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Abstract

Recent results on structure functions measured in charged lepton and charged current neutrino interactions are reviewed. They include new data on quark distributions of proton and isoscalar targets, scaling violations and tests of perturbative Quantum Chromodynamics (QCD), $R = \sigma_L/\sigma_T$, the spin structure of the proton, and nuclear effects in deep inelastic scattering.

1. INTRODUCTION

The title of this review is somewhat misleading. It will be concerned almost exclusively with recent data on structure functions measured in deep inelastic lepton-nucleon scattering and will, for the sake of completeness and coherence, also cover data from charged current neutrino scattering. Twenty years after the beginning of a classic series of experiments at SLAC which established the existence of partons inside nucleons, deep inelastic scattering is sometimes thought to be an old-fashioned subject which has exhausted its physics potential. The wealth of new data which have become available since the last conference in this series and since recent reviews of the subject [1-4], and the large efforts which are being invested in ongoing experimental and theoretical activities, demonstrate that this is an unwarranted prejudice. Of course, at a time where the quark-parton model is not seriously questioned any more, the emphasis of the recent experiments has shifted to detailed studies of more subtle topics:

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- precise measurements of the x dependence of nucleon structure functions, in particular the proton structure function, which are becoming increasingly important for the understanding of $\bar{p}p$ collider results,
- tests of perturbative Quantum Chromodynamics (QCD) and measurements of the QCD mass scale parameter Λ ,
- measurements of the spin structure of the nucleon,
- effects of the nuclear environment on nucleon structure functions (EMC effect).

The present paper concentrates on a purely experimental review of these subjects. Introductions to the phenomenology of deep inelastic scattering can be found in many textbooks and in the more extensive review papers [5]. Recent theoretical developments have been discussed at this conference by W.J. Stirling [6]. The topic of hadronic final states in muon scattering is reviewed by W. Hofmann [7].

2. NEW RESULTS ON NUCLEON STRUCTURE FUNCTIONS

The following groups have submitted to this conference new results on nucleon structure functions:

- (a) The BCDMS Collaboration has recently published final results from their high statistics measurement (700 000 events) of the structure function $F_2^{\mu N}$ on a carbon target in the kinematic range $x \geq 0.25$, $Q^2 > 25 \text{ GeV}^2$ [8].
- (b) The same group has presented preliminary results from a high statistics measurement (2×10^6 events) of the proton structure function $F_2^{\mu P}$ in a larger kinematic range ($x \geq 0.06$, $Q^2 > 7 \text{ GeV}^2$) [9].
- (c) The CHARM Collaboration has reanalyzed their earlier data from neutrino scattering on an isoscalar marble target in terms of parametrizations of proton structure functions, correcting for the ratio F_2^n/F_2^p and nuclear effects [10].
- (d) The WA21 Collaboration has submitted results on flavour separated proton structure functions from a Wide-Band Beam (WBB) exposure of BEBC filled with hydrogen [11]. With 11 800 ν and 7 400 $\bar{\nu}$ events at an average $Q^2 \sim 10 \text{ GeV}^2$, this is the largest data sample now available from neutrino scattering on a pure proton target.

- (e) The WA59 Collaboration has presented a measurement of $F_2^{\nu N}$ and $xF_3^{\nu N}$ from a WBB exposure of BEBC filled with neon [12]. This is a low Q^2 measurement starting at $Q^2 > 0.1 \text{ GeV}^2$.
- (f) Ammosov et al. have determined $F_2^{\nu N}$ and $xF_3^{\nu N}$, from a WBB exposure of the FNAL 15' bubble chamber filled with a neon-hydrogen mixture [13].

Recent data are also available from:

- (g) the CDHSW Collaboration which has done a high statistics WBB measurement of $F_2^{\nu N}$ and $xF_3^{\nu N}$ based on $\sim 10^6$ neutrino interactions in their iron spectrometer. These data were not submitted to this conference but preliminary results have been presented elsewhere [14].

2.1 Structure functions of isoscalar targets

Figs 1 and 2 show the two recent measurements of $F_2^N(x, Q^2)$ which are considered final. The principal interest of these data lies in the analysis of scaling violations which is discussed in more detail below. A comparison of the BCDMS results to earlier high statistics muon data measured by the BFP [15] and EMC [16] Collaborations on iron targets is instructive since it reveals the systematic limitations of these experiments (fig. 3). The BCDMS and BFP data are statistically compatible apart from a $\sim 4\%$ offset in overall normalisation which is well within the systematic uncertainties quoted by the experiments. A similar agreement is observed between high statistics neutrino experiments [3]. $F_2(x)$ measured by the EMC on iron is significantly harder than measured by BCDMS on a carbon target, a trend opposite to what is expected from nuclear effects (sect. 6). This discrepancy is at present not understood.

Comparing the BCDMS and CDHSW data allows the presently best test of the quark-parton model prediction that for isoscalar targets $F_2^{\mu N} = 5/18 F_2^{\nu N}$, where $5/18$ is the mean squared quark charge of a flavour symmetric nucleon. In the x range of the BCDMS data ($x > 0.25$) this relation is not significantly affected by the different quark seas measured in muon and neutrino scattering. It is seen from fig. 4 that this prediction is fulfilled to within $\sim 3\%$, again well within the normalisation uncertainties which are $\pm 3\%$ for each of the experiments. Note, however, that there is again a slight x dependence opposite to the one expected from

nuclear effects. Also, the two data sets exhibit significantly different patterns of scaling violation (sect. 3) and their ratio will therefore depend somewhat on the Q^2 range included in the comparison.

