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Neutron and proton structure today

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We present an abbreviated and personal view of the development of our experimental knowledge of nucleon structure. The fundamentals were verified over 20 years, but the past decade has provided many interesting, even exciting, surprises. Perhaps more surprises are to come.

Keywords: nucleon; structure; scattering; particles

1. Introduction

The paper in this issue by Taylor reviews the experimental discovery of quarks in deep-inelastic scattering (DIS). Altarelli (1989) reviewed how quantum chromodynamics (QCD) provides the rules governing strong forces that hold quarks inside the nucleon. The remaining papers in this issue discuss the status of current issues on these important subjects. This makes me wonder what I am supposed to do. After some thought, I decided to make this paper a snapshot of the following.

(1) How we got from there to here.

(2) What we now *know* about nucleon structure.

(3) What we now *do not know* about nucleon structure.

This article reflects personal perceptions, and makes no attempt at completeness. If I leave you with only a single thought, I hope that it would be on the subject of surprises in experimental particle physics. The existence of nucleon structure was a surprise from the beginning. Corroborating and describing nucleon structure and verifying QCD predictions filled the next two decades. Nevertheless, in this 'complete' subject, surprises have occurred during the past decade and there may yet be surprises in the future.

Let me remind you of the important variables used for descriptions of DIS:

x ($= 1/\omega$) is the fraction of nucleon momentum carried by the struck quark,
Q^2 is the momentum transfer square between leptons and quarks,
y is the fraction of available energy transferred to the quark,
$Q^2 = sxy$,
$W^2 = sy - Q^2 + m_{\mathrm{p}}^2(1 - y)$,

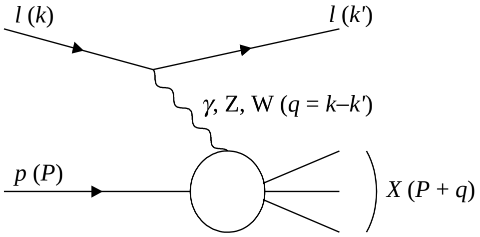

Figure 1. Diagram illustrating the scattering of leptons by nucleons through exchange of a photon or a weak boson.

and also of the 'structure functions' measured from lepton–nucleon cross-sections:

$$\begin{aligned} F_2 &\Rightarrow q + \bar{q} + \kappa, \\ xF_3 &\Rightarrow q - \bar{q}, \\ 2xF_1 &\Rightarrow q + \bar{q}, \\ F_{\mathrm{L}} &\Rightarrow \kappa \Rightarrow F_2 - 2xF_1. \end{aligned}$$

The scattering process is illustrated in figure 1. The structure functions reflect properties of the nucleon's point-like constituents (quarks). For scattering dominated by spin-$\frac{1}{2}$ quarks, the longitudinal structure function (F_{L}) should be small, F_2 is then the sum of all quark constituents and xF_3 (as the difference of quark and antiquark) is the valence quark constituency. The proton contains all quark flavours, though the structure is dominated by low mass flavours u and d.

2. History until 1990

The SLAC revolution (Bloom *et al.* 1969; Breidenbach *et al.* 1969) left us with clear evidence that major constituencies of nucleons were quarks. The earlier development of $SU(3)$ algebra (Gell-Mann 1964; G. Zweig 1964, unpublished research) should have prepared us for the discovery of quarks. The very large inelastic cross-section was a surprise. Approximate scale invariance was also a surprise. That these implied point-like constituents (Bjorken 1969; Feynman 1972) took a little time to sink in. It became clear that the scale invariance seemed to work reasonably well down to very-low-momentum transfers ($Q^2 \sim 1$ GeV^2), but scale invariance was not exactly correct. Assuming point-like quark charges required that half the nucleon momentum was carried by these quarks, and conversely, with half the nucleon momentum carried by quarks, the constituents had quark-like fractional electric charges.

Neutrino–nucleon measurements at energies up to several GeV by the Gargamelle collaboration demonstrated cross-sections that rose linearly with energy, as expected for point-like nucleon constituents. The slope was consistent with half the nucleon momentum carried by the weakly interacting constituents. These data were typically at very-low-momentum transfer, even lower than the electron scattering data of SLAC.

This situation set into motion two decades of experimentation. In parallel, the substantial and effective theoretical work on QCD proceeded. But in the early 1970s, some of us were not very sophisticated. The kinds of questions that bothered many of us were the following.

(1) Scaling. Why should it begin at $Q^2 \sim 1\,\mathrm{GeV}^2$? The simple parton concept predicts that this should occur at infinite momentum transfers (compared with the involved masses, particularly the nucleon). However, for scaling to occur with Q^2 comparable with the square of the nucleon mass seemed, to say the least, peculiar.

(2) Scaling violations. What do these mean? At high enough momentum transfers, would the quarks appear free (i.e. exact scaling)?

(3) Were the tests (e.g. sum rules) predicted from the quark concept correct? Which were fundamental? Which were exact? Some tests involved measures of quark charge and momentum fraction in the nucleon, spins of the quarks and constituency of three valence quarks. What experimental and phenomenological approaches were best to accomplish these tests?

(4) As QCD evolved, specific tests were proposed, but it was initially unclear how to make the best quantitative comparison with prediction.

A panoply of experiments contributed to resolutions of these issues (for a review of the situation in 1989, see, for example, Mishra & Sciulli (1989)). Following the SLAC electron scattering experiments, there were several muon scattering experiments (EMC, BFP, NMC, BCDMS, etc.). Complementing these was a large group of neutrino–nucleon experiments (CCFR, HPWF, CDHSW, CHARM, WA24, WA21, etc.), which used the weak interaction cross-section, independent of quark electric charge, to measure nucleon structure. An early very important issue was whether the low-energy Gargamelle-measured linear cross-section prevailed to higher energies. A series of experiments (CITF–CCFR) beginning in 1975, and extending into the 1980s, corroborated the linear rise with neutrino energy with a rate of increase at higher energies within *ca.* 20% that seen at the lower energies. Clearly established were the fractional constituent electric charges and constituent momentum fraction roughly one-half that of the nucleon. Continued measurements, particularly at SLAC, of the longitudinal structure function $R = F_\mathrm{L}/(F_2 - F_\mathrm{L}) = \sigma_\mathrm{L}/\sigma_\mathrm{T}$ showed that it is small and falling with both Q^2 and x.

