NUCLEON STRUCTURE FUNCTIONS

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INTRODUCTION

In this talk I will try to summarize ideas and plans which have been put forward by members of all collaborations running muon or neutrino experiments at CERN. During our discussions there was general agreement that: i) subtantial improvements of structure function measurements in the SPS range are still possible and necessary and ii) it is the responsibility of the present groups and of CERN to provide a "final" set of structure functions in the present energy range.

1. MAIN PHYSICS INTEREST

a) Nucleon structure functions are very important phenomenological input for hard scattering processes involving hadrons like Drell-Yan lepton pair production, single photon production, high p_T scattering in pp and $\bar{p}p$ etc. For these applications we have to know the flavour composition, i.e. the quark and gluon distributions $xu_v(x,Q^2)$, $xd_v(x,Q^2)$, $x\bar{u}$, $x\bar{d}$, $x\bar{s}$, xc, ..., $xG(x,Q^2)$.

b) The study of scaling violations (Q^2-dependence) provides a good way to study quark-quark interactions. We expect two contributions, one which falls like $(1/Q^2)^n$ plus a $1/\ln Q^2$ contribution, where the first one represent collective parton effects (higher twists), whereas the second one is due to single parton scattering for which we have a solid QCD-prediction.

c) A new subject is the question of parton distributions in nuclear matter (A-dependence) where substantial interest has been triggered by the new EMC-result$^{1)}$. If their result is confirmed then it would reinforce the interest in structure function measurements on H_2 and D_2 targets.

d) We have to cure some experimental defects: We need a decent measurement of $R = \sigma_L/\sigma_T$, we want to fill in some blank kinematic regions (i.e. low x for H_2, large x and low W) and we have to solve normalization problems both for neutrino and muon experiments.

2. PRESENT STATUS

2.1 Reminder

Most of our knowledge at present is coming from heavy targets. Both muon and neutrino experiments measure the structure function $F_2^N = x(u + d + s + c + \bar{u} + \bar{d} + \bar{s} + \bar{c})$ on complex nuclei. Neutrino experiments have the additional virtue to separate sea and valence contributions. They measure $xF_3(x,Q^2) = x(u_v + d_v)$ and $\bar{q}^{\bar{\nu}}(x,Q^2) = x(\bar{u} + \bar{d} + 2\bar{s})$. Finally the observation of opposite sign dilepton events in ν-physics gives a handle on $xs(x,Q^2)$.

The separation of u_v and d_v and of $\bar{u}$ and $\bar{d}$ requires additional measurements on elementary targets. The ratios u_v/d_v and $\bar{u}/\bar{d}$ can be determined by neutrino (and antineutrino) experiments on hydrogen. With some additional uncertainties due to nuclear effects this information can also be obtained from deuterium. Muon experiments measure $F_2^{\mu p}$ and possibly $F_2^{\mu n}$. The main emphasis here is the Q^2-dependence. Any analysis of muon data requires however external information about the sea contributions.

2.2 A-dependence

Let me start by this subject because it may influence substantially the future program. Effective quark distributions in nuclear matter are expected to be different from free nucleons, i.e. due to Fermi motion. The real surprise is that the EMC Collaboration sees a rather brutal effect at a level which jeopardizes the evaluation of nucleon structure functions from heavy targets and reinforces the interest in H_2 and D_2. The EMC observation is shown in Fig. 1: The F_2 structure function differs substantially if measured on iron compared to D_2 in a kinematic range ($<\nu> \simeq 60$ GeV) where we all believe that scattering off single partons should be the dominant process. Figure 2 gives the difference of structure functions $F_2^N(\mathrm{Fe}) - F_2^N(D_2)$ ignoring the large normalization uncertainty. It suggests that the difference might be mainly due to the sea quark contributions, i.e. the sea contribution in iron might be larger by ≈ 40% compared to free nucleons$^{2)}$. This effect needs confirmation by a dedicated experiment.

Actually our present understanding of the Fermi motion effect is also pretty disappointing. The Fermi motion corrections for iron versus x as proposed by various authors differs substantially, mainly at large x. As a result the shape of quark distributions at large x ($x \geq 0.5$) cannot be reliably determined from experiments on heavy targets.

