taken from the doctorate thesis of R. Giles [14] and refers to a hydrogen experiment in BEBC.

The importance of such errors for the measurement of a typical quantity, eg. $\frac{1}{N_{ev}} \frac{dN}{dz}$ can be estimated.

Typically

$$\frac{1}{\sigma} \frac{d\sigma}{dz} = \frac{1}{N} \frac{dN}{dz} \equiv f \sim e^{-6z} \quad \text{where} \quad z = \frac{E_h}{v} = \frac{E_h}{E_H}$$

$$\text{if } \left(\frac{\Delta v}{v}\right)^{\text{Syst}} = a \quad \text{then } \left(\frac{\Delta z}{z}\right)^{\text{Syst}} = a, \quad \text{consequently } \left(\frac{\Delta f}{f}\right)^{\text{Syst}} = -6az$$

If one takes the case of METHOD 2 of fig. 9 then with $E_H > 20$ GeV and high z we obtain $\left(\frac{\Delta f}{f}\right)^{\text{Syst}} \sim 30-40\%$ as shown in fig. 10a). For muon scattering with a 280 GeV beam systematic effects of the order of 1% on E_{μ}^{Scatt} coupled with a desire to limit systematic effects to less than 10% gave [15] a low v cut of 70 GeV (fig. 10b) and again emphasised the importance of a second energy (120 GeV) which allowed scale breaking effects to be measured down to $v = 30$ GeV.

These examples by no means give a complete treatment of systematic errors but are meant to illustrate the level of thought which should go into whatever statement is made about systematic effects. A further practical point is that often the subtleties are only discussed in theses, a serious treatment is never possible in a letter publication.

IV. Structure Functions in the Quark Parton Model

As was seen in section II for a world with only spin $\frac{1}{2}$ partons we have the identification

$$2xF_1(x) = F_2(x) \equiv \sum_i e_i^2 x f_i(x)$$

for charged lepton scattering. Specifically for a proton target

$$F_2^{\mu p}(x) = \frac{4}{9} x [u^p(x) + \bar{u}^p(x)] + \frac{1}{9} x [d^p(x) + \bar{d}^p(x)] + \frac{1}{9} x [s^p(x) + \bar{s}^p(x)]$$

If we define $u^p(x) = u$

$d^p(x) = d$ where the argument x is dropped for brevity, then

isospin invariance yields $u^n = d$

$$d^n = u.$$

It is possible to perform a series of manipulations and obtain Quark Parton Model (QPM) predictions which can be compared directly with the data.

Example I - Proton vs Neutron

$$\frac{1}{x} F_2^{\mu p} = \frac{4}{9} (u + \bar{u}) + \frac{1}{9} (d + \bar{d}) + \frac{1}{9} (s + \bar{s}) + \dots$$

$$\frac{1}{x} F_2^{\mu n} = \frac{1}{9} (u + \bar{u}) + \frac{4}{9} (d + \bar{d}) + \frac{1}{9} (s + \bar{s}) + \dots$$

$$F_2^{\mu p} - F_2^{\mu n} = \frac{x}{3} (u - d)$$

This quantity contains no contribution from sea quarks (since they should be the same in proton and neutron) and we could expect that it should show a quasi-elastic quark scattering peak, the data are shown in fig. 11 and indeed a broad peak at $x \sim 0.3$ is observed. If alternatively the ratio F_2^n/F_2^p is constructed then there are QPM limits

$$\frac{1}{4} \leq \frac{F_2^{\mu n}}{F_2^{\mu p}} \leq 4$$

the value 1 would be expected if the sea dominated and $\frac{1}{4}$ if a single u quark dominated. The data are shown as a function of x in fig. 12 and we see that they push close to the lower QPM limit.

Example II - Measurement of Quark Sea with neutrinos and antineutrinos

$$d\sigma^{\nu} + d\sigma^{\bar{\nu}} \rightarrow F_2^{\nu N}$$

$$d\sigma^{\nu} - d\sigma^{\bar{\nu}} \rightarrow F_3^{\nu N}$$

$$F_2^{\nu N} = 2x [u + d + \bar{u} + \bar{d} + \dots]$$

$$xF_3^{\nu N} = 2x [u - \bar{u} + d - \bar{d} + \dots]$$

$$\frac{F_2^{\nu N} + xF_3^{\nu N}}{2} = 2x [u + d + \dots] \rightarrow q(x)$$

$$\frac{F_2^{\nu N} - xF_3^{\nu N}}{2} = 2x [\bar{u} + \bar{d} + \dots] \rightarrow \bar{q}(x)$$

Recent data from CDHS are shown in fig. 13, the $\bar{q}(x)$ distribution clearly peaks towards $x = 0$ as we expect.

Example III - Total Quark Momentum

$$\int F_2^{\nu N}(x)dx = \int 2x [u(x) + d(x) + \bar{u}(x) + \bar{d}(x) + \dots] dx$$

$$\int F_2^{\nu N}(x)dx = 2(1-\epsilon)$$

where ϵ is the fraction of the proton momentum which is carried by partons which have no coupling to the exchanged boson. Alternatively

$$\int F_2^{\mu N}(x)dx = \int \frac{5}{9}x [u(x) + \bar{u}(x) + d(x) + \bar{d}(x) + \dots] dx$$

$$\frac{9}{5} \int F_2^{\mu N}(x)dx = 1-\epsilon$$

The data since 1970 have indicated that $\epsilon \sim 50\%$ and this fact was at the origin of the term "gluon", the theory of QCD came later.

Example IV - Relation μN to νN

As implied in the previous example there is a clear QPM prediction for the relationship between $F_2^{\mu N}$ and $F_2^{\nu N}$

$$F_2^{\nu N} = 2x [u + \bar{u} + d + \bar{d} + \dots]$$

$$F_2^{\mu N} = \frac{5}{9}x [u + \bar{u} + d + \bar{d} + \dots]$$

$$\frac{F_2^{\mu N}}{F_2^{\nu N}} \approx \frac{5}{18}$$

A recent data comparison between EMC, BCDMS and CDHS is shown in fig. 14 and in the high x region there is remarkable agreement. At low x the presence of strange and charm quarks gives a correction term

$$F_2^{\mu N} - \frac{5}{18} F_2^{\nu N} = \frac{1}{3} (C-S)$$

The problem with using this relation is that the fact that $M_{\text{charm}} \neq 0$ gives very significant threshold corrections to the contribution of s, $\bar{s}$, c and $\bar{c}$ to the neutrino data and to the contribution of $c\bar{c}$ to the muon data.

As has already been to some extent shown in these previous examples, the QPM gives a wealth of predictions and relationships with which the data agree very well. Most of the predictions however are sensitive only to the u, $\bar{u}$, d, $\bar{d}$, ie. light quark distributions. We can also see what the data can say about the $s\bar{s}$ and $c\bar{c}$ distributions.