By 1990, the delineation of the x-dependence of the structure functions had been demonstrated in many experiments and was generally consistent with the nucleon structure functions shown in figure 2 (Oltman *et al.* 1989, 1992): F_2 (sum of quark–antiquark) and xF_3 (difference). In figure 3 are seen the sum and difference, which are the quark and antiquark nucleon densities. The 'sea' of antiquarks and quarks dominates the low-x behaviour, and 'valence' quarks dominate the high-x behaviour. Along with this came clear and decisive measurements of the valence quarks and the flavour dependencies of the quark densities.

During the same period, important theoretical developments culminated in QCD, along with specific predictions that could be compared with experiment. Probably the best known (and still used) perturbative QCD predictions are what are now known as the DGLAP equations (Gribov & Lipatov 1972*a*, *b*; Altarelli & Parisi 1977; Dokshitzer 1977), which predict the Q^2-dependence of the structure functions. The leading-order forms are given below. These make firm predictions about the Q^2-dependence of the quark and gluon (G) densities in terms of the x-dependence of these same structure functions. The scale of the strong coupling (α_s) must be input,

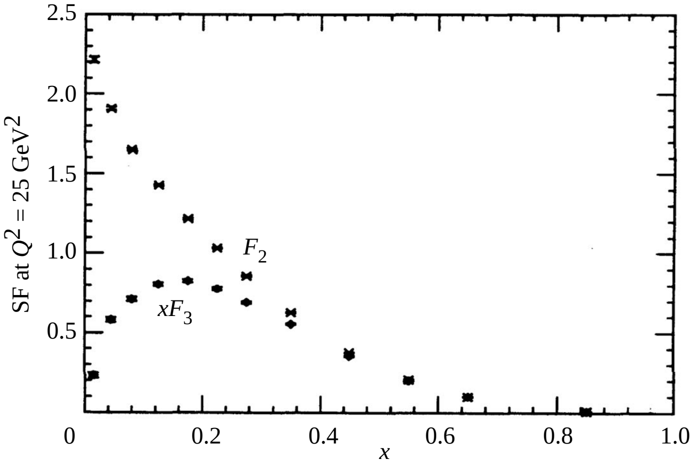

Figure 2. The structure functions F_2 and xF_3 measured with neutrinos scattered by iron (approximately equal neutrons and protons). The xF_3 structure function is also the valence quark distribution.

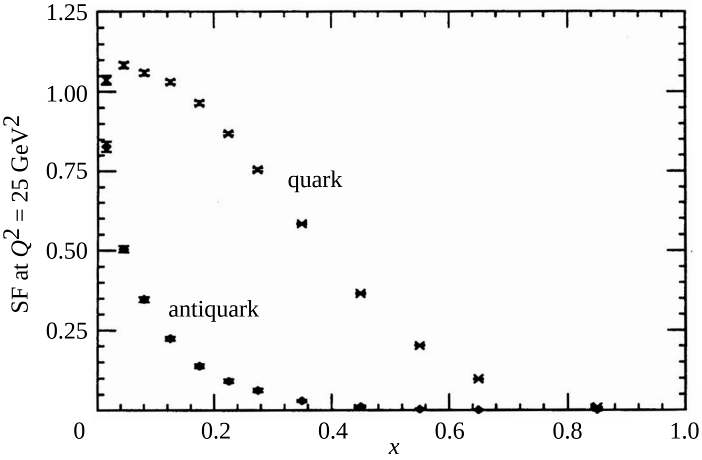

Figure 3. The quark and antiquark components of the nucleon extracted from the structure functions of figure 2. The quark and antiquark components are equal at $x = 0$.

though the functional form is predicted. All other parameters in the equations are predicted by the theory,

$$\frac{\partial F_2}{\partial \ln Q^2} = \frac{\alpha_s}{2\pi}\int_x^1 \frac{d\xi}{\xi}\left\{F_2(\xi, Q^2)P_{qq}\left(\frac{x}{\xi}, \alpha_s\right) + 2fG(\xi, Q^2)P_{qg}\left(\frac{x}{\xi}, \alpha_s\right)\right\},$$

$$\frac{\partial G}{\partial \ln Q^2} = \frac{\alpha_s}{2\pi}\int_x^1 \frac{d\xi}{\xi}\left\{F_2(\xi, Q^2)P_{gq}\left(\frac{x}{\xi}, \alpha_s\right) + G(\xi, Q^2)P_{gg}\left(\frac{x}{\xi}, \alpha_s\right)\right\}.$$

The two terms on the right-hand side result, respectively, from 'gluon bremsstrahlung' and quark pair production from intrinsic gluons. These relationships provide a decisive method for testing the consequences of perturbative QCD. The involvement of the gluon density, on the right-hand side, allows its determination but conversely

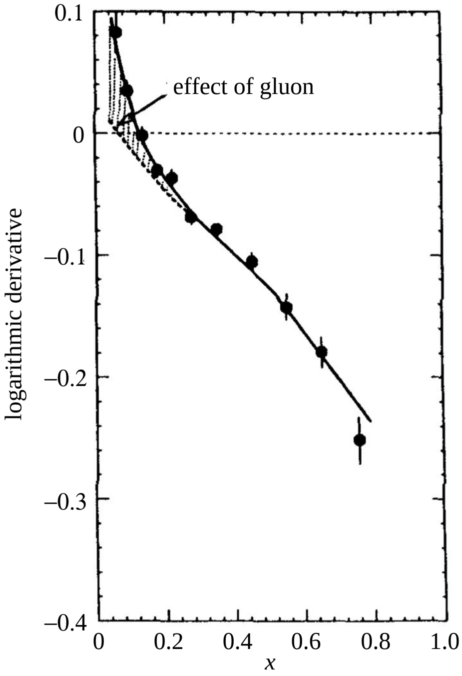

Figure 4. The logarithmic derivative ($\mathrm{d}\ln F_2/\mathrm{d}\ln Q^2$ with Q^2) of the F_2 structure function observed by the BCDMS group (BCDMS singlet fit for H_2). The effect of the gluon density in the DGLAP evolution is clearly seen in the low-x region.