The study of the A-dependence is an interesting subject by its own. For particle physicists we might say that we can study the "long range confining phenomena" in QCD. For nuclear physicists we might say that these experiments could help to clarify the role of quarks and gluons in the nuclei. A detailed discussion of the physics aspects can be found in the talk of Ch. Llewellyn Smith in this volume$^{4)}$. Depending on the verification of the EMC result there may evolve interest in a long term program.

2.3 Flavour composition of the nucleon

The present situation is well documented. See for instance, Ref. 3. Shortly, for isoscalar heavy targets we have a complete set of structure functions F_2, xF_3, $\bar{q}^{\bar{\nu}}$ and xs(x). They are reasonably well measured including their Q^2-dependence. Main defects are: i) the poor knowledge of $R = \sigma_L/\sigma_T$ which affects the determination of F_2 and $\bar{q}^{\nu}$ mainly at small x, ii) normalization uncertainties of up to 20%, iii) a rather poor knowledge of xF_3 at small x. For H_2 and D_2 targets, the experimental situation is less satisfactory. The structure function $F_2^{\mu p}$ is quite well measured at large x including the Q^2-dependence, the small x region ($x \lesssim 0.1$) is however missing. A combination with measurements on D_2 allows to measure $\sigma n/\sigma p$ which, outside of the sea region is related to d(x)/u(x). The present experimental knowledge is given in Fig. 3 combining low energy SLAC data and high energy muon data from EMC. These measurements require separation of neutron and proton interactions in D_2 and therefore suffer from uncertainties due to Fermi-motion especially at large x. Hydrogen experiments with neutrinos and antineutrinos can do better in principle since they are able to separate valence and sea contributions in the whole x-range using H_2 data only. Present knowledge is summarized in Fig. 4. The knowledge on d_V/u_V at present is rather modest. It is limited by statistics at small and medium x, whereas the large x region is unaccessible due to large smearing corrections which are due to poor total hadron energy measurement. The flavour composition of the sea, especially the measurement of $\bar{u}/\bar{d}$ is only accessible to neutrino experiments and is poorly known at present.

The longitudinal structure function F_L (related to $R = \sigma_L/\sigma_T \approx F_L/F_2$) is by far the hardest to determine and has been a pain in the neck of the experimentalists for a long time. The present experimental situation is summarized in Fig. 5a and b. R is still very poorly known at small x leading to substantial uncertainties for F_2 and $\bar{q}^{\nu}$. We have however, tight bounds at large x due to a new measurement of the CDHS Collaboration which is only possible for neutrino experiments.

2.4 Q^2-dependence of structure functions

The knowledge of the Q^2-dependence is important for two reasons:

i) the fractional momentum carried by constituents changes with Q^2 substantially and has therefore to be known for hard scattering processes. (This assumes that we will make theoretical improvements which allow us to use this knowledge, i.e. what is the mass scale for hard-scattering processes, etc.);

ii) the study of scaling violations gives a good handle to study q-q interactions. We may be able to separate $(1/Q^2)^n$ effects from $1/\ln Q^2$ effects, i.e. to separate collective parton phenomena (+ kinematic effects) from perturbative QCD effects.

The main interest up to now has been to test QCD predictions. All experiments agree that there are significant scaling violations which extend to high Q^2 and they are well described by QCD (for large enough hadron masses $W \gtrsim 3.3$ GeV). Figure 6 shows $d \ln F_2/d \ln Q^2$ for the three high statistics experiments at the CERN SPS to illustrate this point. Though there are differences in detail outside statistical errors, the agreement as a whole is encouraging. These experiments have achieved a determination of Λ corresponding to a measurement of α_s to about ±10% and a determination of the gluon distribution. We also have first indications that non-perturbative contributions are important at low W.

Most people are aware by now, that the study of scaling violations cannot prove QCD. It should be pointed out however, that QCD might be disproven. So I think further improvements are important, especially since deep inelastic scattering is one of the few fields where perturbative QCD predictions are based on solid grounds.