Minority Quark Distributions I - Determination of the Strange Sea

When a neutrino interacts with the various quarks there are two ways to produce charm quarks

$$\begin{array}{ll} \nu + d \rightarrow \mu^- + c & \text{valence, Cabibbo Suppressed} \\ c \rightarrow s + \mu^+ + \nu & \end{array}$$

$$\nu + s \rightarrow \mu^- + c \quad \text{sea, Cabibbo Favoured}$$

and for antiquarks

$$\begin{array}{ll} \bar{\nu} + \bar{d} \rightarrow \mu^+ + \bar{c} & \text{sea, Cabibbo Suppressed} \\ \bar{c} \rightarrow \bar{s} + \bar{\mu} + \nu & \end{array}$$

$$\bar{\nu} + \bar{s} \rightarrow \mu^+ + \bar{c} \quad \text{sea, Cabibbo Favoured}$$

In all these processes the charm hadron produced decays $\sim 10\%$ of the time semileptonically giving a second muon in the final state and also a significant missing energy corresponding to the neutrino. This clear experimental signature allows the s quark distribution in the nucleon to be determined from the following expressions

$$d\sigma^{\nu} = \frac{G^2 ME_{\nu} x}{\pi} [U_{cd}^2 [u+d] + |U_{cs}^2| 2s]$$

$$d\sigma^{\bar{\nu}} = \frac{G^2 ME_{\nu} x}{\pi} [U_{cd}^2 [\bar{u}+\bar{d}] + |U_{cs}^2| 2\bar{s}]$$

the charm quark mass necessitates the use of

$$\xi = x + \frac{M_c^2}{2M\nu} \quad \text{in place of } x \text{ and gives an extra factor } (1 - y + \frac{xy}{\xi})$$

in the cross-section. The results of measurements by CDHS [16] are shown in fig. 15, it is clear that the antineutrino case with a negligible light quark contribution is very clean. The result for the relative SU(3) breaking is given by

$$\frac{\int x (s(x) + \bar{s}(x)) dx}{\int x (\bar{u}(x) + \bar{d}(x)) dx} = 0.52 \pm 0.09$$

Minority Quark Distribution II - Determination of Charm Sea

In terms of quark interactions the charm quark should contribute to muon interactions through

and should give the dimuon + missing energy signature as for the strange sea in neutrino interactions. In fact because the data in general are not far above threshold for $c\bar{c}$ production, the data seem to be better described if the

c and $\bar{c}$ are correlated as for example in the photon gluon fusion model

The data [17] show (fig. 16) very strong scale breaking compared to the full F_2 and, although their total contribution is small, it must be subtracted from the F_2 data before detailed analysis can be made. There have also been proposals [18] that there could be a significant intrinsic charm component in the proton wave function. The muon data put a rather stringent limit [19] on this, the result is illustrated in fig. 17 where the data clearly do not accomodate the 1% intrinsic charm suggested.

V. Structure Functions: Perturbative QCD Effects

i) Measurement of R

The quantity R is defined by

$$R \equiv \frac{\sigma_L}{\sigma_T} = \frac{F_2(1+Q^2/v^2) - 2xF_2}{2xF_1}$$

and is the ratio between the absorption cross-sections for longitudinal and transverse polarised photons. A similar quantity often used by neutrino experiments is

$$R' \equiv \frac{F_L}{F_2} = \frac{F_2 - 2xF_1}{F_2} \quad (R' < R)$$

The importance of R appears at several levels. Basically it is impossible to deduce F_2 from the cross-section without having a measurement of R and it is this fact which allows R to be measured.

Within the parton model with massless quarks and no transverse momenta, $R = 0$. In general, if there is a p_T from no matter what source and a quark mass M then

$$R = 4 \frac{p_T^2 + M^2}{Q^2}$$

One source of p_T^2 could be the intrinsic "Fermi motion" k_T of the quarks within the nucleon which can only be guessed. On the other hand perturbative QCD gives the explicit expression

$$F_L = \frac{\alpha_s(Q^2)}{2\pi} x^2 \int_x^1 \frac{dz}{z^3} \left[\frac{8}{3} F_2(z, Q^2) + 4a \left(1 - \frac{x}{z}\right) zG(z, Q^2) \right]$$

so that in principle at least a measurement of F_L is directly related to α_s .

In practice the experiments are only slightly sensitive to R over the major part of their kinematic range so that the determination of its value is extremely difficult.

Neutrinos: Method I

$$\frac{d\sigma^{\nu}}{dx dy} + \frac{d\sigma^{\bar{\nu}}}{dx dy} = \frac{G^2 M E^{\nu}}{\pi} \{ F_2 [1 + (1-y)^2 - R'y^2] + [\delta(q-\bar{q}) + 2(s-c)] (2y-y^2) \}$$

so that a determination of the y^2 term in the y dependence gives a measure of R . This method [20] required that the neutrino and antineutrino ratio be renormalised to 1 at $y = 0$ and the difficulty of the measurement is demonstrated by fig. 18 where the difference between the $R = 0$ curve and the best fit is barely visible. The method is also sensitive to the relative yield of π and K neutrinos in order to have a y dependence at fixed ν . Nevertheless systematic errors of ~ 0.1 are claimed and the results as a function of ν and then x are shown in fig. 19. There is no evidence within errors of any dependence on these variables.

Neutrinos: Method II

If one considers the cross-section for antineutrinos as x and y tend to 1 then one finds

$$\frac{d\sigma_{\bar{\nu}}}{dx dy} \xrightarrow{x \rightarrow 1, y \rightarrow 1} \sim \frac{G^2 M E_{\nu}}{\pi} x F_3 \left(\frac{1}{1-R'} - y \right) (1-y)$$

ie.   if $R' = 0$ $\sim (1-y)^2$
           if $R' \neq 0$ expect more events at high x, y

This method has been used to give an upper limit [21] which is extraordinarily restrictive ($R = 0.02 \pm 0.025$). The small error comes basically from the confidence that the event reconstruction is highly efficient. It is not yet clear however what the final published systematic error will be.

Charged Leptons, Electrons, Muons

Since these experiments employ discrete energy beams then the separation of σ_L and σ_T is based on the cross-section

$$\frac{d\sigma}{dQ^2 dv} \sim \Gamma_t (\sigma_T + \epsilon \sigma_L) = \Gamma_t \sigma_t (1 + \epsilon R)$$

being linear in ϵ at fixed Q^2 and ν . The different ϵ values come from different energies. The results from a recent measurement [22] for three different Q^2 ranges are shown in fig. 20. It is clear that the determination of R from such fits is sensitive to the relative normalisations and it is useful to have regions where the data are completely insensitive to R : R as a function of x is shown for hydrogen in fig. 21. Table II, which is an updated version of that prepared by Drees [23], shows that the high energy data with small systematic errors (CDHS, EMC) tend to favour low (zero) values of R in contrast to the classical low energy measurements from SLAC which stubbornly [24] insist on remaining at $R \sim 0.2 \pm 0.1$. Unfortunately SLAC measurements are at high x and EMC at lowish x so that no conflict exists but nor is a Q^2 dependence detectable. The QCD calculations would prefer rather higher values at low x than are being obtained although the errors are not small enough to allow contradiction.

ii) What is expected from QCD?

The transition from QPM to QCD can be illustrated by

and the result of the presence of the gluon emission is that the quark distributions change as a function of Q^2 .