complicates the predictions at small x. Unfortunately, the data extant in the later 1980s did not quantitatively obey these equations for any reasonable gluon density. Finally, the BCDMS muon scattering data (Benvenuti *et al.* 1987*a*, *b*) showed consistency with expectations of pQCD at high x, where the gluon density was expected to be small. At smaller x, the effect of the gluon density could clearly be seen. Figure 4 shows the good agreement of these data with the QCD leading-order prediction.

Even simpler is the prediction for the xF_3 structure function, which does not involve the unknown gluon density,

$$\frac{\partial xF_3}{\partial \ln Q^2} = \frac{\alpha_s}{2\pi}\int_x^1 \frac{\mathrm{d}\xi}{\xi}\left\{\xi F_3(\xi, Q^2) P_{\mathrm{qq}}\left(\frac{x}{\xi}, \alpha_s\right)\right\}.$$

This relation involves known data (xF_3) on both sides of the equation along with a known ‘splitting function’, which passes through zero. Hence the zero in the logarithmic derivative was unambiguously required to pass through zero for x in the range $0.1 < x < 0.2$. Data at that time did not show this.

Figure 5 shows the rate of xF_3 increase with Q^2 versus x, in which earlier data (Vallage 1987; Berge *et al.* 1991) did not pass through zero in the expected region. CCFR data (see Mishra & Sciulli 1989) clearly show the expected behaviour and conform to the DGLAP prediction.

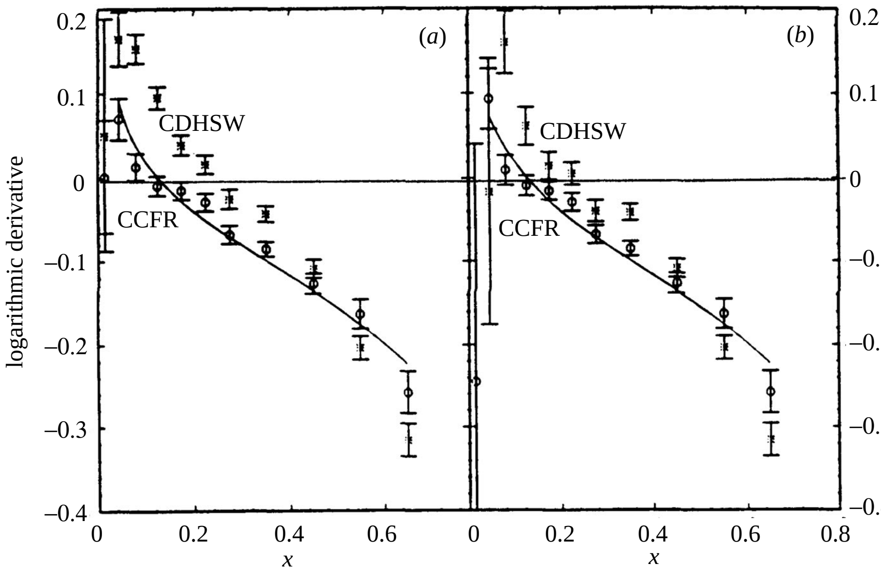

Figure 5. Data, from the late 1980s, on the logarithmic derivative ($\mathrm{d}\ln xF_3/\mathrm{d}\ln Q^2$) of xF_3 versus x from neutrino nucleon scattering at two different values of Q^2: (*a*) $Q^2 > 1\ \mathrm{GeV}^2$; (*b*) $Q^2 > 5\ \mathrm{GeV}^2$. The earlier CDHSW data did not intercept zero as predicted by the DGLAP equations. The later CCFR data behaved as expected in perturbative QCD.

3. The 1990s: understandings and surprises

The examples above illustrate a few of the many ways by which experimental data corroborated the quark composition of the nucleon. The early ideas developed into a more complete understanding of the quark and gluon constituency of hadrons. Where QCD did not yet provide explicit predictions, the Quark Model and/or current algebra provided guidance. A few examples of issues that seemed qualitatively understood by 1990 are as follows.

(1) Spin constituency of the nucleon, at least approximately as used successfully in the original $SU(3)$ Quark Model.

(2) Individual quark densities (u, d, s, etc.) and their dependence on the nucleon momentum fraction x.

(3) Gluon densities, from the experimental dependence of quark densities on Q^2 used in the DGLAP equations.

(4) Quantitative predictions of structure function dependencies at higher Q^2.