A last note: whatever we have leaned about QCD from DIS is not affected by the possible A-dependence of structure functions. Effective parton distributions in iron will follow the same evolution equations as the distributions in free nucleons. The results may depend however on the way how the analysis is done because the data have to be extrapolated to large x outside the measured region ($x \gtrsim 0.7$). Most groups nowadays use the Altarelli-Parisi equations directly to follow the (x,Q^2) dependence. This technique is fairly independent of the detailed behaviour at large x in contrast to, e.g. a moment analysis. Further discussion of this point may be found in Ref. 4.

2.5 Missing kinematic regions

Some kinematic regions are poorly covered at present. The low x region is not accessible to present muon experiments due to acceptance. It is covered by neutrino experiments but suffers both from statistics and the large uncertainty due to $R = \sigma_L/\sigma_T$. This is very bad since the low x-region contains most of the information about QCD. Discriminative tests of

QCD[5)], the check of the QCD prediction on R and the determination of the gluon structure function via scaling violations all require precise data, at low x. The large x region ($x \gtrsim 0.7$) is unaccessible due to large smearing in the variable ν. This leaves a large unexplored region $0.7 < x < 56$ in the case of iron which might contain quite interesting physics. Finally, the region at large x and low Q^2, i.e. low invariant hadron mass W is not covered by present high energy experiments. This kinematic region is important to separate higher twist contributions $\sim (1/Q^2)^n$ from perturbative $1/\ln Q^2$ contributions.

3. EXPERIMENTAL PROGRAM AND NECESSARY IMPROVEMENTS

i) A verification of the EMC result on A-dependence is urgent since it has impact on the long term future.

ii) A precise measurement of the longitudinal structure function $F_L(x,Q^2)$ would be highly desirable since the present uncertainty seriously affects the determination of all structure functions except xF_3. Also, the analysis of scaling violations at small x and hence the determination of the gluon distribution suffers. Moreover there is a QCD prediction for F_L to test.

iii) Concerning the flavour composition we would like to improve our knowledge on $xF_3(x,Q^2)$ mainly at small x and to improve our knowledge of $d_v(x)/u_v(x)$ and $\bar{u}(x)/\bar{d}(x)$. If it turns out that the parton distributions in nuclear matter are really substantially different from free nuclei, then there is a real job to be done. In this case we have to restart the determination of xu_v, xd_v, $x\bar{u}$, $x\bar{d}$, $x\bar{s}$ and of the gluon distribution for free nucleons. Remember that according to the measured effect of the EMC Collaboration, the sea might differ by a very large amount. Such a goal would certainly need an extensive neutrino program on H_2 and possibly D_2. The measurement of $F_2^{\mu p}(x,Q^2)$ and $F_2^{\mu n}(x,Q^2)$ by muon experiments would be also needed especially for the Q^2-dependence.

iv) We should improve our QCD tests and the determination of the gluon distribution. The analysis of $xF_3(x,Q^2)$ measured by neutrino experiments on heavy targets is our best handle to measure Λ. A substantial improvement is possible there, both in statistics and systematics. A good singlet analysis needs precise data at small x and a good knowledge of $R = \sigma_L/\sigma_T$. Muon experiments should improve their acceptance at small x to cover this region with good statistics.

4. FUTURE PROGRAM AT THE SPS

4.1 Neutrino experiments on heavy targets (iron, marble, etc.)

These experiments aim at a substantial improvement in the measurement of F_L, $\bar{q}^{\bar{\nu}}$, xF_3 and the gluon distribution and this can only be achieved by them.

The CDHS Collaboration has installed new calorimeter modules with improved resolution and systematics. They also have learned how to use high statistics from wide band beams. This collaboration foresees an extended structure function run corresponding to a total of $\sim 3 \times 10^{18}$ protons in WBB leading to about $10^6 \nu$ and $10^6 \bar{\nu}$ events above $E_\nu = 20$ GeV. This will happen in 1983/84. CHARM has improved their detector. A specific merit of this detector is that the useful hadron energy range can be extended down to about 2 GeV ($\approx$ 5 GeV for CDHS). They have presented a new analysis based on 50'000 ν and 110'000 $\bar{\nu}$ charged current events from wide band beam[6)] at this meeting. Based on this experience they foresee an extended program in wide band and possibly high band beams. In 1983/84 they expect about 5×10^{18} protons on WBB targets (450 GeV) leading to 10^6 neutrino and $\sim$ 500'000 antineutrino events with average energies $<E_\nu> \simeq 35$ GeV and $<E_{\bar\nu}> \simeq 25$ GeV. After 1984 they think of extending towards higher energy by working in a quadrupole focused beam$^{7)}$ which is expected to yield for 5×10^{18} protons on target 300'000 ν and 100'000 $\bar\nu$ events with average energies $<E_\nu> \simeq 100$ GeV and $<E_{\bar\nu}> \simeq 70$ GeV.