How they change is governed to some extent by how they are to begin with and this is explicitly expressed by the Altarelli-Parisi evolution equation [25]

$$\frac{d}{d \ln Q^2} q(x, Q^2) = \frac{\alpha_s(Q^2)}{2\pi} \int_x^1 \frac{dz}{z} [q(z, Q^2) P_{qq}(\frac{x}{z}) + G(z, Q^2) P_{Gq}(\frac{x}{z})]$$

$$\frac{d}{d \ln Q^2} G(x, Q^2) = \frac{\alpha_s(Q^2)}{2\pi} \int_x^1 \frac{dz}{z} [q(z, Q^2) P_{qG}(\frac{x}{z}) + G(z, Q^2) P_{GG}(\frac{x}{z})]$$

These equations prompt two remarks

- 1) When CHIO, CDHS, CFRR, EMC, BFP, BCDMS et al. were designed the designers did not realise they were looking for logarithms (if they had, many would have stayed at home).

- 2) The coupled system makes for a difficult life, so the first move is usually to simplify things which reduces to finding a situation where $G(x, Q^2) \sim 0$.

Charged Lepton Data Analysis

This analysis is based on the procedures proposed by Gonzales-Arroyo, Lopez and Yndurain [26] and also by Abbott and Barnett [27]. For $x \geq 0.25$ the gluon and sea quark distributions are expected to be negligible, in which case the evolution equation for F_2 can be reduced to the form

$$F_2(x, Q^2) = \int_x^1 dz F_2(z, Q_0^2) b(x, z; Q_0^2, Q^2)$$

the validity of ignoring the glue and sea must of course be checked. A parametric form for the structure function at Q_0^2 is chosen

$$F_2(x, Q_0^2) = Ax^\alpha (1-x)^\beta (1-\gamma x)$$

which is sufficiently general. The actual use of Q_0^2 is symbolic since the data at all Q^2 are then fitted simultaneously to yield A , α , β , γ and also Λ_{QCD} . The procedure is also available at next to leading order [28]. The fits, as shown in figs 22, 23, 24, give a reasonably good description of the data with

BCDMS	Carbon	$\Lambda_{LO} = 85^{+60}_{-40}$ MeV
EMC	Iron	$= 125^{+22}_{-20}$ MeV
	Hydrogen	$= 110^{+58}_{-46}$ MeV

The errors quoted are statistical only, there is a systematic error of approximately ± 100 MeV. At next to leading order the fits are of similar quality and in general $\Lambda_{\overline{MS}} \sim 1.3 \Lambda_{LO}$ is obtained. The result survives a wide range of checks on the procedure [29], in particular it can be shown that to significantly change the result one needs $G(x, Q_0^2) \sim \frac{(1-x)^n}{x}$ with $n < 4$ at $Q_0^2 = 5 \text{ GeV}^2$. As discussed later the CDHS neutrino data indicate that this is very unlikely.

The analysis can be extended to all x values provided some information on the proton-neutron difference is included, in this case the full coupled

evolution form is used with the parametric forms

$$F_2^{\text{Singlet}}(x, Q_0^2) = Ax^\alpha(1-x)^\beta + B(1-x)^\gamma$$

$$F_2^{\text{Non singlet}}(x, Q_0^2) = Cx^{1/2} (1-x)^\delta (1-\epsilon x) \quad (\text{SLAC-EMC } F_2^p/F_2^n)$$

$$xG(x, Q_0^2) = D(1-x)^{5.9} (1+3.5x) \quad (\text{CDHS})$$

at $Q_0^2 = 5 \text{ GeV}^2$. Since there is a significant contribution of charm at low x a first attempt is made in which, for $x < 0.08$, only the lowest Q^2 points are retained. In a second stage the contribution from charm [17] is explicitly subtracted and all data points are illustrated for the low x region in fig. 25. There is therefore the satisfactory conclusion that a combination of perturbative QCD and measured charm contribution provides a good description of the muon scattering F_2 data sets. This comment is not however exclusive, and it has been shown [30] that just as good a description of the data can be obtained within the framework of the Massive Quark Model [31].

Neutrino Data Analysis, CDHS [32], Determination of the Gluon Distribution

The most advanced analysis of the neutrino (antineutrino) data employs yet another representation of the Altarelli-Parisi equations which is particularly suited to what they measure

$$\frac{d}{d \ln Q^2} F_2(x, Q^2) = \frac{\alpha_s}{2\pi} (Q^2) \int_x^1 [P_{qq}(\frac{x}{z}) F_2(z, Q^2) + 2N_{F_2} P_{Gq}(\frac{x}{z}) G(z, Q^2)] \frac{dz}{z^2}$$

$$\frac{d}{d \ln Q^2} F_2(x, Q^2) = \frac{\alpha_s}{2\pi} (Q^2) \int_x^1 [P_{qq}(\frac{x}{z}) \bar{q}(z, Q^2) + N_q^- P_{Gq}(\frac{x}{z}) G(z, Q^2)] \frac{dz}{z^2}$$

$$\frac{d}{d \ln Q^2} F_2(x, Q^2) = \frac{\alpha_s}{2\pi} (Q^2) \int_x^1 [P_{Gq}(\frac{x}{z}) F_2(z, Q^2) + P_{GG}(\frac{x}{z}) G(z, Q^2)] \frac{dz}{z^2}$$

with

$$N_{F_2} = N_q^- = 4 \quad \text{and} \quad \alpha_s(Q^2) = \frac{12\pi}{25 \ln Q^2/\Lambda^2}$$

The "measured" input is $\bar{q}(x, Q^2)$ and $F_2(x, Q^2)$ and the quantities extracted from the analysis are Λ_{L0} and $G(x, Q_0^2)$. $F_2(x, Q_0^2)$, $\bar{q}(x, Q_0^2)$ and $G(x, Q_0^2)$ are parameterised and the choice for the latter is extremely important since, as $G(x, Q^2)$ is not directly measured, there is no direct check on the form for the gluon. The description obtained is shown in figs 26 and 27 and the trends

in the data are well reproduced although at low x an extension in Q^2 range of both the F_2 and $\bar{q}$ measurements would be welcome. The shapes of the distributions at Q_0^2 have already been shown in fig. 13. This is probably the most thorough determination of the form of the gluon distribution yet made. The parameterisation obtained is

$$G(x, Q_0^2) = a(1 + bx) (1-x)^c$$

although it is emphasised that this form is valid for no other Q^2 . In the standard analysis the normalisation of the gluon distribution is constrained by the momentum sum rule, if its normalisation is free the value 0.55 ± 0.11 is obtained for the fraction of the nucleon momentum carried by the gluons. The value for $A_{L0} = 0.18 \pm 0.02$ (stat.) is slightly higher than that obtained by analysis of the muon data however given the systematic errors (not quoted in the neutrino case) there is no disagreement.

Alternative Determination of the Gluon Distribution [17]

Although it is very nice to have an internally consistent determination of the gluon distribution as in the above neutrino analysis, it is nevertheless interesting to search elsewhere for a determination. Such a possibility is offered by the muon charm production data which, as remarked in section 4, is well described by the photon gluon fusion model

The data can be fitted using the form $\eta G(\eta) = A (1-\eta)^m(Q^2)$ and the power m obtained for each bin in Q^2 . A supplementary point is obtained by including the J/ψ production data. The result is compared with various gluon models in fig. 28 with the two choices Q^2 and $Q^2 + \hat{s}$ for the argument of the evolution. The data give $m \approx 5$ and are in agreement with the neutrino evaluation and it can be further remarked that comparatively little evolution with Q^2 is observed.