By 1990, phenomenology groups were forming to provide quark and gluon densities as a function of Q^2 and x by fitting all available data to the hypothesis of perturbative QCD. One can now (see, for example, Lai *et al.* 1997; Martin *et al.* 1996) from the MRS, CTEQ and other groups, obtain computer programs or even dial up on the World Wide Web to obtain the best-known structure density for any constituent of the nucleon. These formulations, sometimes fit to a wide range of data (not just DIS), are generally consistent with each other and with the evolution equations. Figure 6

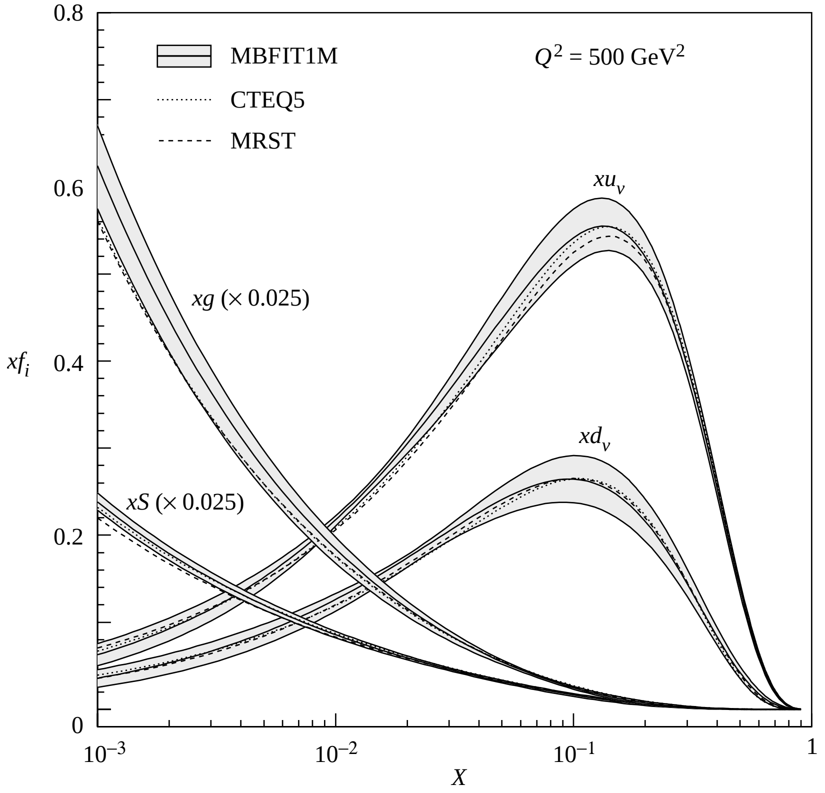

Figure 6. Recent fits to available data on nucleon structure. Note that the gluon (xg) and sea (xs) are reduced in the figure by a factor of 40. The continuous curve with associated shaded band indicates a fit by the ZEUS group; the band is the RMS error obtained by propagating errors quoted with the experimental data used as input. The fits are generally consistent with each other.

shows some present-day comparisons of these structure functions by several groups (CTEQ5 and MRST) compared with a fit (Yoshida 2000) (ZEUS) that propagates errors implicit from the input data.

However, this past decade has brought some interesting surprises, many of which are the subjects of later papers in this issue. Some are the following.

1. Spin structure of the nucleon *cannot* be described simply (EMC, SLAC, SMC, Hermes).
2. Very-low-x-dependence of structure functions is *not* as expected from specific quantitative predictions (ZEUS, H1).
3. A new category of DIS events (with rapidity gap), an experimental discovery with substantial implications for QCD (ZEUS, H1).
4. The ratio of the low-mass quark densities, $d(x)/u(x)$, as well as the antiquark density ratio, required revision (many experimental inputs).

Since most of these items are the subjects of later talks, I will concentrate only on items 2 and 4. There may also be something in store at very high x and high Q^2, as

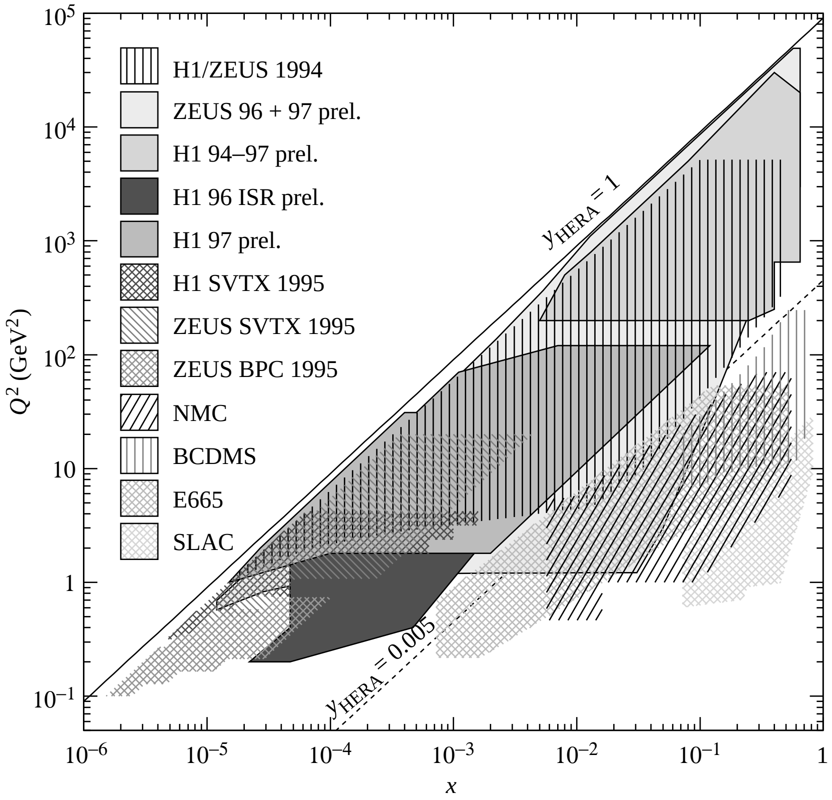

Figure 7. The values of x and Q^2, on logarithmic scales, available to fixed target experiments like NMC, BCDMS, E665 and SLAC, compared with that available to the collider experiments H1 and ZEUS. The figure makes clear how these experiments complement each other. The range of x (at reasonable Q^2) has been extended from *ca.* 10^{-2} down to below 10^{-4}. The high-x region will extend ultimately up to nearly the kinematic limit $Q^2 \sim 10^{-5}$ GeV^2.

indicated by recent ZEUS and H1 data (Adloff *et al.* 1997; Breitweg *et al.* 1997), but I leave this out of the above list since such effects are not clearly fact yet. A short discussion is included in § 7.