Both experiments will certainly provide a precise consistent set of structure functions on heavy targets and a substantial improvement of our QCD tests.

4.2 Experiments on H_2 and D_2

Muon experiments

These experiments have made substantial progress in the control and understanding of systematic errors, which is their major worry.

The BCDMS (NA4) Collaboration has an approved program for the years 1982-84 to do high statistics runs on H_2 at 100, 200 and 250 GeV beam energy. They expect altogether more than 3×10^6 events in an increased kinematic range $x > 0.1$ and $Q^2 > 7$ GeV^2/c^2. They may also do some D_2 running though there are no definite plans yet. The main emphasis is on the Q^2-dependence and QCD-comparisons.

The upgraded EMC detector after 1984 will allow to measure down to very low x-values by adding a small angle system. The kinematic range $Q^2 \geq 1.5$ GeV^2/c^2 for $0.003 < x < 0.1$ would be accessible. Using this detector, a precise measurement of H_2 and D_2 structure functions in the whole x-range would be possible after 1984. However, no definite plans have yet evolved.

Neutrino experiments on H_2 and D_2

These experiments are indispensable to separate valence and sea components and to determine the flavour composition separately for up, down and strange quarks. The interest in H_2 and D_2 experiments is substantially increased if quark distributions in nuclei differ from free nucleons as suggested by the EMC result. In this case, there is a substantial job to be done which might take a long time. Could BEBC be a suitable detector for this work? It has already seen a lot of neutrinos. At present, the WA21 experiment has reconstructed 3400 neutrino and 2900 antineutrino charged current events and twice as many are on film. For D_2 a large exposure is underway for experiment WA25, where about 20'000 neutrino and 20'000 antineutrino events are expected for 3×10^{18} protons on target.

Clearly, a large amount of effort and money is required to do structure function work with bubble chambers. We should however, keep in mind, that structure function determinations are just one facet of a large bubble chamber exposure.

The most interesting question is: Could large BEBC exposures provide good measurements of $x\bar{u}$, $x\bar{d}$, xu_V, xd_V as a function of x and possibly also Q^2?

Present H_2 and D_2 data in BEBC have a major defect: the total hadron energy cannot be measured but has to be inferred from the charged energy using an empirical correction based on the missing transverse momentum. Figure 7 shows the resulting resolution function due to this procedure as obtained from a Monte Carlo simulation. For bare BEBC filled with hydrogen the resolution function looks just awful to me, especially since it has large asymmetric tails which can only be obtained by model-dependent Monte Carlo.

The effect on the measurement of x-distributions due to this smearing has been estimated by Myatt[8]. The smearing corrections are around -10% for small x and rise very rapidly above x = 0.6 such that a measurement above x = 0.7 is not possible. The systematic uncertainties of these smearing corrections are estimated to exceed 10% for x > 0.4. The situation could be substantially improved if the neutral component of the showers would also be measured by an electromagnetic calorimeter inside BEBC. A solid argon calorimeter has been proposed[9] and would indeed help a lot as shown in Fig. 7.

As a result, for bare BEBC, about four times more statistics could be useful for antineutrinos which would correspond to 5×10^{18} protons on target. Further increase of statistics would not really help since the systematic uncertainties exceed the statistical errors. Therefore, substantial improvements would require additional gadgets like, i.e. an electromagnetic calorimeter. In this case an exposure which yields about 30'000 charged-current events is expected to yield statistical errors similar to the systematic uncertainties.

It should be clear that the main motivation to use neutrino experiments is the separation of valence and sea distribution in the small x region. Up to now I have not seen a clear strategy how this can be achieved for H_2 and D_2. Also the relative merits of H_2 and D_2 exposures have to be revaluated.