Fig. 1 $F_2^{\nu N}(x, Q^2)$ measured by the WA59 Experiment. Statistical and systematic errors are combined quadratically. The solid lines represent QCD fits.

Fig. 2 $F_2^{\mu N}(x, Q^2)$ measured by BCDMS. Only statistical errors are shown. The solid lines show a fit of the scaling violations by perturbative QCD.

Fig. 3 The ratio of $F_2(x)$ measured by the BCDMS Collaboration on a carbon target over $F_2(x)$ measured with iron targets by the EMC and BFP Collaborations. Only statistical errors are shown.

Fig. 4 Test of the mean squared quark charge from a comparison of $F_2^{\mu N}$ and $F_2^{\nu N}$ (BCDMS and CDHSW data). Only statistical errors are shown.

2.2 The structure function of the free proton

The proton structure function is at present in the focus of much interest mainly because it is needed to compute reliable predictions for W and Z production cross sections at $\bar{p}p$ colliders. New preliminary results from muon scattering have recently been presented by the BCDMS Collaboration [9] and are shown in fig. 5 together with earlier electron data from the SLAC-MIT Group [17] and the EMC muon data [18].

Prominent features of the comparison between EMC and BCDMS data are the drastic improvement in statistical accuracy especially at large x , and the steeper x dependence of the BCDMS data which is similar to the one observed in the heavy target data and leads to discrepancies of $\sim 15\%$ in the region of small x . A small part of this effect is due to the different choice of $R = \sigma_L / \sigma_T$ applied by the two groups ($R = 0$ for the EMC and $R = R_{QCD}$ for the BCDMS data). Preliminary estimates of the systematic uncertainties on the BCDMS data indicate that the remaining difference is unlikely to be covered by the systematic errors quoted by the two experiments and will have to be ascribed to experimental problems which are at present not understood.

Measurements with neutrino beams on pure hydrogen targets have been presented by the CDHS [19] and recently by the WA21 Collaborations [11]. In another BEBC Experiment by the WA25 Collaboration, data were taken with

Fig. 5 The proton structure function $F_2^p(x, Q^2)$ from deep inelastic scattering of charged leptons on hydrogen targets. Where necessary, the SLAC-MIT and EMC data are interpolated to the x bins of the BCDMS data.

a deuterium fill and interactions on protons and neutrons distinguished by counting the total charge of the hadronic final state [20]. A novel approach has been adopted by the CHARM Collaboration [10] which has converted their earlier structure function data from an isoscalar marble target [21] to proton distributions, correcting the original data statistically for the u/d ratio [19,20] and nuclear effects [22]. The results are presented in the form of parametrizations of flavour separated quark distributions at a fixed $Q^2 = 10 \text{ GeV}^2$ fitted to the data with a QCD evolution program [23]. The errors are strongly reduced by imposing sum rules.

All available muon and neutrino data are compared in fig. 6 at $Q^2 = 10 \text{ GeV}^2$. The neutrino data, which are usually published as flavour separated quark distributions, were converted to $F_2^{\mu p}(x)$ correcting for quark charges and assuming $s = \bar{s} = \frac{1}{2} \bar{d}$, $c = \bar{c} = 0$. Where necessary, they were rescaled to the new total cross section calibration of the CERN neutrino beam [24]. With the exception of the WA25 data, the neutrino

experiments also favour an F_2^P which is larger than measured by the EMC in the region of small x .

Fig. 6 Compilation of data on the proton structure function $F_2^{up}(x)$ at $Q^2 = 10 \text{ GeV}^2$. The treatment of the neutrino data is discussed in the text. Only statistical errors are shown.

Theoretical predictions for the production of intermediate vector bosons at $\bar{p}p$ colliders depend directly on the proton structure function and it is well known that such predictions are at present in rather marginal agreement with the experimental data [25]. The UA1 and UA2 results on $(\sigma \cdot B)_W$ and $(\sigma \cdot B)_Z$ are compared to the calculations of Altarelli et al. [26] in fig. 7, where the "theoretical" error band largely reflects uncertainties on the F_2 parametrization and the choice of Λ used in the QCD evolution to collider energies. The W and Z cross sections are roughly proportional to $|F_2^P(x_{W,Z})|^2$, where $x_{W,Z} = M_{W,Z}/\sqrt{s} \sim 0.15$ at CERN collider energies ($\sqrt{s} = 546$ and 630 GeV). Altarelli et al. use parametrizations of $F_2^P(x)$ by Duke and Owens [27], Glück, Hoffmann, and Reya [28], and by Eichten et al. [29] most of which are based on the EMC data. From fig. 6,

the predicted W and Z cross sections are therefore expected to rise by 20-30% when using the BCDMS data or the CHARM parametrization, thus improving substantially the agreement with the data. It must however be noted that a top quark mass heavier than $m_t = 40$ GeV as assumed by Altarelli et al. would also increase the predictions for σ_B by up to 20% [30]. A comprehensive discussion of recent collider results and their comparison to theoretical predictions can be found in ref. [31].

Fig. 7 Experimental results on W and Z cross sections σ_B from the CERN $\bar{p}p$ collider compared to QCD predictions by Altarelli et al. [31].