Of course, an important technical development during the past decade was the commissioning of HERA as an experimental tool. Figure 7 shows how the available kinematic regions changed with the advent of this collider and its associated experiments, H1 and ZEUS.

4. Small x: HERA behaviour different from fixed target

The discovery of the small x rise in structure functions was a surprise to many. Because there was some objection to this sentence at the Discussion Meeting, I would like to expand on it for this paper. Historically, as the new HERA collider was being prepared, there was considerable effort aimed at predicting the structure function behaviour, particularly at small x where the rate would be high. The most popular quantitative predictions (Kwiecinski *et al.* 1990; Morfin & Ki-Tung 1991; Glück *et al.* 1990) came from extensions of the lowest x measurements obtained from fixed

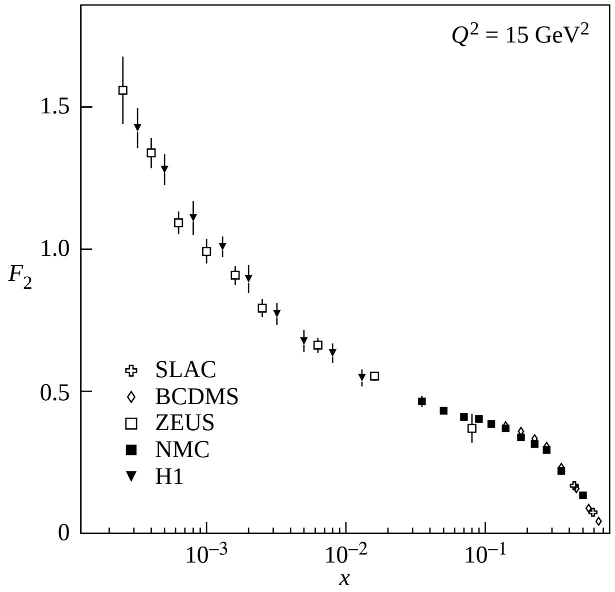

Figure 8. Structure function measurements by various experiments versus $\log x$ compiled for one particular value of $Q^2 = 15$ GeV^2. The fixed target points, from SLAC, BCDMS and NMC, lie mostly with $x > 0.02$ and the points below this from HERA. The clear change in the behaviour of the structure function at this value of x is evident in the figure.

target DIS data. A simple argument (Donnachie & Lanshoff 1992), based on Regge theory, states that the behaviour of the structure function at small x should behave like $x^{-\delta}$. The exponent is the same as the (small) exponent describing the rise with the square of centre-of-mass energy (s) of the photoproduction (and hadron–hadron) cross-section at high energies, $\sigma_{\gamma p} \propto s^{\delta}$.

This approach provided a specific and quantitative prediction for very-small-x structure functions. The value of the exponent was empirically (in both γp and low-x fixed target DIS) found to be very close to $\delta = 0.08$. This success provided evidence for a quantitative and definitive prediction for the behaviour of the structure functions at HERA: continue to behave as it had over the regions where it had been measured and where it was thought to connect simply to photoproduction and hadron–hadron processes. Conversely, phenomenological fits (Martin *et al.* 1993*a*, *b*) showed that this behaviour was not absolutely required by fixed target data; implicit assumptions about the gluon density were important.

However, it had been recognized as early as 1974 that QCD ultimately requires the structure function to rise faster than this (De Rújula *et al.* 1974). Later QCD developments (Lipatov 1976; Gribov *et al.* 1982) corroborated the need for a much faster rise at small x. Indeed, the gluon density should rise inversely like a substantial power of x. However, although it was clear that QCD should behave this way in limiting situations, no one provided quantitative predictions *at which values of* x and Q^2 this rise would begin. The earliest HERA results discovered where this rise occurs. Given the qualitative agreement of fixed-target small-x quark density with Regge predictions, most *quantitative* predictions for HERA structure functions anticipated a slow rise with smaller x.