Therefore, I can say that there is a clear need to get precise neutrino structure functions from free protons and neutrons, especially if the A-dependence of structure functions is confirmed. It has however still to be demonstrated if and how the present systematic problems can be overcome. High statistics alone are not sufficient.

4.3 A-dependence measurements

i) Verification of effect

A first check could be made using the D_2 exposure in BEBC. The analysis is in progress. It could be checked if the ratio of sea to valence distribution is larger in iron than in D_2. The EMC effect suggests a 40% difference which should be easy to check. A direct check can be performed by the BCDMS exposure in 1983 in a parasitic run at 280 GeV. They will be able to run with D_2 and Fe targets simultaneously which will reduce systematic uncertainties substantially. They expect a statistics comparable to the present EMC data.

ii) Future program if confirmed

Both muon collaborations have shown interest in a series of exposures to study the A-dependence after 1984. Neutrino experiments will also be needed to separate the effect on valence and sea contributions.

4.4 Polarization measurements

Muon experiments using a polarized target are approved for the EMC collaboration for the year 1984. After 1984 BCDMS might be willing to collaborate using the polarized target in front of the NA4 detector. Unfortunately the polarization effect is strongly diluted by the small fraction of free protons in the target and the small degree of polarization.

4.5 Beams and runs for structure function experiments

Shown below is a tentative program of the SPS for structure function measurements. The solid lines show runs which have been requested and are partially approved. Dashed lines indicate experiments where serious thoughts are underway in the collaborations. Finally the dotted lines give some vague ideas of how the program could continue in the far future.

Experiment	Beam	83	84	85	86	> 86
BEBC	$\nu + \bar{\nu}$ WBB 450 GeV quadrupole beam $> 10^{19}$ proton on target	D_2		H_2	+ calorimeter	
CDHS		$\nu,\bar{\nu}$		....?....		
CHARM			$\nu,\bar{\nu}$			
BCDMS		H_2, D_2		polarization A-dependence		
EMC		shadowing	polarization	H_2, D_2	A-dependence	

5. COMPARISON WITH THE DOUBLER (Fermilab)

Both muon and neutrino experiments will be operational starting in 1984. The Q^2 and W^2-range are doubled such that this machine offers a unique chance to find thresholds, to establish the propagator effect and hopefully something unexpected which happens to be in this new energy domain.

The main emphasis in my presentation has been on the conservative issues like flavour composition, ln Q^2-dependence, A-dependence, which do not profit necessarily from higher energy. There high statistics, well understood detectors etc., are much more important.

The main limitation of the Doubler is flux (or event rate). There will be about 2×10^{18} protons on target/year (100 days running) and this lack of protons is not compensated by the higher flux and cross-section. Moreover, it will take quite some time to understand and control the partially new detectors in the new energy range. It is surely more interesting to work at the Doubler, but I think structure functions will not be the main issue at the Doubler. SPS experiments are in good shape to lead in all fields, where the increase in energy is not essential.

6. SUMMARY

i) We need a reliable set of structure functions for the nucleons: xu_v, xd_v, $x\bar{u}$, $x\bar{d}$, $x\bar{s}$, $xG(x)$. The CERN neutrino and muon experiments are in a unique position to provide this information. We know how to improve our present knowledge on F_2, xF_3, F_2^p, F_2^n, $\bar{q}^{\nu}$, ..., and experiments are underway or planned for the near future to do so.

ii) We have strong indication that structure function measurements on heavy nuclei may not be used to derive the nucleon structure functions. For example, the sea quark distributions might differ by about 40%. If this is confirmed, then there is work to be done which might take quite long and would involve large neutrino and muon experiments on H_2 and D_2.

iii) The study of scaling violations is one of the most reliable ways to study parton dynamics and to test QCD. Substantial improvements are still possible and new experiments will give much better determinations of Λ, the gluon distribution and more insight into the question of higher twist contributions.

These experiments are notoriously difficult and there may not be much fun in them any longer. Nevertheless they are important and they should be supported provided a sufficient number of dedicated and persistent physicists is willing to spend their time on them.