3. SCALING VIOLATIONS AND TESTS OF PERTURBATIVE QCD

It is well known that QCD is not yet able to calculate quark and gluon distributions from first principles, but that the perturbative branch of the theory makes definite predictions for the Q^2 variation of structure functions (scaling violations) from their measured x dependence [32]. This prediction is quantitatively expressed by the Altarelli-Parisi equations [33] as a function of a single free parameter, the QCD mass scale parameter Λ which governs the size of the strong coupling constant $\alpha_s(Q^2)$. Deep inelastic scattering is generally considered one of the cleanest processes to test perturbative QCD predictions and to measure Λ . Recent high statis-

tics data have substantially enlarged the testing ground but, as it turns out, the question whether perturbative QCD is experimentally proven in deep inelastic scattering is far from being answered unambiguously.

3.1 Perturbative versus non-perturbative effects

The mathematical simplicity of the Altarelli-Parisi equations which describe scaling violations due to gluon bremsstrahlung and quark pair production is offset in practice by non-perturbative (higher twist) effects from quark-quark interactions which give rise to additional scaling violations. There is agreement in the theoretical literature that $F_2(x, Q^2)$ can be expanded in a power series in $1/Q^2$ as

$$F_2(x, Q^2) = F_2^{LT}(x, Q^2) \left[1 + \frac{H_4(x)}{Q^2} + \frac{H_6(x)}{Q^4} + \dots \right],$$

where scaling violations of the "leading twist" term $F_2^{LT}(x, Q^2)$ obey the Altarelli-Parisi equations. In most analyses presented so far [12,13,18], this series has been truncated after the first higher twist term and $H_4(x)$ fitted either simultaneously with Λ , or for a fixed Λ determined from large Q^2 data. A review of the substantial theoretical debate about the x dependence of the higher twist coefficients $H_4(x)$, $H_6(x)$... is beyond the scope of this paper^(*). The simplest ansatz is obviously to leave their functional form unconstrained; all available experimental data from such fits are shown in fig. 8. For the combined analysis of the EMC and SLAC-MIT data, the latter had to be renormalized by a factor 0.925 to obtain an acceptable fit [18]. A similar fit to the same SLAC-MIT and the BCDMS hydrogen data does not need any renormalisation and gives almost identical results at large x . A fit to the BCDMS data alone gives $H_4(x)$ compatible with zero over the full x range of the data, albeit with large errors as expected from the large Q^2 of these data [34]. The analysis by Ammosov et al. [13] which yields a strong negative higher twist correlated to a high value of Λ is not totally conclusive since it is very similar in χ^2 to pure perturbative QCD fits which give $\Lambda \sim 200$ MeV [35]. Negative higher twist terms of much smaller size are found from the WA59 data. They are shown in fig. 8 for a fixed $\Lambda_{\overline{MS}} = 100$ MeV but change very little when $\Lambda_{\overline{MS}}$ is increased to 200 MeV [36], indicating that the scaling violations observed in these data are mainly of non-perturbative origin. This is probably the

(*) Refs [12] and [18] are good guides to the theoretical literature.

most conclusive analysis presented so far since it is based on genuine low Q^2 data and does not rely on combining results from different experiments. Note that there are speculations that higher twist effects are different in size and even in sign for weak and electromagnetic scattering [37,38]; in the light of such models, the experimental situation would be less controversial than it appears from fig. 8. In any case, however, the problem of non-perturbative scaling violations is far from being settled.

Fig. 8 Experimental data on the higher twist coefficient $H_4(x)$. Only statistical errors are shown.

3.2 New results on Λ_{QCD}

A discussion of the plethora of physical and technical problems involved in obtaining reliable QCD fits to deep inelastic scattering data is again far beyond the scope of this discussion. The reader is referred to recent reviews of the subject [39] and to the original experimental papers. All recent results on Λ were obtained from direct fits of the Altarelli-Parisi equations to the measured scaling violations and all groups now quote results obtained in a next-to-leading order QCD expansion in the $\overline{\text{MS}}$ renormalisation scheme such that the numerical results are directly comparable. WA59 [12] finds $\Lambda_{\overline{\text{MS}}} = 100^{+110}_{-80}$ MeV from a simultaneous fit to F_2 and xF_3 restricted to a kinematic region where higher twist effects are expected to be small ($\langle Q^2 \rangle > 4 \text{ GeV}^2$, $W^2 > 10 \text{ GeV}^2$). BCDMS has done fits

in a flavour non-singlet approximation (i.e. ignoring the effect of the gluon distribution) to their data on $F_2(x, Q^2)$ from carbon [8] and hydrogen [9] targets restricted to $x \geq 0.275$. They find $\Lambda_{\overline{MS}} = 230 \pm 20$ (stat.) ± 60 (syst.) MeV from the carbon and $\Lambda_{\overline{MS}} = 210 \pm 20$ (stat.) ± 60 (syst.) MeV from the hydrogen data. Similar results are found from leading order QCD fits ($\Lambda_{LO} = 220$ and 180 MeV, respectively). For all reasonable assumptions about the width of the gluon distribution, the uncertainty due to the neglect of singlet terms in these fits is small compared to the experimental systematics.

As an example, the next-to-leading order fit to the BCDMS carbon data is superimposed to the data in fig. 2. A much more conclusive method of comparing QCD fits to the data is illustrated by fig. 9 which shows the logarithmic derivatives $d \ln F_2(x, Q^2) / d \ln Q^2$ and which represents the only genuine QCD prediction which can at present be tested in deep inelastic scattering, namely the x dependence of the measured scaling violations. The excellent agreement between data and theory is a non-trivial result since Λ is the only free parameter of the QCD fit in this representation,

Fig. 9 Scaling violations $d \ln F_2(x, Q^2) / d \ln Q^2$ observed in the BCDMS carbon data. The errors are statistical only. The solid lines are non-singlet QCD predictions corresponding to the best fit ($\Lambda_{\overline{MS}} = 230$ MeV) and two other values of $\Lambda_{\overline{MS}}$.

i.e. a measurement of Λ at a fixed value of x allows to predict $d\ln F_2/d\ln Q^2$ at any other value of x and the data are seen to follow this prediction very precisely over the entire kinematic range of the data.