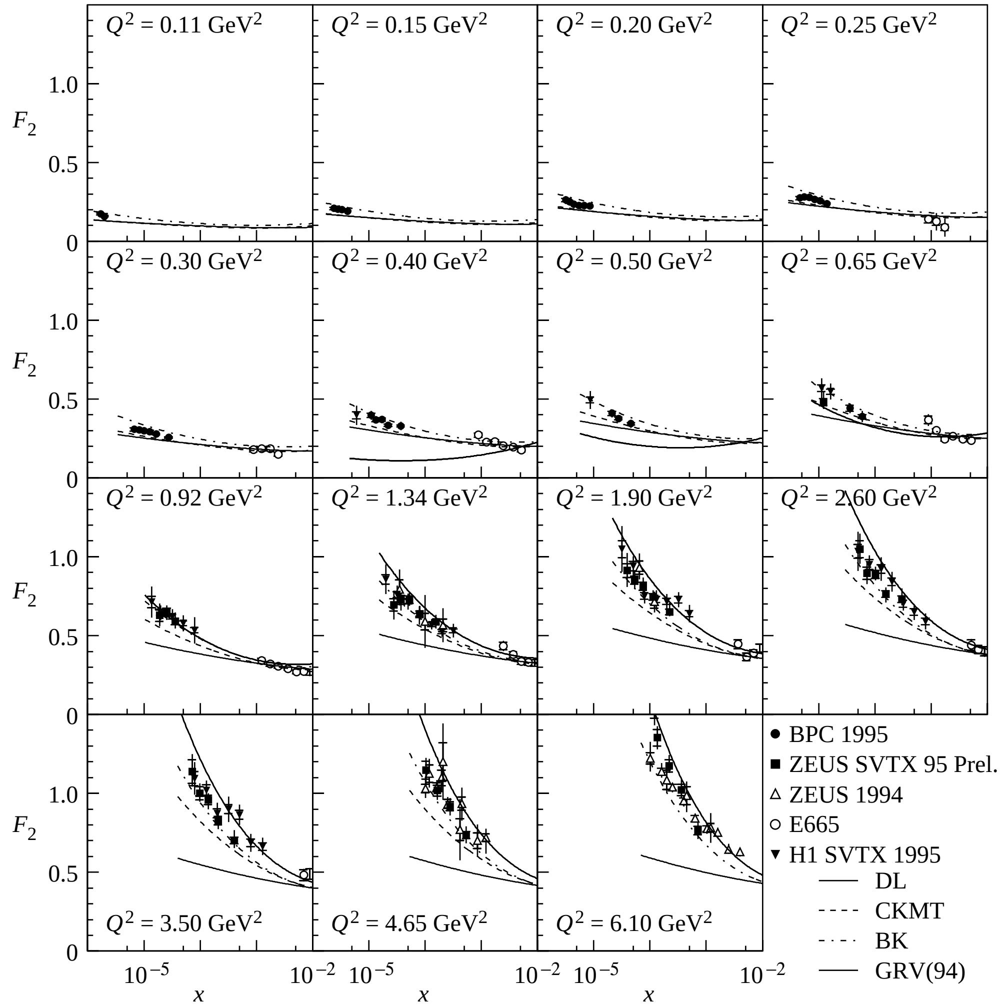

Figure 9. Structure function, F_2, as a function of x for various fixed values of Q^2. The lowest values of momentum transfer are at the upper left and the highest values at the lower right. This figure clearly shows the low x rise at higher Q^2, but the x-dependence becomes flat as one moves to lower Q^2, so that the data mesh nicely with the $Q^2 = 0$ photoproduction prediction.

The early HERA data (a more recent version is shown in figure 8) showed clearly where (in x) the substantial rise at low x begins, and that this is a qualitative change. There is little question that this feature was anticipated by some, but the precise nature of the change and the value of x at which it occurs was an experimental discovery. The precise nature of this rise is still the subject of important research. The connections with other phenomena (like diffraction), and whether the parton densities become so large that observable saturation sets in, are questions still requiring answers.

In the ensuing years, the behaviour of the structure functions has been measured over a much extended range of x *and* Q^2 (for a recent review, see, for example, Abramowicz & Caldwell 1999). Figure 9 shows some of the richness of this data at

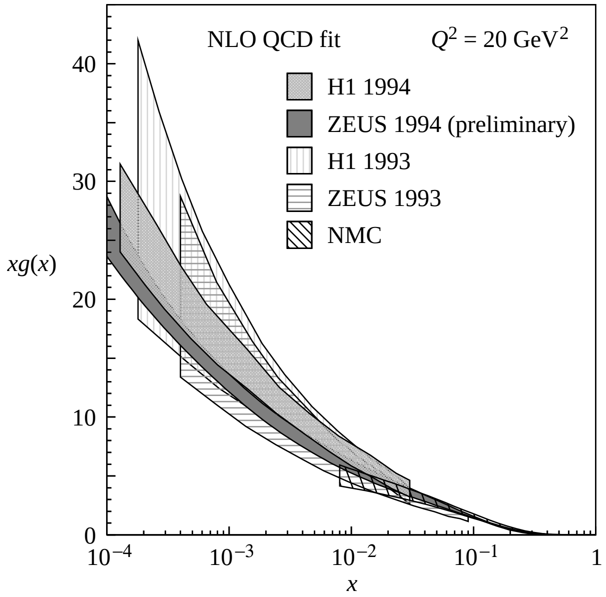

Figure 10. The proton gluon densities extracted from the logarithmic derivatives of the F_2 structure function at higher Q^2. These are obtained using the DGLAP equations for various datasets indicated. All such fits now agree with a strong rise at very small x.

lower values of momentum transfer. The figure illustrates that the structure function indeed approaches photoproduction ($Q^2 = 0$) behaviour smoothly. Figure 10 shows the gluon densities extracted from the logarithmic derivatives of the F_2 structure function at higher Q^2. The extension of the kinematic range provided by HERA is very visible in the comparison between the ZEUS and H1 data (going to very small x) with that of NMC (at larger x). Also, it is clear that increased luminosity and time will provide measurements of high accuracy.

5. Low-mass quark flavour asymmetry

As data and phenomenological fits get better and more sophisticated, we expect more accurate predictions of structure functions. Continued comparison of observations with predictions is essential. My favourite example of a surprise provided by such a comparison is the flavour asymmetry of the nucleon. Inherent in the Quark Model of the proton, and known empirically since the days of SLAC, is the proton's larger u quark density (than d quark density). Inherent in parametrizations of structure functions, at high x, is a factor that behaves like $(1 - x)^n$, where n is a different power for d quarks and u quarks. This functional dependence forces the ratio of the quark flavours to approach zero at high x. Essentially all parametrizations have this formulation built in.

A recent effort (Yang & Bodek 1999) to reconcile many sources of information has indicated that the flavour density ratio may not be as simple as previously thought. The conclusion was that the usual parametrizations (e.g. MRS) underestimate this ratio by a factor

$$\Delta(d/u) = 0.1x(1 + x).$$

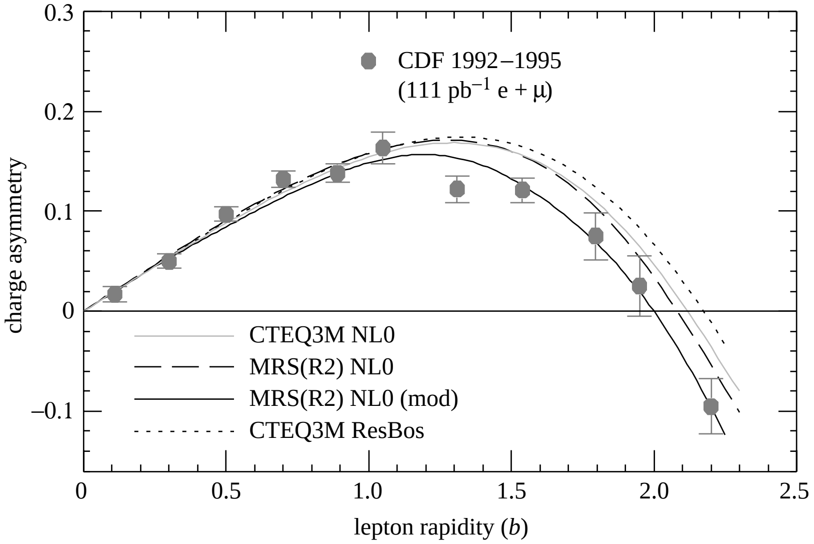

Figure 11. The charge asymmetry of the lepton, from the decays, by single bosons produced in proton–antiproton collisions. Clearly, the prediction modified by the proposed correction agrees much better with the data than the several MRS and CTEQ predictions then available.