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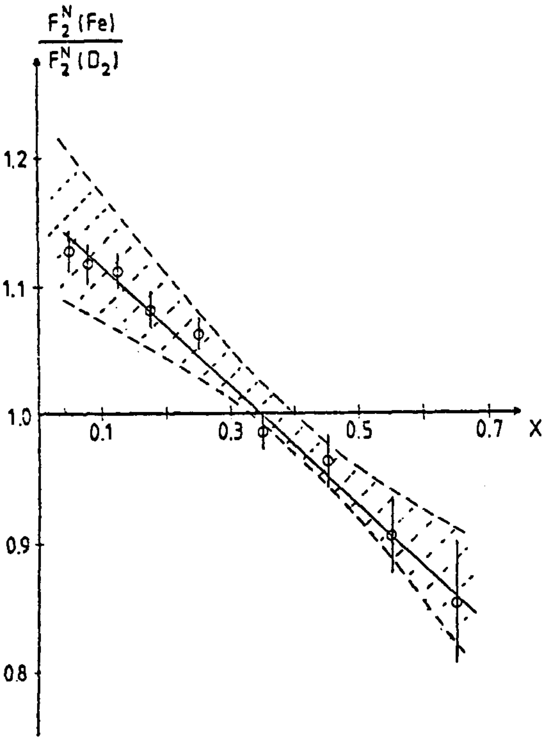

Fig. 1 Ratio $F_2^{iron}/F_2^{D_2}$ versus x as measured by the EMC Collaboration. The dashed region indicates the systematic uncertainty.

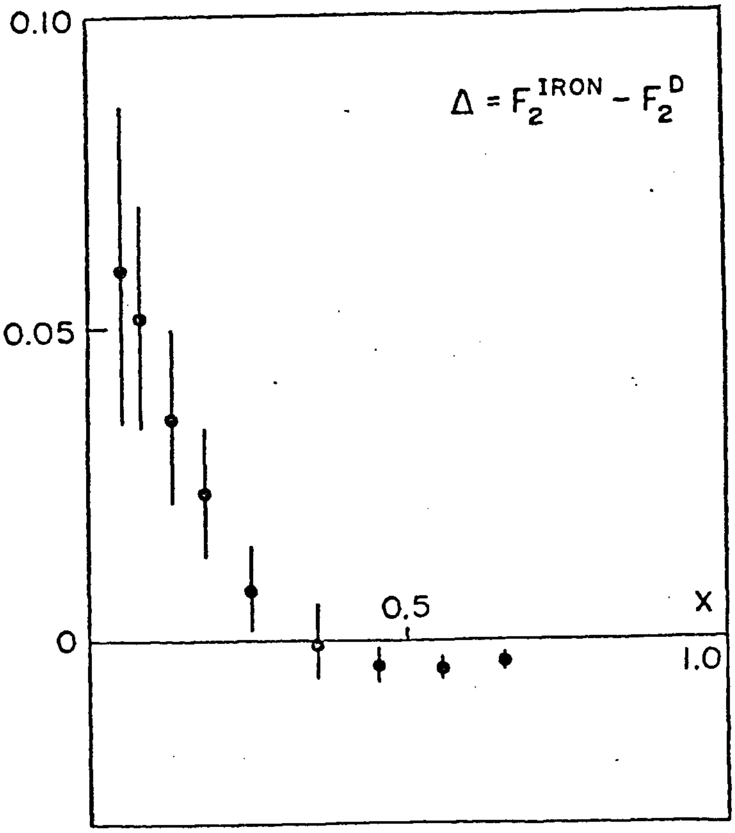

Fig. 2 Difference $F_2^{iron} - F_2^{D_2}$ from EMC data. No account is given to the large (∿7%) normalization uncertainty between iron and D_2 measurements.