The CDHSW Collaboration reports very different conclusions from QCD fits to their preliminary results on the non-singlet structure function $xF_3(x, Q^2)$ [40]. Scaling violations are observed in these data but are only poorly described by QCD evolution within the statistical errors, the study of systematics not yet being completed. The numerical results of Λ depend strongly on kinematic cuts and this group consequently prefers to quote a range of $50 \text{ MeV} \leq \Lambda_{\overline{\text{MS}}} \leq 300 \text{ MeV}$ which can be accommodated by the data rather than a central value.

Finally, Ammosov et al. [13] report a $\Lambda_{\overline{\text{MS}}} = 200 \pm 70 \text{ (stat.)} \pm 120 \text{ (syst.) MeV}$ from their aforementioned analysis of data from the FNAL 15' bubble chamber.

3.3 A critical review of QCD fits to scaling violations

Complete compilations of all available results on QCD fits in deep inelastic scattering can be found in several earlier reviews and do not need to be repeated here^(*). The consistency between numerical results on Λ_{QCD} has never been very impressive and several of the recent high statistics measurements are only in marginal agreement at the limit of the systematic errors. Even worse, the BCDMS and CDHSW Collaborations report conclusions on the global agreement of QCD with their data which are in striking contradiction. It is therefore timely to investigate this problem in some more depth.

In general, results on Λ from different experiments are difficult to compare directly for various reasons. Each experiment applies its own kinematic cuts which are usually tuned to provide a good compromise between a suppression of higher twist effects and loss of statistical accuracy. In case where low Q^2 data ($Q^2 \sim 1 \text{ GeV}^2$) are included in the fits, there is no universally accepted procedure to apply target mass corrections which become important in this region.

(*) For the most recent summary of this type see ref. [4].

Additional problems come about in flavour singlet fits due to uncertainties on the gluon distribution, $R = \sigma_L/\sigma_T$, and the size of the strange and charmed sea. Finally, biases from the different QCD fit programs cannot be excluded.

This section therefore gives a brief account of a more uniform attempt to fit all available deep inelastic data, restricted to a non-singlet approximation:

- (a) For the muon data, $F_2(x, Q^2)$ is used at $x \geq 0.25$.
- (b) $xF_3(x, Q^2)$ is used for the neutrino data but is replaced by $F_2(x, Q^2)$ at $x \geq 0.4$ to improve the statistical accuracy. This is a technique frequently applied in the analysis of neutrino data. Using only xF_3 , or only F_2 at $x \geq 0.25$ as for the muon data, does not affect the conclusions from this study in any significant way.
- (c) Only data points with $Q^2 \geq 10 \text{ GeV}^2$ are included in the fits to reduce higher twist effects to an acceptable level.
- (d) The same QCD fit program was used for all data. This program was developed by Virchaux and Ouraou for an analysis of the recent BCDMS data and treats the Q^2 evolution with a purely numerical algorithm to avoid any biases from internal approximations or parametrizations [41]. For the BCDMS carbon data, this program was extensively cross-checked against several other QCD fit programs [23,42,43,44]. In most cases, the results on Λ from the different programs were found to be compatible within 10 MeV in leading and next-to-leading order [8].

Apart from the BCDMS and CDHSW results discussed above, data from the BFP [15] (μ -Fe), CHARM [21] (ν -CaCO₃), CCFRR [45] (ν -Fe), CDHS [46] (ν -Fe), EMC [16,18] (μ -H₂ and μ -Fe) and BEBC-WA25 [20] (ν -D₂) Experiments were fitted. The WA59 data [12] are centred at too low Q^2 to allow a meaningful fit at $Q^2 > 10 \text{ GeV}^2$ and the paper by Ammosov et al. [13] arrived too late to be included in this comparison.

The results on $\Lambda_{\overline{\text{MS}}}$ from these fits are shown in fig. 10. This figure also shows the corresponding χ^2 probabilities which are calculated from statistical errors only. These χ^2 's refer to the comparison of data and QCD prediction for the logarithmic slopes $d\ln F_2/d\ln Q^2$ as shown e.g. in fig. 9 which represents a direct test of the theory. They do not refer to the global QCD fits as shown e.g. in fig. 2 where most of the degrees of

Fig. 10 $\Lambda_{\overline{MS}}$ from flavour non-singlet QCD fits at $Q^2 \geq 10 \text{ GeV}^2$ vs the χ^2 probability of the fit. Only statistical errors are shown.

freedom serve to describe the x dependence of F_2 resp. xF_3 which is not predicted by QCD. Two groups of measurements can clearly be distinguished. The BFP, CDHS, CDHSW and EMC iron data yield poor fits with probabilities of $\sim 1\%$ or below; probabilities smaller than 10^{-3} are not given explicitly since they have little physical meaning when calculated from statistical errors only. The origin of these poor χ^2 's can be seen from fig. 11 where $d\ln F_2/d\ln Q^2$ is compared to the respective QCD fits. Only the EMC and CDHSW WBB data which have the smallest statistical errors are shown for clarity but are in good agreement with the BFP and CDHS Narrow-Band Beam (NBB) data which also exhibit a much steeper decrease of $d\ln F_2/d\ln Q^2$ with x than

Fig. 11 Scaling violations in the EMC and CDHSW iron data compared to their respective best QCD fits in next-to-leading order. Only statistical errors are shown.

predicted by the theory. Although these experiments agree well on the measured scaling violations they give strikingly different results on Λ due to the different distribution of errors along x , i.e. for statistical and not for physical reasons. The systematic errors on $dF_2/d\ln Q^2$ published by the EMC [16] do not cover the difference to the QCD fit; these errors refer to a larger Q^2 range but it is unlikely that they increase drastically with the Q^2 cut. Systematic errors on the $\ln Q^2$ slopes of the CDHSW data are still under evaluation but are also not expected to account for the disagreement with the QCD prediction.