Higher Twist

The analyses of the structure function data discussed so far contemplate the interaction of the exchanged boson with a single quark only, commonly known as the Leading Twist terms. There are in addition also terms which involve more than one parton and possibly parton composites (eg. diquarks). These terms can be thought of as analogous to the quasi-elastic α -particle contribution to electron scattering from nuclei and their main property is that they are expected to decrease in importance as inverse powers of Q^2 . There is little theoretical constraint on their behaviour, perhaps the complete series can be written

$$F_i(x, Q^2) = F_i^{\text{Pert QCD}}(x, Q^2) \left(1 + \frac{h_4(x)}{Q^2} + \frac{h_6(x)}{Q^4} + \dots \right)$$

but unfortunately not even the signs of $h_4, h_6 \dots$ have yet been predicted. The phenomenological analyses which look for these terms must necessarily use the maximum Q^2 range available. The CDHS group [33] combine their neutrino data with SLAC measurements of eD . This may or may not be a valid procedure since both beam and target are different. Assuming

$$F_2(x, Q^2) = F_2^{\text{QCD}}(x, Q^2) + F_2^{\text{HT}}(x, Q^2)$$

with

$$F_2^{\text{HT}}(x, Q^2) = \frac{h_4(x)}{Q^2} \quad \text{or} \quad \frac{h_6(x)}{Q^4}$$

they find that either form will fit the data and that, as shown in fig. 29, F_2^{HT} is positive and rises as a function of x . The EMC group [29] have combined their data on hydrogen with that of SLAC in which case there is no dispute possible about either the equivalence of the measurements or the effect of Fermi motion, there is none. For each bin in x , $h_4(x)$ is determined using

$$F_2(x, Q^2) = F_2^{\text{QCD}}(x, Q^2) \left(1 + \frac{h_4(x)}{Q^2} \right)$$

The results for h_4 are shown in fig. 30 and they can be described by the functional form $x^2/(1-x)^2$. The value of $\Lambda_{\overline{\text{MS}}} = 130^{+5}_{-4} \text{ MeV}$ is compatible with that determined by a fit to the high energy data alone.

Structure Functions and QCD: Summary

- i) For the experiments performed in the period 1969-1978, mainly but not exclusively low energy, the data could be described if $\Lambda \sim 400-700$ MeV. The data were also compatible with $1/Q^2$.
- ii) For the recent experiments 1978-1982, the data are described by $\Lambda \sim 100$ MeV, by themselves they are also compatible with power law behaviour.
- iii) If a combined analysis of low and high Q^2 data is made, then neither logarithmic nor $1/Q^2$ behaviour alone is sufficient and this allows some preliminary determination of higher twist behaviour to be made. However an infinite series $\sum_{i=1}^{\infty} a_i / (Q^2)^i$ can always be made to fit anything.
- iv) As summarised by Drees [23] and Buras [34], there is remarkable consistency between the determination of Λ from the data which is even more impressive if expressed in terms of α_s for which the precision is better than 10% from Deep Inelastic Scattering.

VI. The Quark Parton Model and Hadron Production Data

The Quark Parton Model describes hadron production as indicated in fig. 31 in which the kinematic definitions are also given. The production cross-section then has the form

$$\frac{1}{N_{\mu}} \frac{dN^h}{dz} = \frac{\sum_i e_i(x) D_i^h(z)}{\sum_i \epsilon_i(x)}$$

$$\epsilon_i = e_i^2 q_i(x) \qquad i = u, d, \bar{u} \dots$$

$$h = \pi^{\pm}, 0, K^{\pm}, \bar{0}$$

in which we see explicitly the product form which goes by the name "factorisation" and the independence of Q^2 which is called scaling. In addition to these two properties the QPM allows rather straightforward predictions based on isospin symmetry. In addition various models are more or less specific about the form of $D_i^h(z)$, but in general the treatment is mainly based on experimental data.

An example of a particular model is the Feynman-Field [35] model which envisages the fragmentation process as a series of independent emissions of mesons by the original quark. At each stage the meson takes a fraction z of the remaining quark momentum such that $f(z) = 1 - a_F + 3a_F(1-z)^2$. At each branch point the necessary $q\bar{q}$ pair receives a transverse momentum controlled by σ_q which results in the hadrons picking up a fragmentation p_T , σ_{Frag} , each pair internally conserves p_T . Normally only light quark pair production is admitted with relative probabilities

$$u:d:s = \gamma:\gamma:\gamma_s$$

such that $\gamma_s = 1 - 2\gamma$. Pseudoscalar and vector mesons are assumed to be produced with probabilities α_s and α_v respectively, $\alpha_s + \alpha_v = 1$. So there are 4 parameters α_F , σ_q , γ_s and α_v with which to describe the data.

For $e^+ e^-$ interactions

we have

$$\frac{d\sigma}{dz} (e^+ e^- \rightarrow q\bar{q} + h) = \sigma_{q\bar{q}} (D_q^h(z) + D_{\bar{q}}^h(z))$$

Summing over all quarks i we then obtain

$$\begin{aligned} \frac{d\sigma}{dz} (e^+ e^- \rightarrow h) &= \sum_i \sigma_i [D_i^h(z) + D_{\bar{i}}^h(z)] \\ &= \sum_i e_i^2 \sigma_{\mu\mu} [D_i^h(z) + D_{\bar{i}}^h(z)] \end{aligned}$$

Now, if there are only u and d quarks and pions

$$\frac{d\sigma}{dz} (e^+ e^- \rightarrow \pi) = \sigma_{\mu\mu} [e_u^2 (D_u^{\pi^+} + D_{\bar{u}}^{\pi^+} + D_u^{\pi^-} + D_{\bar{u}}^{\pi^-}) + e_d^2 (D_d^{\pi^+} + D_{\bar{d}}^{\pi^+} + D_d^{\pi^-} + D_{\bar{d}}^{\pi^-})]$$

$$D_u^{\pi^+} = D_d^{\pi^-} = D_{\bar{u}}^{\pi^-} = D_{\bar{d}}^{\pi^+}$$

$$D_u^{\pi^-} = D_d^{\pi^+} = D_{\bar{d}}^{\pi^-} = D_{\bar{u}}^{\pi^+}$$

$$\begin{aligned}
 &= \sigma_{\mu\mu} [e_u^2 2(D_u^{\pi^+} + D_u^{\pi^-}) + e_d^2 2(D_u^{\pi^+} + D_u^{\pi^-})] \\
 &= [\sigma_{\mu\mu} (e_u^2 + e_d^2)] 2[D_u^{\pi^+} + D_u^{\pi^-}]
 \end{aligned}$$

$$\boxed{\frac{1}{\sigma} \frac{d\sigma}{dz} (e^+e^- \rightarrow h) = 2 D_u^{\pi}}$$