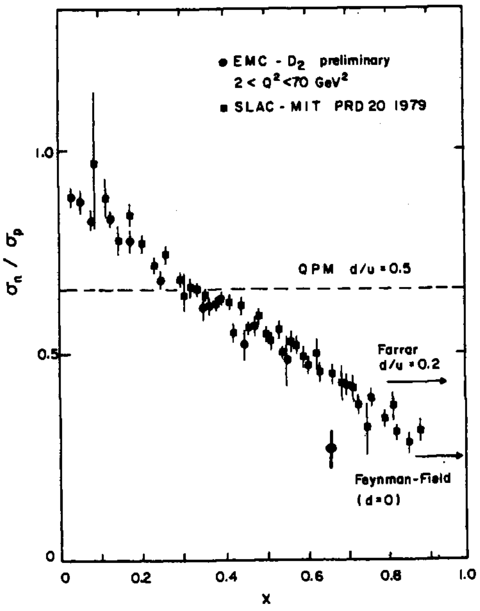

Fig. 3 Ratio of cross-section on neutrinos and protons as determined by the SLAC-MIT and the EMC experiments.

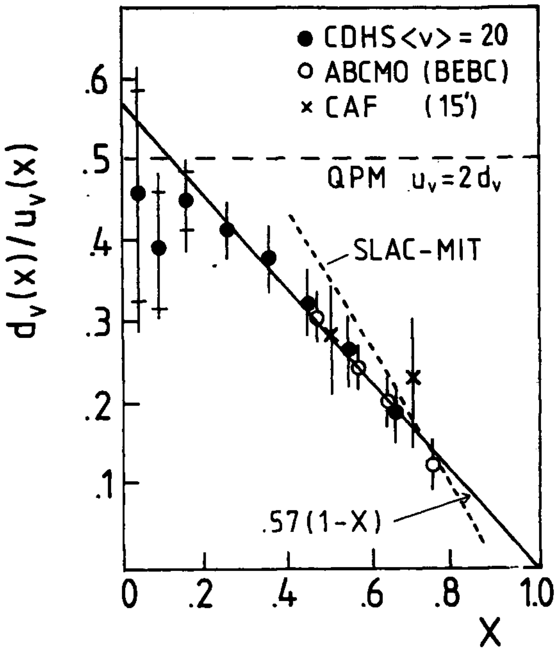

Fig. 4 The ratio of valence down and up quarks versus x measured by neutrino experiments on hydrogen. The dashed line indicates the measurement of SLAC-MIT at lower energy.

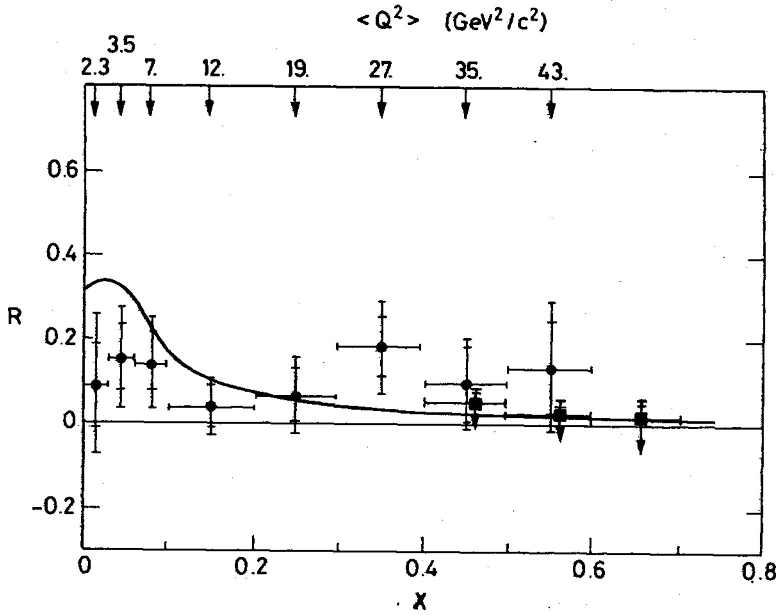

Fig. 5a Measurement of R = σ_L/σ_T versus x for the CDHS experiment. $\langle\nu\rangle$ 50 GeV.