Several explanations seem possible for this effect:

- (a) The experiments in question have seriously underestimated their systematic errors. This hypothesis is not very convincing in view of the good agreement between the different measurements.
- (b) A striking feature of fig. 10 is that the four experiments giving poor fits are all measurements on iron targets. One may therefore suspect that fig. 11 reflects a nuclear effect not accounted for by the Altarelli-Parisi equations. So far, no individual experiment on

nuclear effects has observed a Q^2 dependence of the structure function ratio $F_2^{\text{Fe}}/F_2^{\text{d}}$ but a quantitative study shows that none of these experiments is sufficiently precise to rule out an effect of the size shown in fig. 11. More stringent limits can be derived by combining data from the SLAC E139 [47] and from the BCDMS [48,49] Experiments which are the most precise measurements available today and which combined cover a Q^2 range of almost 2 orders of magnitude. Such a limit, calculated for the hypothesis that scaling violations in deuterium are correctly described by perturbative QCD, is also shown in fig. 11 for the example of the EMC iron data and for 95% confidence level. It should not be taken at face value since combining data from different experiments is always a risky procedure, but it nevertheless shows that nuclear effects in scaling violations do not provide a satisfactory explanation either.

- (c) A related explanation would be that the gluon distribution is much more energetic in iron than in light targets, such as to invalidate the singlet approximation assumed in the fits shown in fig. 11. Flavour singlet fits to iron data [16,46] do in fact yield consistently harder gluon distributions than data from light targets (sect. 3.4) but do not improve the agreement between data and QCD at large x .
- (d) In contradiction to a popular prejudice, higher twist effects in iron could account for a substantial part of the scaling violations even at large $Q^2 > 10 \text{ GeV}^2$. Such higher twist terms would need to be much larger than those shown in fig. 8. This possibility has not yet been investigated in much detail.

In conclusion, there is at present no convincing solution to the heavy target problem and more data and more theoretical work will be needed to clarify the situation. However, figs 10 and 11 clearly show that - independent from what may be at the origin of this puzzle - numerical results on Λ from iron target data are, in general, not reliable and should consequently not be included in calculating a "best" world average of Λ . The safest approach is to include into such an average only the upper six experiments in fig. 10 (CCFR, WA25, EMC hydrogen, BCDMS carbon, BCDMS hydrogen and CHARM) which have acceptable χ^2 probabilities and which give a mean value of

$$\Lambda_{\overline{\text{MS}}} = 215 \pm 15 \text{ (stat.)} \pm 50 \text{ (syst.)} \pm 25 \text{ (theor.) MeV .}$$

This average is largely dominated by the two BCDMS measurements which have correlated systematic errors since they were made with the same apparatus. The systematic uncertainty on the average is therefore similar to the individual systematic errors of 60 MeV quoted in refs [8] and [9]. The "theoretical" error was estimated by subtracting the higher twist terms measured by WA59 [12] from the BCDMS hydrogen data. Fig. 8 shows that this estimate is at most an educated guess and should be used with much care. Note that the average $\Lambda_{\overline{\text{MS}}}$ is nevertheless in excellent agreement with the most recent mean value from $e^+e^- \rightarrow \text{hadrons}$ [50]. It is also compatible with a "naive" average over all deep inelastic scattering data [4] but figs 10 and 11 show that this agreement is to a large extent fortuitous.

3.4 Flavour singlet fits and the gluon distribution

The BCDMS Group has also done a combined flavour singlet and non-singlet fit over the full x range of their proton data which yields a new estimate of the gluon structure function. The gluon momentum is parametrized as $xG(x) \propto (\eta + 1)(1 - x)^\eta$ at $Q_0^2 = 5 \text{ GeV}^2$ and the Altarelli-Parisi equations are fitted to the data for fixed values of η . The best fits (fig. 12) are found for

$$\begin{aligned} \eta_{\text{LO}} &= 5 \pm 1.5 & \Lambda_{\text{LO}} &= 190 \pm 20 \text{ MeV} , \\ \eta_{\overline{\text{MS}}} &= 10 \pm 1.5 & \Lambda_{\overline{\text{MS}}} &= 210 \pm 20 \text{ MeV} , \end{aligned}$$

in leading and next-to-leading order, respectively. The results on Λ are in excellent agreement with those from the non-singlet fits. The slope parameters $d \ln F_2 / d \ln Q^2$ from the next-to-leading order fit are compared to the data in fig. 13. A noteworthy feature of this analysis is that the correlation between η and Λ (fig. 12(b)) is much weaker than observed in previous fits of this type and allows for the first time a reliable simultaneous determination of both parameters, in particular at next-to-leading order. This is a consequence of both the softness of the gluon distribution found and of the statistical power of these data. The significant difference between the gluon distributions in leading and next-to-leading order is not necessarily a surprise since the definition of $G(x)$ beyond leading order is factorization scheme dependent; the convention introduced by Curci et al. [51] is used in the BCDMS analysis. The obvious conclusion is that one should be consistent and not use earlier gluon distributions, which are all determined from leading order fits, in higher order QCD calculations.