A similar derivation yields in the three different deep inelastic cases

Neutrino

$$\frac{1}{N_{\nu}} \frac{dN}{dz} = D_u^{\pi}$$

Antineutrino

$$\frac{1}{N_{\bar{\nu}}} \frac{dN}{dz} = D_u^{\pi}$$

Muons, Electrons

$$\frac{1}{N_{\mu}} \frac{dN}{dz} = D_u^{\pi}$$

These simple results allow a direct test of the basic QPM conjecture and a typical data comparison [36] is shown in fig. 32. A comparable compilation [37] of data from many different experiments shows also good agreement. The data can be compared in further detail with the QPM by considering the charges separately. In neutrino interactions we have

$$\begin{array}{lcl}
 \nu + d & \rightarrow & u + x \\
 & \searrow & \\
 & & D_u^{\pi^+} \text{ favoured} \\
 & & D_u^{\pi^-} \text{ unfavoured}
 \end{array}$$

and for antineutrinos

$$\begin{array}{lcl}
 \bar{\nu} + u & \rightarrow & d + x \\
 & \searrow & \\
 & & D_d^{\pi^+} \text{ unfavoured} \\
 & & D_d^{\pi^-} \text{ favoured}
 \end{array}$$

from which we expect

$$\frac{1}{N} \frac{dN^{\nu+\pi^+}}{dz} \sim \frac{1}{N} \frac{dN^{\bar{\nu}+\pi^-}}{dz}$$

Such behaviour is nicely shown in fig. 33 where we see that the data agree in the forward ($x_F > 0$) region where the quark fragmentation should dominate, but not in the backward, target fragmentation region. In muon scattering the quark composition can be varied by varying the x_{Bj} and it can be shown that

$$\frac{\pi^+}{\pi^-} \sim \frac{[\frac{4}{9}u + \frac{1}{9}\bar{d}] D_u^{\pi^+} + [\frac{1}{9}d + \frac{4}{9}\bar{u}] D_u^{\pi^-}}{[\frac{1}{9}d + \frac{4}{9}\bar{u}] D_u^{\pi^+} + [\frac{4}{9}u + \frac{1}{9}\bar{d}] D_u^{\pi^-}},$$

if $x_{Bj} \sim 0$ then the quark sea dominates and $u \sim d \sim \bar{u} \sim \bar{d}$ gives $\frac{\pi^+}{\pi^-} \sim 1$, in contrast for $x_{Bj} \rightarrow 1$ we expect $\frac{\pi^+}{\pi^-} \gg 1$. The data [38] are shown in fig. 34 and they demonstrate the expected features mainly for $z \rightarrow 1$ indicating that the particles in this region of phase space are more faithful indicators of the parent quark.

The isospin invariance test is shown for muons in fig. 35 in which π^0 data are compared with identified pions. A fraction 0.27 ± 0.02 (stat.) ± 0.05 (syst.) of the energy of the virtual photon is carried by the π^0 s [39]. Equivalent data from Tasso (e^+e^-) [40] are shown in fig. 36. These and data from other groups, eg. the fraction of energy in γ rays is measured by the Cello group [41] to be $0.251 \pm 0.003 \pm 0.04$, suggest that in high energy e^+e^- the situation may be more complicated.

As alluded to with respect to fig. 33 the QPM envisages a fairly well defined "quark fragmentation region" and at high energies one might expect a clear separation from the target fragmentation. Possible evidence for this [42] is shown in fig. 37 where positive hadron, negative hadron yields and their difference are plotted as a function of centre of mass rapidity y . For $W > 8$ GeV there is indeed an indication of a separation at $y = 0$. Preliminary high energy muon data with the EMC vertex system [43], fig. 38, also suggest that something is happening in the region of $y_{cms} = 0$.

The idea of separating a quark fragmentation region was pushed to its limit with the idea [44] that the quark charge could be measured if the mean charge of resultant hadrons were measured. However any cut in the chain of quark antiquark pairs is made at the boundary of a hadron in which case

$$\langle Q_q \rangle = e_q - \sum_i \gamma_i e_i$$

$$\langle Q_u \rangle = 1 - \gamma_u \quad \langle Q_d \rangle = \langle Q_s \rangle = -\gamma_u$$

so it becomes clear that the quark charge cannot be measured in this way.

Furthermore the resultant measure of $\gamma_u = 0.45 \pm 0.04$ [45] yields

$\gamma_s/\gamma = 0.22^{+0.12}_{-0.18}$ which is not very discriminative either. The attempts have become more sophisticated [46] and, as shown in fig. 39 where the weighted charge distribution

$$Q_w = \sum_i z_i^r Q_i \quad \text{with } r = 0.5$$

is plotted, the data are very consistent with model predictions which of course have $Q_u = \frac{2}{3}$, $Q_d = \frac{1}{3}$. It cannot unfortunately be called a measurement of the quark charge.

VII) Fragmentation Properties

As mentioned in the previous section most fragmentation models have at least four parameters characterising the longitudinal fragmentation, the transverse fragmentation, the strange particle production and the ratio of vector to pseudoscalar particles. The latter two have always been the least well constrained by experiment but there is some progress which is worth discussing.

Strange Mesons - γ_s/γ

From muon scattering the strange particle system is quite involved but with some assumption can be reduced to a manageable problem

$$\frac{1}{N_\mu} \frac{dN^{K^+}}{dz} \approx \epsilon_u D_u^{K^+} + \epsilon_{\bar{u}} D_u^{K^-} + \epsilon_{\bar{s}} D_u^{\pi^+}$$

$$\frac{1}{N_\mu} \frac{dN^{K^-}}{dz} \approx \epsilon_u D_u^{K^-} + \epsilon_{\bar{u}} D_u^{K^+} + \epsilon_s D_u^{\pi^+}$$

$$\frac{1}{N_\mu} \frac{dN^{K^0}}{dz} \approx 2\epsilon_u D_u^{K^-} + (\epsilon_d + \epsilon_{\bar{d}}) D_u^{K^+} + (\epsilon_s + \epsilon_{\bar{s}}) D_u^{\pi^+}$$

The original Feynman-Field guess of $\gamma_s/\gamma = 0.5$ was based on "high p_T " $\frac{K}{\pi}$ data, the electron and muon data [47], fig. 40, favour something like $\gamma_s/\gamma = 0.25$ and a recent neutrino measurement of the K^0/π^0 ratio [48] yields 0.27 ± 0.04 . For e^+e^- data the plethora of strange particle sources makes life difficult (see fig. 41), but a recent determination [49] also gives a value consistent with the deep inelastic data.

Vector Mesons - α_v/α_s

The standard FF models of fragmentation consider the production of either pseudoscalar mesons or vector mesons and assign the probabilities α_s , α_v respectively such that $\alpha_s + \alpha_v = 1$. The measurement of the relative magnitude α_v/α_s is quite difficult since it involves the determination of the relative yields of a direct pseudoscalar and vector production in the presence of decay products. Perhaps the most direct measurement has been made in muon scattering in which the yields of ρ^0 and π^0 (fig. 42) mesons is measured for $z \rightarrow 1$. At this point only direct production contributes, the result is $\frac{\rho^0}{\pi^0}(z=1) = \alpha_v/\alpha_s = 1 \pm 0.3 \pm 0.4$ (syst.). While this is the standard value assumed by Feynman and Field it is not clear why the ratio should not be 3 corresponding to the number of possible spin states.