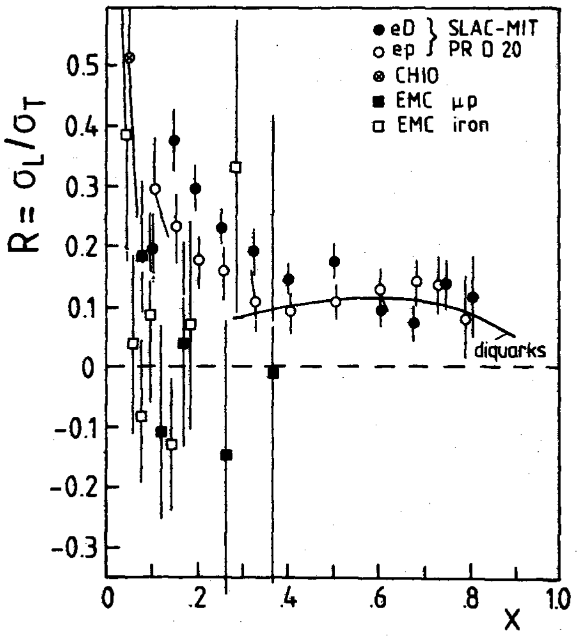

Fig. 5b Measurements of R = σ_L/σ_T versus x for the EMC experiment (preliminary) and the SLAC-MIT experiment (statistical errors only).

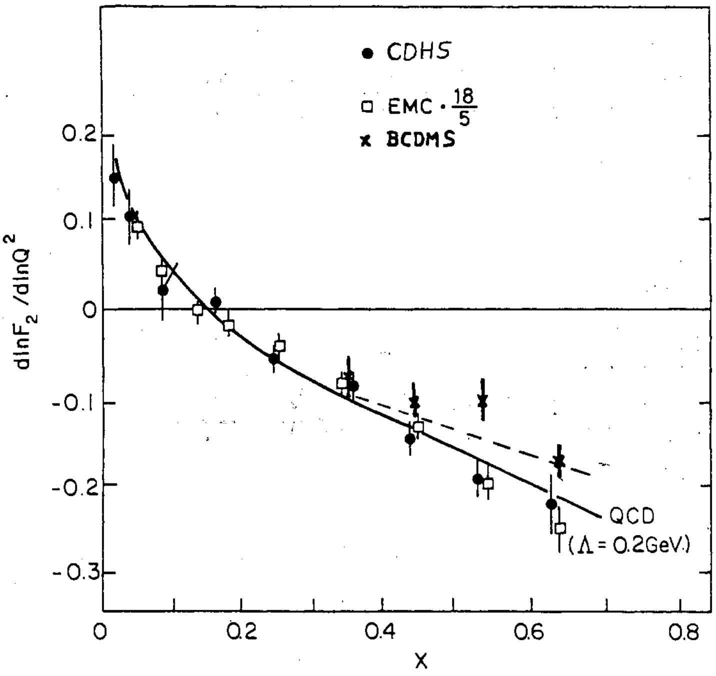

Fig. 6 : The slopes d ln $F_2^{\nu N}$/d ln Q^2 for three experiments as obtained from power law fits to the whole Q^2-range. The lines are QCD predictions for $\Lambda_{L.0}$ = 0.2 GeV.

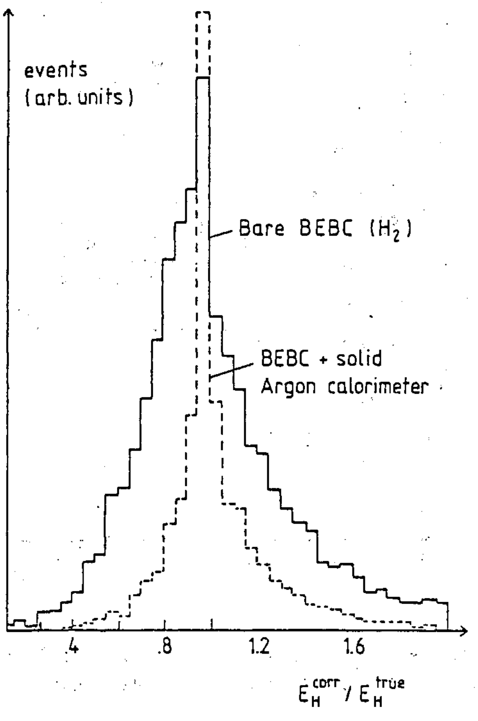

Fig. 7 : Total hadron energy resolution for a hydrogen bubble chamber (BEBC) (solid line). The dashed line shows the expected resolution if an electromagnetic calorimeter would be added within the chamber volume.