Fig. 12 (a) The χ^2 of the QCD fits to scaling violations measured in the BCDMS hydrogen data versus the power η of a gluon distribution $xG(x) \propto (1-x)^\eta$. The χ^2 is calculated from the representation of fig. 9.
 (b) Λ_{LO} and $\Lambda_{\overline{MS}}$ from the same fits.

A new determination of $G(x)$ in next-to-leading order has also been done by the CHARM Collaboration in the framework of their parametrization of proton distributions [10] discussed above, for a fixed $\Lambda_{\overline{MS}} = 310$ MeV. CHARM observes a less pronounced softening of the gluon distribution compared to their earlier leading order analysis although their QCD fit program [23] is based on the same factorization scheme as the one used by BCDMS. However, the two CHARM distributions cannot be compared directly since they refer to targets of different quark composition and since other assumptions changed in the analysis [52]. They do therefore not necessarily contradict the BCDMS result.

Fig. 13 Scaling violations at $Q^2 > 10 \text{ GeV}^2$ observed in the BCDMS hydrogen data compared to next-to-leading order QCD fits for different assumptions on the gluon distribution.

All data on the gluon distribution from deep inelastic scattering are compiled in fig. 14. In leading order there is impressive agreement between the different results from light and medium weight targets. The gluon distributions from iron target data are consistently harder but, as mentioned earlier, originate from QCD fits which are of comparatively poor quality and should therefore be used with caution.

4. NEW MEASUREMENTS OF $R = \sigma_L/\sigma_T$

The ratio $R = \sigma_L/\sigma_T$ of absorption cross sections for longitudinally and transversely polarised virtual photons is related to the structure functions $F_1(x)$ and $F_2(x)$ by

$$R(x) = \frac{\sigma_L}{\sigma_T} = \frac{F_2(x) - 2xF_1(x)}{2xF_1(x)},$$

i.e. measures the violation of the Callan-Gross relation $F_2(x) = 2xF_1(x)$ predicted for spin 1/2 quarks in the infinite momentum frame [53]. Non-

Fig. 14 Estimates of the gluon momentum distribution $xG(x)$ from BCDMS [9], CDHS [46], CHARM [10,21] and EMC [16,18].

zero values of R are expected at finite energies from the transverse momentum of quarks due to internal Fermi motion in the nucleon [54] and gluon radiation [55]. Experimental measurements of R are too difficult to provide a precise test of perturbative QCD predictions but they constitute an important consistency check. A major progress has recently been achieved in measurements at small Q^2 where several earlier experiments at SLAC [56] had consistently found R to be large ($R \sim 0.2$) without a significant dependence on x and Q^2 , a trend very different from QCD predictions. New preliminary data of high statistical accuracy from the SLAC E140 Experiment on a deuterium target [57], although not in direct conflict with the previous data, have changed this picture significantly and are now in good agreement with QCD calculations when target mass corrections are included, except at very small $Q^2 \sim 1 \text{ GeV}^2$ where the strong coupling constant is of order unity and perturbative QCD is not expected to hold (fig. 15).

Fig. 15 (a) $R = \sigma_L / \sigma_T$ at $x = 0.5$ from the SLAC E140 Experiment on deuterium [57] compared to earlier SLAC data [56]; (b) $R = \sigma_L / \sigma_T$ at $x = 0.5$ from the SLAC E140, CDHSW and BCDMS Experiments. The dashed and solid lines are QCD predictions without and with target mass corrections.

New data at large Q^2 from carbon and hydrogen targets come from the BCDMS structure function measurements [8,9]. They are shown in fig. 16 together with earlier EMC data covering a similar kinematic range. All data tend to rise at small x as expected from QCD. The BCDMS carbon data extend over a limited x range which does not allow to distinguish between $R = 0$ and the QCD prediction but provide now the most precise measurement of R at large Q^2 , giving $R = 0.015 \pm 0.013$ (stat.) ± 0.026 (syst.) at an average $\langle Q^2 \rangle = 60 \text{ GeV}^2$.

5. THE SPIN STRUCTURE OF THE NUCLEON

The EMC Collaboration has recently reported first results from their measurement of the spin dependent structure function $g_1^p(x)$ of the proton with a polarized NH_3 target [58]. This structure function is defined as

$$g_1^p(x) = \frac{1}{2} \sum_i e_i^2 [q_i^+(x) - q_i^-(x)] ,$$

where e_i are the quark charges and q_i^+ (q_i^-) is the probability distribution of quark flavour i with a spin parallel (antiparallel) to the nucleon spin [59]. This structure function is kinematically related to the cross section asymmetry

$$A = \frac{d\sigma^{\uparrow\downarrow} - d\sigma^{\uparrow\uparrow}}{d\sigma^{\uparrow\downarrow} + d\sigma^{\uparrow\uparrow}} ,$$

Fig. 16 $R = \sigma_L / \sigma_T$ from muon scattering. Inner error bars are statistical errors, outer error bars statistical and systematic errors added linearly. The solid lines are perturbative QCD predictions: (a) BCDMS carbon data compared to EMC results on iron, (b) proton data from BCDMS and EMC measurements.

where $d\sigma^{\uparrow\downarrow}$ ($d\sigma^{\uparrow\uparrow}$) are the differential scattering cross sections for muons with a spin orientation antiparallel (parallel) to the nucleon spin. The measured asymmetry is in excellent agreement with earlier data from SLAC [60].