Baryon Production

Until recently the primary source of baryons was assumed to be target fragmentation and the presence of protons in the forward region was assumed to be due to the comparatively low energies which did not allow separation. Within the last years however there have been measurements of baryon and antibaryon yields in both Deep Inelastic [50] and e^+e^- production [51]. These data as a function of the fragmentation variable are shown in figs 43 and 44. One conceivable source of these baryons is diquark-antidiquark production in the fragmentation chain [52] and a consistent description of the present proton/antiproton production can certainly be obtained. In addition, the deep inelastic lambda production also fits in the model as shown in fig. 45. An exciting possibility is that baryon (antibaryon) production is enhanced for gluons [53] and indeed there is some indication [54] that baryon production is

enhanced on the Upsilon resonances which are expected to have a significant three gluon decay mode. Some further hints in the same direction are provided by some new muon data [43] which, as illustrated in fig. 46, show a rise of the antiproton/proton yield as a function of p_T . (As we shall see later, a high p_T with respect to the photon axis is a good indicator for events with the characteristics associated with gluon emission.)

VIII) Hadron Production: Perturbative QCD Effects

Given the remarkable success, demonstrated in the previous section, of the QPM, it is clear (at least in retrospect) that a search for QCD effects implies high statistics data.

Scale Breaking, Factorisation Breaking

The acquisition of a Q^2 dependence is taken as the basic sign of QCD in the structure function data and there are analogous predictions for the fragmentation function [55]. The QPM is modified in leading order as indicated in fig. 47a). In next to leading order (fig. 47b) the explicit terms of order α_s in the parton cross-section [56,57] are supplemented [58] by order α_s terms from the quark distribution functions and fragmentation functions which further modify the expected Q^2 dependence.

The characteristic scale breaking and, in next to leading order, factorisation breaking, have been searched for in neutrino interactions [59] and moderate energy electroproduction [60] with inconclusive results. The most statistically powerful measurement [61] has been made with high energy muons. The factorisation breaking (x dependence) of the sum of positive and negative hadrons is shown in fig. 48. The systematic errors on these data (as discussed in section II) are limited to $\leq 10\%$ and the observed effect is of the order of 25-30% depending on z . The factorisation breaking demands that the Q^2 dependence be displayed for small ranges in x as shown in fig. 49. The scale breaking is weak but hardly compatible with the scaling (dotted lines) expected from the QPM. The solid curves are a phenomenological calculation from Baier and Fey [57]. If the data are plotted as a function of W^2 there is then no

dependence at fixed W^2 on either x or Q^2 , but the W^2 dependence is quite marked (fig. 50). What is also interesting is that the model curves behave qualitatively in a very similar manner. None of the parameters in the calculation have been modified and in particular no value for the QCD scale parameter Λ has yet been extracted. This is also the case for e^+e^- in which scale breaking similar in magnitude has been observed [62]. In this case the situation is complicated by the need to have a very complete understanding of the effect of heavy quark (c and b) production and decay which may well account for a large part of the observed effect [63].

QCD Effects in the Transverse Momentum Distributions

Before considering the data it is necessary to enumerate the sources of transverse momentum available in Deep Inelastic Scattering.

- Fragmentation p_T
  - generated by the quark antiquark pair production and locally balanced, denoted by σ_q or $\langle p_T^2 \rangle_{\text{Frag}}$
- Intrinsic k_T
  - quark motion within the target nucleon analogous to the classical Fermi motion of a nucleon in a nucleus. A hadron receiving a fraction z of the quark momentum would expect on average to receive $z^2 \langle k_T^2 \rangle$.
- QCD Effects
  - Non-collinear gluon emission and the photon gluon fusion graphs lead to additional p_T with respect to the photon direction

The predictions are therefore: i) extra p_T beyond σ_q should be observed, and eventually separated jets should appear; ii) the $\langle p_T^2 \rangle$ should vary as the kinematics of the current are changed [64]

$$\begin{aligned} \langle p_T^2 \rangle &\sim \alpha_s(Q^2) \cdot Q^2 \cdot f(x,y) \\ &\sim \alpha(Q^2) \cdot W^2, \end{aligned}$$

the proportionality to W^2 is understood as coming from the integration over the phase space available for gluon emission; iii) the current interacts with a single quark which then suffers gluon emission, therefore there should be an asymmetry between the forward quark system and the backward diquark system

$$\langle p_T^2 \rangle|_{x_F > 0} > \langle p_T^2 \rangle|_{x_F < 0},$$

following ii) this asymmetry should rise as a function of W^2 .

The p_T^2 distributions of charged hadrons observed in two neutrino experiments is shown in fig. 51 [59]. The tail for $W^2 > 50 \text{ GeV}^2$ is clearly more marked in each case. Fig. 52 shows the p_T^2 distribution of charged hadrons observed in high energy muon interactions in comparison with a model [65] with and without the QCD effects included. If the QCD effects are not present then a very big modification of the fragmentation model is necessary. The qualitative behaviour of the data is very similar to e^+e^- data [66]. The behaviour of $\langle p_T^2 \rangle$ with W^2 is illustrated in fig. 53 in which charged and neutral hadron data from muon scattering are collected together with neutrino data. Within their limited W range the latter are in agreement and a clear rise, in agreement with the QCD model is seen. That the behaviour is different in the backward cms region is shown in fig. 54. Fig. 54a) shows the forward and backward "seagulls" for two different W ranges from a neutrino experiment [67]. The forward seagull is more marked at high W whereas the backward seagull is hardly changed. This asymmetry has been exploited by a Fermilab neutrino group [68] who use the backward as a measure of non QCD effects and take the forward-backward difference in $\langle p_T^2 \rangle$ as a function of W^2 and compare directly with a QCD calculation as shown in fig. 55.

Remembering the list of predictions, the item for which evidence has not yet been demonstrated is "and eventually separated jets should appear". In order to look for radiative jets it is necessary to consider event shapes.

Provided that a natural axis exists, as given by the exchanged boson direction in deep inelastic scattering, and is well measured, as is the case in muon interactions, then the procedure is very straightforward. As indicated in the sketch the event is rotated about the photon axis such that $\int p_{T\text{ out}}^2$ with respect to a plane is minimised.

The ambiguity in this procedure is resolved by ordering the highest p_T particle to $\psi < 0$. There is then a series of interesting quantities which can be studied.

eg.	$\langle p_{T\text{ in}}^2 \rangle$	$\langle p_{T\text{ out}}^2 \rangle$
	$\int \vec{p}_{T\text{ in}}^2$	$\int \vec{p}_{T\text{ out}}^2$
Energy flow	$\frac{d\int}{d\psi} = \frac{1}{\sigma} \int z \frac{d\sigma}{dzd\psi} dz$	

The behaviour of $\langle p_{T\text{ in}}^2 \rangle$ as a function of W^2 for neutrino interactions [69] is plotted in fig. 56 and is seen to rise such that a comparatively smooth continuation to e^+e^- measurements is possible. It can also be seen that the $\langle p_{T\text{ out}}^2 \rangle$ also rises with W^2 even though (as must be) it is much smaller in absolute terms. What is perhaps more striking is the length of the tail seen in $\int p_{T\text{ in}}^2$ in muon interactions [70], fig. 57, the growth of which with W^2 cannot be easily reproduced by modified fragmentation. The energy flow in the corresponding high energy data is shown with and without a $p_{T\text{ in}}^2$ cut in fig. 58. A less marked structure is obtained with a similar but lower $p_{T\text{ in}}^2$ cut in the 120 GeV data although in this case and for similar W neutrino data [67,68] the gymnastics required of "No QCD" fragmentation models to reproduce the data is not great and the major part of the effect can be attributed to the analysis procedure and momentum conservation. The interpretation of the effect seen in fig. 58 as being due to the presence of two forward jets is supported by the

azimuthal correlation observed between other tracks and the high p_T track (not included in fig. 59) [71]. If no cuts are applied an expected "away side" enhancement is seen. If a p_T cut is applied this enhancement is accentuated and a positive correlation in the region of the "trigger particle" is also seen which cannot be reproduced by resonances.