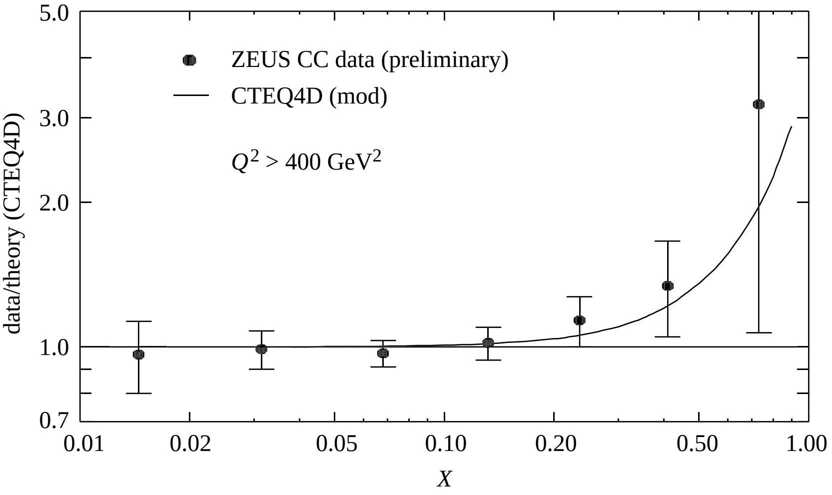

Figure 12. The comparison of ZEUS charged current event rate versus x divided by Standard Model prediction using the CTEQ4D parton distribution. The curve corresponds to adding to the Standard Model prediction the d/u correction proposed.

Much of the argument revolves around the nuclear binding corrections in deuterium. Figure 11 shows the most compelling (to me) evidence that an increase in the flavour density is required.

Figure 12 shows the effect of the proposed change on the charged current ($e^+ + p \rightarrow \bar{\nu}_e + X$) event rate observed by ZEUS. Predictions without (horizontal line) and with (curve) the u/d modification show this. A change in event rate of about a factor of

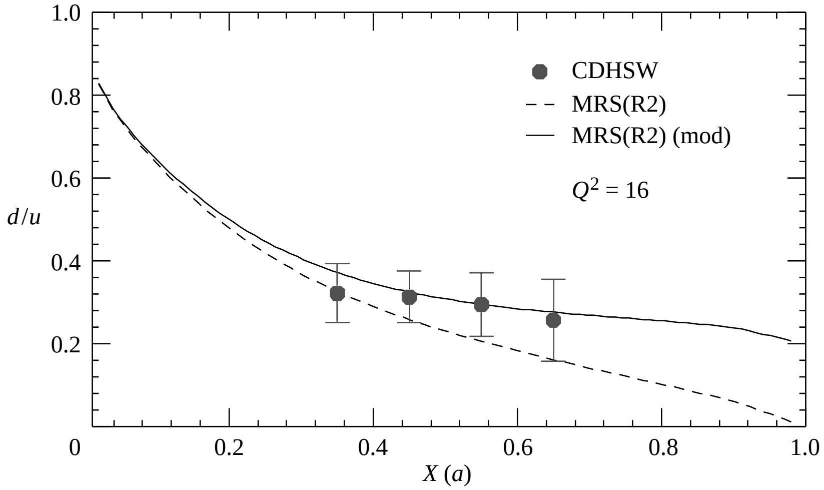

Figure 13. Effect of the predicted correction to the d/u quark ratio. The data are measurements by the CDHSW neutrino experiment.

two is predicted for the very highest x values. Though of statistically limited, present data are more consistent with the added d/u component.

Figure 13 shows the effect of the proposed d/u correction directly: rather than going to zero at $x = 1$, d/u is extrapolated to a finite value. Incidentally, this prediction agrees somewhat better with the measured flavour asymmetry using charged current fixed target measurements. There is presently some question whether a finite flavour ratio is required at $x = 1$ (Kuhlmann 1999; Martin *et al.* 1999).

Clearly, though an increase in the flavour ratio is required, all is not known. More information from many sources and with better precision will continue to be important in delineating correctly the large-x structure of nucleons. Precise measurements at large x by HERA will bring this issue a long way.

6. Low-mass antiquark flavour asymmetry

The simplest assumption within the Quark Model for the sea of antiquarks (formed from gluons) would be that the d and u antiquark densities are the same. Such an assumption is implicit in the Gottfried sum rule (Gottfried 1967),

$$\int_0^1 [F_2^{\mathrm{p}} - F_2^{\mathrm{n}}] \frac{\mathrm{d}x}{x} = \frac{1}{3} - \frac{2}{3} \int_0^1 [\bar{d}_{\mathrm{p}} - \bar{u}_{\mathrm{p}}] \,\mathrm{d}x.$$

Experimental measurements of the left-hand side did not give the simplest answer, 0.333. On the contrary, the NMC group (Amaudruz *et al.* 1991; Arneodo *et al.* 1994, 1997) found a value substantially different: 0.235 ± 0.026. The obvious resolution is an intrinsic flavour asymmetry to give a positive and substantial value to the integral in the second term.