The measured structure function $g_1^P(x)$ is shown in fig. 17. Also shown is the integral $\int_x^1 g_1^P(x) dx$ which is of importance to test sum rules for polarized structure functions. The celebrated Bjorken sum rule [61], a cornerstone of the quark-parton model, is not tested in this experiment since $g_1(x)$ is not measured for the neutron. Separate sum rules for proton and neutron are due to Ellis and Jaffe [62]

$$\int_0^1 g_1^{P(n)}(x) dx = \frac{1}{12} \left| \frac{A}{G_V} \right| \left[(-)1 + \frac{5}{3} \cdot \frac{3F-D}{F+D} \right] = 0.20 \ (-0.01) \pm 0.005,$$

Fig. 17 The spin dependent structure function $xg_1(x)$ and the integral $\int_x^1 g_1(x) dx$ for the proton. Only statistical errors are shown. The smooth curves are parametrizations of the data.

where G_A and G_V are the axial vector and vector coupling constants measured in nuclear beta decay and F and D are $SU(8)$ couplings measurable in hyperon decays [63]. Extrapolating the EMC measurement to $x = 0$ (fig. 17) gives

$$\int_0^1 g_1^P(x) = 0.113 \pm 0.012 \text{ (stat.)} \pm 0.025 \text{ (syst.)}$$

(at $\langle Q^2 \rangle = 10.7 \text{ GeV}^2$). This violation of the Ellis-Jaffe sum rule does not need to be of fundamental nature [64].

A more surprising result which can be derived from this measurement is the total proton spin S_q carried by quarks. Defining $\Delta q(x) = q^+(x) - q^-(x)$ and assuming the strange and charmed quark sea to be unpolarised,

$$\int_0^1 g_1^P(x) = \frac{1}{2} \int_0^1 \left[\frac{4}{9} \Delta u(x) + \frac{1}{9} \Delta d(x) \right] dx = .113 \pm .012 \pm .025$$

from the EMC data. Imposing the Bjorken sum rule

$$\int_0^1 [g_1^P(x) - g_1^n(x)] dx = \frac{1}{6} \left| \frac{G_A}{G_V} \right| \left(1 - \frac{\alpha_s}{\pi} \right),$$

the corresponding integral for the neutron is

$$\int_0^1 g_1^n(x) = \frac{1}{2} \int_0^1 \left[\frac{1}{9} \Delta u(x) + \frac{4}{9} \Delta d(x) \right] dx = -0.08 \pm 0.028.$$

After some simple algebra,

$$S_q = \frac{1}{2} \int_0^1 [\Delta u(x) + \Delta d(x)] dx = \frac{1}{2} (0.12 \pm 0.20) ,$$

i.e. only 1/8 of the total proton spin - within large errors - is carried by quarks, the remaining part being due to gluons and orbital angular momentum. This is very much different from SU(6) model calculations which typically attribute ~ 50% of the nucleon spin to quarks [65].

6. NUCLEAR EFFECTS

During the last year, there has been much progress in experimental measurements of nuclear effects in deep inelastic scattering. Final data from muon scattering are available from BCDMS on the structure function ratio $F_2^{\text{Fe}}/F_2^{\text{d}}$ [50] and from a new EMC Experiment on $F_2^{\text{A}}/F_2^{\text{d}}$ for $A = \text{C}, \text{Cu}, \text{Sn}$ [66]. Final results on $F_2^{\text{Ne}}/F_2^{\text{d}}$ measured in neutrino scattering by the BEBC-WA59 Collaboration were also submitted to this conference [67]. Preliminary data were presented from another EMC Experiment using a different target set-up to measure $F_2^{\text{Cu}}/F_2^{\text{d}}$ [66], and on $\sigma^{\text{Fe}}/\sigma^{\text{d}}$ from the SLAC E140 Experiment [57]. All recent data on $F_2^{\text{Fe}}/F_2^{\text{d}}$ and $F_2^{\text{Cu}}/F_2^{\text{d}}$ from charged lepton scattering are compiled in fig. 18. Also shown are the WA25-WA59 results which are representative insofar as they are based on the largest data sample now available from neutrino scattering. All data now agree on little or no enhancement in the region of small x , in contrast to the original EMC measurement [68] although there are no incompatibilities within the systematic errors. The good agreement between the low Q^2 electron data and the muon data at larger Q^2 makes obsolete earlier speculations that $R = \sigma_{\text{L}}/\sigma_{\text{T}}$ may depend on nuclear weight A [69]. This was recently confirmed by the SLAC E140 Group which did a measurement on deuterium, iron and gold in the same experiment. The preliminary result $R_{\text{A}} - R_{\text{d}} = 0.03 \pm 0.02 \text{ (stat.)} \pm 0.06 \text{ (syst.)}$ [57] now also rules out such an effect. At $x < 0.05$, the EMC data show clear indications for shadowing ($F_2^{\text{A}}/F_2^{\text{d}} < 1$). This effect has recently been confirmed by an independent dedicated measurement by the EMC [70] and by data from the WA25-WA59 Collaborations [71].