Measurement of k_T ?

A source of hadronic p_T which in any general discussion must be present is the intrinsic k_T of the quarks in the nucleon corresponding to their confinement. This is analogous to the classical Fermi motion of nucleons in a nucleus. However the inability of theorists to solve the confinement problem has lead to the use of the term intrinsic k_T as a useful repository for all not understood but measured p_T values. An example is the Drell-Yan process for lepton pair production, the observed values of apparent k_T [72] exceeded what was reasonable for some time and it is only recently that at least some part of this large p_T has been explicitly calculated. In deep inelastic scattering the simplest observable indication of a k_T is, as indicated earlier, that a hadron carrying a fraction z of the quark momentum should also carry a fraction z of its k_T , hence at high z

$$\langle p_T^2 \rangle \sim z^2 k_T^2.$$

As shown in fig. 60 such a term is necessary to describe the data.

A second effect which is more difficult to measure experimentally is related also to the R measurement (see section V). The general expression for the azimuthal distribution of hadrons with respect to the lepton scattering plane is given by

$$\frac{dN}{d\phi} = a + b f_1(y) \cos\phi + c f_2(y) \cos 2\phi.$$

The term in $\cos\phi$ arises from an interference between transverse and scalar photons and the $\cos 2\phi$ term from an interference between photons in the two transverse polarisation states. These effects are extremely difficult to measure because the error on the direction of the virtual photon must be very small. This measurement was once advertised as a gold plated QCD test [73]

however it was pointed out [74] that the presence of any k_T could also generate similar effects. Recent data [75] (fig. 61) shows an appreciable $\cos\phi$ term which compares in magnitude with a calculation [76] including phase space limitations and fragmentation. The major contribution is from k_T and the value required, as for the high z^2 single particles, is of the order of $0.7-0.8 \text{ GeV}^2$. Like the Drell-Yan measurements this is an "unreal" value.

Yet another measure of k_T^2 can be obtained by taking the vector sum of all the hadron fragments from a given quark. The problem of course lies in defining all the products not more not less. If the $(\text{vector sum of } p_T)^2$ for those events for which $\sum z_h > 0.7$ is plotted (fig. 62), the data fit well with a Monte Carlo using $k_T^2 = 0.4 \text{ GeV}^2$. This is again a large value but suspiciously different to the previous values. Eventually the repeated quoting of such large values had the desired effects and some theoreticians attempted to understand the effect in terms of soft gluon emission [77]. This alternative explanation gave a perfectly good description of the existing data, eg. fig. 56, but predicted that rather than having the p_T balanced almost entirely by target fragments as for k_T , there should be some balancing in the central region. The high energy muon scattering data are compared with these two models in fig. 63 and indeed the data favour the soft gluon explanation.

The residual k_T^2 required by the data is $\langle k_T^2 \rangle \sim 0.2 \text{ GeV}^2$ which is also compatible within errors with the null measurement of $R = \frac{\sigma_L}{\sigma_T}$.

Summary, Conclusions

Despite the warning comments with respect to experimental effects and systematic errors, the general picture given in these lecture was, I think, optimistically slanted.

The basic structure function measurements from muon and neutrino experiments faithfully follow the QPM picture to the level of $\sim 10\%^{*}$). The deviations are measured with high enough statistics and sufficient experimental

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*) There is perhaps an interesting blip on the horizon with the presentation by EMC of a comparison between iron and deuterium data which indicates a surprising difference in the behaviour as a function of x .

care for a "measurement" of Λ_{QCD} such that the relevant value of α_s is known to about 10%. The present understanding of the corrections suggests that this is one of the more reliable sources of such a measurement. Nevertheless there are higher twist effects expected and indeed within a limited sense the data provide an indication of their size and behaviour as a function of x .

As with the structure function data the QPM works so well that the measurement of deviations from the model is quite difficult. The recent deep inelastic data have refined the determination of various model parameters γ_s , α_v and have caused the major step of introduction of baryons into the fragmentation models. It remains to be seen whether these baryons are the signal of more fundamental effects.

The highest energy data pass qualitatively all the tests required for them to be advanced as data showing QCD bremsstrahlung effects. This is of primary importance, given that the structure functions measured in the same events provide one of the best quantitative measured of α_s . However the transition from fragmentation tail to out and out QCD effect is very blurred and makes the progression to quantitative comparison with QCD difficult^{*)}.

Overall, given that deep inelastic scattering is, as stated in the introduction, an indirect means to study parton interactions, the results of the study are so transparent that the disadvantage at times seems minimal. Furthermore the progress made with improved high energy data in the last two years suggests that it is a field worthy of further effort.

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^{*)} This has also been retrospectively appreciated in the case of e^+e^- [54].

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TABLE I

Experiment	Quantities Measured		
Muons			
BCDMS	E_{μ}	E'_{μ}	θ_{μ}
EMC	E_{μ}	E'_{μ}	θ_{μ}
	(also E_H for Iron expt)		
Neutrinos			
CDHS, CFRR	E_H	E'_{μ}	θ_{μ}
	(calorimetry)		
BEBC, 15'	E_H VIS	E'_{μ}	θ_{μ}
	(measured track momenta)		

Quantities measured in different types of experiments.

TABLE II

Experiment	Reaction	R	R'
SLAC	ep	0.21 ± 0.10	
SLAC-MIT	ed	0.17 ± 0.07	
CHIO ($x > 0.01$)	μp	0.38 ± 0.38	
EMC	μp	0.0 ± 0.10	
	μFe	0.03 ± 0.13	
HWP FOR	νN		0.18 ± 0.07
CDHS I	νN	0.10 ± 0.07	
CDHS II (High x)	νN	$< 0.02 \pm 0.025$	
BEBC	νN		0.04 ± 0.16
FIIM	νN		0.03 ± 0.12
CHARM	NC		0.10 ± 0.10

Table of R measurements based on [23].

FIGURE CAPTIONS

Fig. 1 - Deep Inelastic Scattering process and kinematics.

Fig. 2 - CERN neutrino beam flux.

Fig. 3 - Sketch of CDHS experiment apparatus.

Fig. 4 - Ratio between F_2^{True} and F_2^{Meas} assuming a systematic error in the measurement of E_H the total hadronic energy.

Fig. 5 - a) EMC experiment apparatus.
b) BCDMS experiment apparatus.

Fig. 6 - Dimuon spectrum showing J/ψ peak as measured with H_2/D_2 targets in EMC experiment.

Fig. 7 - Effect of 1% systematic error in beam energy on measurement of F_2 with 280 GeV muon beam.

Fig. 8 - Overall systematic errors on F_2 for EMC iron data.

Fig. 9 - Bias resulting from using different methods to estimate the total hadronic energy in a hydrogen bubble chamber experiment [14].

Fig. 10 - a) Systematic error in $\frac{1}{N} \frac{dN}{dz}$ resulting from bias of method 2, fig. 9.
b) Systematic error as a function of v in $\frac{1}{N} \frac{dN}{dz}$ resulting from 1% systematic error in scattered muon momentum.