Measurements of Drell–Yan processes in a fixed target experiment have recently provided the functional dependence of this asymmetry (Hawker *et al.* 1998; Gagliardi *et al.* 2000). Figure 14 shows that the dependence is not simple, with a peak at $x \sim 0.17$. This is an important piece of information that illustrates the lack of simplicity

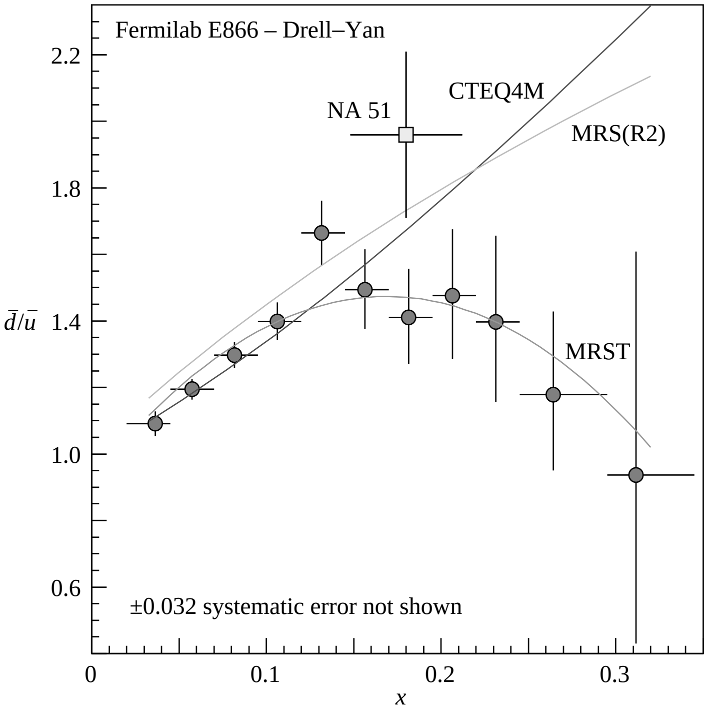

Figure 14. The antiquark flavour ratio measured directly from Drell–Yan processes.

in the actual proton structure. This lack of simplicity was not predicted from first principles. It is clear that experimental data continue to keep the structure function parametrizations honest and provide guidance to those who deign to calculate proton properties from basic principles.

7. High x at HERA

Data at high x are difficult to measure because cross-sections are very small. The HERA accelerator was designed to permit measurements of the high-x region at Q^2 previously unattainable—approaching $Q^2 \sim 10^5\,\text{GeV}^2$. In preliminary data, both ZEUS and H1 have observed interesting anomalies that could be due to statistical limitations (for a more detailed review, see Abramowicz & Caldwell (1999)). There is the possibility that this region, as in the previous examples, will provide some surprises. Exploration of the high-x region will require the HERA luminosity upgrade scheduled for later this year.

One question to answer now is how accurately the structure functions are predicted at such high Q^2, so that measurements can be judged consistent or not. Predictions follow directly from the DGLAP equations, with appropriate input of existing data. These equations reflect the tendency of QCD to move higher x partons at low Q^2 to lower x at higher Q^2 because of gluon radiation. It follows that precise predictions at high x require reasonable knowledge of the quark densities from lower Q^2 at very high x. Present techniques require assumptions of functional forms for the quark densities at some nominal $Q^2 = Q_0^2$. The constants are then determined by fitting all available data. The usual functional form looks like

$$Ax^b(1+\gamma x)(1-x)^d \quad \text{at } Q^2 = Q_0^2.$$

This functional form forces all quark densities to approach zero at $x = 1$ like a power of $(1-x)$. The previous discussion of the flavour ratio, d/u, should make us question and test such assumptions.

It is interesting that few data presently exist on the proton structure function at large x ($x > 0.5$) in the deep-inelastic regime. The most-constraining data come from BCDMS at large x values, with Q^2 extending up to several hundred GeV^2. Essentially all fits to these data, using the functional forms described above, agree with each other at the several per cent level on high-Q^2 predictions. Fits which incorporate experimental errors to provide an estimate of the effects of error propagation estimate an error of *ca.* 10% in the prediction at $x = 0.75$.

The effects of the extrapolation inherent in the assumption of the specific functional form have been studied (Kuhlmann *et al.* 1997). A recent look (Paganis 2000) concludes that such effects could change predictions for HERA of order 25% for radically different high-x functional assumptions, but it is unlikely that they could change by factors of two. To obtain even 25% effects requires violent distortions at nominal Q^2 near $x = 1$. (This conclusion relies on a small amount of fixed target data at large x.) Though it is impossible to prove that no distortion of the functional form would produce a large effect, the predictions for the structure function behaviour at large x is rather precise. The predictions for the high-x structure functions should be accurate to 50% or higher. If, when the experiments are done, the predictions disagree by substantially more, something unanticipated must be occurring.

8. Conclusions

At the beginning of the last decade, a considerable knowledge of nucleon structure had emerged from a large number of diverse experiments in deep inelastic scattering. These involved electrons, muons and neutrinos incident on a variety of nucleon and nuclear targets. The experiments confirmed the quark constituency of nucleons, measured various flavour components of this constituency, verified the predictions of perturbative QCD as the force holding these quarks inside, and measured the density of gluons within the nucleon.

While these beautiful data were essential to our description of nucleon structure, experiments during the 1990s have continued to point out areas in which our pictures were still incomplete, and even naive. Much of the focus of this Discussion Meeting was on such areas: spin structure, low-x behaviour and flavour issues. Some of these results have been surprises to many; indeed, careful measurements of nucleon structure continues to provide exciting issues and new fields even though it is thought that the basics are well understood.

New measurements on nucleon structure are coming from many sources. The next frontier for the HERA accelerator is the study of the high-x region of the proton. The luminosity upgrade planned for later this year will provide the tools necessary to explore this critical region. With so many surprises in our recent history, it is possible that more surprises on nucleon structure are yet to come.

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