More data from muon scattering exist from BCDMS for nitrogen [49] and from the EMC for carbon and tin [66]. Unfortunately, the range in A covered by these data is too small and their statistical errors are still

Fig. 18 Recent data on:
 (a) $F_2^{\text{Fe}}(x)/F_2^d(x)$ and $F_2^{\text{Cu}}(x)/F_2^d(x)$ from muon scattering, and
 (b) $\sigma^{\text{Fe}}/\sigma^d$ and $\sigma^{\text{Au}}/\sigma^d$ from electron scattering at SLAC.
 Also shown in (a) are WA25-WA59 data on $F_2^{\text{Ne}}(x)/F_2^d(x)$. Only statistical errors are shown.

too large to allow any conclusion as to the A dependence of the nuclear effect in the large Q^2 region.

There is no space to discuss recent theoretical developments in this field and a statistical review must suffice. Fig. 19 shows that the dust is settling but also indicates the danger that theoretical activities will die out before a universally accepted model has been found. The reader is referred to recent reviews for more profound discussions of the subject [72].

Fig. 19 Original experimental and theoretical papers on nuclear effects in deep inelastic lepton scattering versus the year of publication.

7. CONCLUSIONS

A wealth of new data from deep inelastic scattering experiments has recently become available. Many of them are of impressive statistical and systematic accuracy and have turned out to be important to settle open or controversial issues. All data on scaling violations from light and medium weight targets are in impressive agreement with perturbative QCD and agree on an average QCD mass scale parameter $\Lambda_{\overline{MS}} = 215 \pm 60$ MeV. All data on $R = \sigma_L/\sigma_T$ now fit into a coherent picture and measurements of nuclear effects have well converged to within a few percent. A first measurement of the polarized target cross section asymmetry has given unexpected results on the spin structure of the proton. Problem areas are the proton structure function where different experiments disagree by $\sim 15\%$, and measurements of scaling violations on heavy targets (iron) where different experiments are in good mutual agreement but follow QCD predictions at best qualitatively.

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DISCUSSION

D.H. Perkins (Oxford): In view of 15% fluctuations in CERN neutrino cross sections over the last fifteen years, how reliable is the value quoted for agreement within 4% with the 5/18 ratio from comparison of F_2 in neutrino and charged lepton scattering?

R. Voss: Unlike earlier comparisons, the one I have shown here is based on the BCDMS and the new CDHSW data. During recent years, the CERN neutrino and muon experiments have invested large efforts in a precise calibration of their cross section normalization. From the mutual agreement of the different muon experiments, and from the good agreement of the measurements of the total neutrino cross section at Fermilab and CERN, I would conclude that the quoted systematic errors of 3% per experiment are now reliable estimates.

K. Kleinknecht (Mainz): It is obvious that the most reliable QCD test is the non-singlet structure function xF_3 . xF_3 cannot be measured in muon scattering. Your non-singlet fits to F_2 must assume a vanishing gluon distribution and a vanishing sea quark distribution. Therefore, your conclusions on the non-singlet fits are very misleading. It is just not possible to compare the good fits in the high x region to the xF_3 fits in the whole range. They have a different physical meaning and both can be valid.

R. Voss: You are of course perfectly right in saying that F_2 and xF_3 represent different physics. Nevertheless, I believe that - for numerical purposes - I am allowed to make the non-singlet approximation within the kinematic range I have chosen. For the BCDMS data, we have investigated very carefully possible errors due to this approximation. For all reasonable assumptions on the gluon distribution - including the one published by CDHS - any error due to the neglect of $G(x)$ is much smaller than the systematic error or the uncertainty from higher twist effects which presumably are present in both F_2 and xF_3 .

H. Wahl (CERN): Looking at your plot of probability versus $\Lambda_{\overline{MS}}$, and the slopes of $F_2(x, Q^2)$ versus x for the CDHSW and EMC data, I find your conclusions totally misleading. As you have neglected the systematic errors, I do not believe that your evaluation of probabilities is

meaningful. In fact, the fits to the CDHS NBB structure functions have been published years ago, and are in fact reasonably good. In addition, the calculation of slopes and their errors for structure function data cannot be done without proper treatment of systematic errors and their correlations.

R. Voss It is possible that I mistreat the BFP and the earlier CDHS NBB data. These groups have unfortunately not published their systematic errors on $d\ln F_2/d\ln Q^2$ and it is impossible to calculate them for an outsider without knowing about all possible correlation effects. As to the EMC iron and to the new CDHSW WBB data, my point of view is that the systematic errors would need to be so large to cover the disagreement with the QCD prediction that these data are meaningless as a quantitative test of QCD and not useful for a measurement of Λ .

M. Virchaux (Saclay): I would like to comment on the statement made by Professor Wahl. The χ^2 probability of 50% he mentioned for the QCD fits to the published CDHS data is due to the large number of degrees of freedom in the global QCD fits. Most of these degrees of freedom are related to the x dependence of F_2 which is not predicted by the theory. When the probability is calculated for the degrees of freedom which really test the QCD prediction, i.e. the scaling violations, it decreases to $\sim 1\%$ in the case of the CDHS data.

P. Schöler (Yale): I would like to add a remark regarding the measurements of the spin dependent structure function of the proton made by the EMC Collaboration. Since the proton data saturate only about half of the famous sum rule prediction of Bjorken, this means that a very large (and unexpected) contribution of similar magnitude must come from the neutron.

S. Bethke (LBL): Calculating α_s from the $\overline{MS}$ formula at different Q^2 , the number of flavours may change by several units, so that either α_s or $\Lambda_{\overline{MS}}$ has to be a step function in Q^2 . How did you treat this problem when comparing with results at the higher Q^2 in e^+e^- annihilation?

R. Voss: The number of flavour changes from 4 assumed in the analysis of the deep inelastic scattering data to 5 in the e^+e^- data. This does not result in a big effect on α_s .