Fig. 11 - Difference $F_2^p - F_2^n$ from EMC.

Fig. 12 - Ratio F_2^n / F_2^p as a function of x .

Fig. 13 - Decomposition of F_2^{vN} , xF_3^{vN} into F_2 , $\bar{q}$ and gluon distributions at $Q_0^2 = 5 \text{ GeV}^2$ (CDHS).

- Fig. 14 - Comparison between F_2^N measured in νN interactions by CDHS and in muon interactions by BCDMS and EMC assuming ratio 5/18.
- Fig. 15 - Measurements of strange sea distribution using dimuon production [16].
- Fig. 16 - Structure function $F_2^{c\bar{c}}$ from EMC.
- Fig. 17 - x distribution of charm sea compared to intrinsic charm predictions.
- Fig. 18 - Basic data for CDHS determination of R
 ----- $R' = 0$, ——— best fit.
- Fig. 19 - CDHS R measurement as a function of ν and x .
- Fig. 20 - Basic data for EMC determination of R .
- Fig. 21 - EMC results for R as a function of x .
- Fig. 22 - BCDMS (D. Bollini et al., Phys. Lett. 104B (1981) 403) measurement of F_2 and QCD fit.
- Fig. 23 - EMC measurement of F_2^P and QCD fit.
- Fig. 24 - EMC measurement of F_2^N (Iron) and QCD fit.
- Fig. 25 - QCD fit to low x EMC F_2^P data showing the contribution of charm (see text).
- Fig. 26 - Measurement of $F_2^{\nu N}$ and QCD fit from CDHS.
- Fig. 27 - Measurement of $q^{\nu N}$ and QCD fit from CDHS.
- Fig. 28 - Power n of $(1-x)^n$ in gluon distribution from EMC.
- Fig. 29 - Higher twist contribution to F_2 from CDHS (νN) + SLAC (eD) data.
- Fig. 30 - $h_4(x)$ determined from EMC (μp) and SLAC (ep) data.

Fig. 31 - Deep inelastic hadron production and kinematics in QPM.

Fig. 32 - Comparison of fragmentation data from different processes.

Fig. 33 - Comparison of π^+ production by neutrinos and π^- production by antineutrinos as a function of x_F .

Fig. 34 - Dependence of h^+ and h^- production, as a function of z , on x .

Fig. 35 - Comparison of π^0 production with $(\pi^+ + \pi^-)/2$ from EMC.

Fig. 36 - Comparison of π^0 and charged pion production in e^+e^- interactions.

Fig. 37 - Positive and negative hadron yields and their difference as a function of x_F in neutrino interactions.

Fig. 38 - Positive and negative hadron yields as a function of x_F in muon scattering.

Fig. 39 - Weighted charge distribution in neutrino and antineutrino interactions.

Fig. 40 - K^+ production data as function of z ;
 K^- production data as function of z , by charged leptons.

Fig. 41 - Strange particles in e^+e^- production.

Fig. 42 - Yields of π^0 and ρ^0 mesons as a function of z in muon interactions.
The $z = 1$ point for the ρ^0 contains "elastic production".

Fig. 43 - z dependence of p and $\bar{p}$ yields in high energy muon scattering.

Fig. 44 - Ratio of p to all positive charged hadrons and $\bar{p}$ to all negative charged hadrons.

Fig. 45 - High energy lambda production in deep inelastic scattering.

Fig. 46 - Proton and antiproton production compared to all hadrons as a function of p_T^2 in muon scattering.

Fig. 47 - a) QPM or QCD leading order;

b) Next to leading order QCD corrections.

Fig. 48 - x -dependence of $\frac{1}{N} \frac{dN}{dz}$ in muon interactions.

Fig. 49 - Q^2 dependence of $\frac{1}{N} \frac{dN}{dz}$ in muon interactions for different x ranges, the solid line is the QCD model.

Fig. 50 - W^2 dependence of $\frac{1}{N} \frac{dN}{dz}$, the line is the QCD model.

Fig. 51 - Observed p_T^2 spectra in high energy neutrino experiments.

Fig. 52 - Observed p_T^2 spectra in high energy muon scattering compared with model predictions.

Fig. 53 - Dependence of $\langle p_T^2 \rangle$ on W^2 , solid line is QCD prediction.

Fig. 54 - a) Dependence of $\langle p_T^2 \rangle$ on x_F in neutrino interactions.

b) Dependence of forward and backward $\langle p_T^2 \rangle$ on W^2 .

Fig. 55 - W^2 dependence of forward and backward p_T^2 and the difference compared to QCD model in neutrino interactions.

Fig. 56 - $\langle p_T^2 \rangle_{in, out}$ as a function of W^2 and comparison with e^+e^- results.

Fig. 57 - $\langle p_T^2 \rangle_{out}$ and $\langle p_T^2 \rangle_{in}$ for muon interactions in different W^2 ranges, comparison with models.

Fig. 58 - Energy flow of hadrons produced in high energy muon interactions.

Fig. 59 - Azimuthal correlation between "trigger" hadron and other hadrons in the event, — QCD model, - · - · - QPM broad fragmentation.

Fig. 60 - Dependence of $\langle p_T^2 \rangle$ on z^2 in deep inelastic muon scattering. The curves represent the various contributions, the shaded part is the contribution of k_T^2 .

Fig. 61 - $\langle \cos \phi \rangle$ and $\langle \cos 2\phi \rangle$ as measured in high energy muon scattering.

Fig. 62 - Distribution of $\int (\vec{p}_T)^2$ for $\int z_h > 0.7$, curve corresponds to $\langle k_T^2 \rangle = 0.4 \text{ GeV}^2$.

Fig. 63 - Distribution of the p_T which balances the "trigger" particle as a function of azimuth and as a function of y^* . The dotted line is from model with no soft gluons and $\langle k_T^2 \rangle = 0.7 \text{ GeV}^2$, the solid line from model with soft gluons but $\langle k_T^2 \rangle = 0.2 \text{ GeV}^2$.

$$Q^2 = 4EE' \sin^2 \frac{\theta}{2}$$

$$\nu = E - E'$$

$$x = Q^2 / 2M\nu$$

FIG. 1

FIG. 2

CDHS DETECTOR

IRON / SCINTILLATOR CALORIMETER

FIG. 3

FIG. 4

EXPERIMENTAL SET-UP (TOP-VIEW)

FIG. 5

FIG. 6

FIG. 7

FIG. 8

FIG. 9

FIG. 10

FIG. 11

FIG. 12

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FIG. 25

FIG. 26

FIG. 27

Power of the glue - EMC

FIG. 28

FIG. 29

FIG. 30

FIG. 31

FIG. 32

FIG. 33

Z

FIG. 34

FIG. 35

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FIG. 54

FIG. 55

FIG. 56

FIG. 57

$\mu p, 280 \text{ GeV}$

$100 \leq W^2 \leq 460 \text{ GeV}^2$

$Q^2 > 3 \text{ GeV}^2$

$\geq 4 \text{ charged hadrons}$

$p_{\text{lab}} \geq 6 \text{ GeV}$

FIG. 58

FIG. 59

FIG. 60

FIG. 61

FIG. 62

FIG. 63