MEASUREMENTS OF α_s FROM ν−N DEEP INELASTIC SCATTERING AT CCFR

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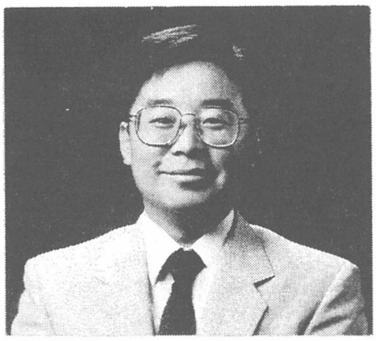

Abstract

We present the values of the strong coupling constant, α_s, from the fit to the scaling violation of nucleon structure functions, F_2 and xF_3, and from the Gross-Llewellyn-Smith sum rule. The resulting value of $\Lambda_{\overline{MS}}^{(4),NLO}$ from the combined systematic fit on both F_2 and xF_3 from the CCFR experiment is $331 \pm 24(exp) \pm 13(HT)$ MeV which results the value of α_s at $Q^2 = M_Z^2$ of $0.119 \pm 0.002(exp) \pm 0.001(HT) \pm 0.004(Scale)$. The preliminary value of $\alpha_s^{NNLO}(M_Z^2)$ from the GLS sum-rule analysis is $0.112^{+0.011}_{-0.013}(combined)$. These values are consistent with each other within their uncertainties and are in good agreement with other measurements of α_s.

Introduction

Neutrino-nucleon (ν-N) deep inelastic scattering (DIS) experiment provides a good testing field of Quantum Chromo-Dynamics (QCD), the theory of strong interactions. The ν-N DIS experiments probe the structure of nucleons and provide an opportunity to test QCD evolutions and to extract the QCD scale parameter, Λ, which sets the scale of strong interactions. They are complementary measurements to charged lepton DIS experiments of nucleon structure functions. The advantage of ν-N DIS measurements over the charged lepton experiments is that ν-N experiments can measure both $F_2(x, Q^2)$ and $xF_3(x, Q^2)$ due to pure V-A nature. The $\nu - N$ differential cross section are written, in terms of structure functions:

$$\frac{d^2\sigma^{\nu(\overline{\nu})}}{dxdy} = \frac{G_F^2 M E_\nu}{\pi}[(1 - y - \frac{Mxy}{2E_\nu} + \frac{y^2}{2}\frac{1 + 4M^2x^2/Q^2}{1 + R(x, Q^2)})F_2^{\nu(\overline{\nu})} \pm (y - \frac{y^2}{2})xF_3^{\nu(\overline{\nu})}] \quad (1)$$

where $R(x, Q^2) = \sigma_L/\sigma_T$, the ratio of longitudinal to transverse absorption cross sections. In this paper, we present the determination of the strong coupling constant, α_s, using QCD evolution of the nucleon structure functions, F_2 and xF_3, from Fermilab E770 and E744 [1].

We also present the next-to-next leading order (NNLO) determination of α_s from the Gross-Llewellyn-Smith (GLS) sum rule which states that the total number of valence quarks are given by the integration of the non-singlet structure function xF_3 over entire regions of x, the momentum fraction carried by the struck quark.

The Experiment

CCFR (Columbia-Chicago-Fermilab-Rochester) experiment is a neutrino-nucleon deep inelastic scattering experiment at the Tevatron in Fermilab. The experiment uses broad momentum beam of neutrinos and antineutrinos from the decays of the secondary pions and kaons, resulting from the interactions of 800GeV primary protons with a Beryllium-Oxide (BeO) target.

The detector consists of two major components : target calorimeter and muon spectrometer. The target calorimeter is a iron-liquid scintillator sampling calorimeter, instrumented with drift chambers to provide track information of the muons, resulting from charged-current (CC) interactions where a charged weak boson (W^+orW^-) is exchanged between the neutrino (antineutrino) and the parton. The calorimeter provides dense material in the path of neutrinos (anti-neutrinos) to increase the rate of neutrino interactions. The hadron energy resolution of the calorimeter is measured from the test beam and is found to be : $\sigma/E_{Had} = (0.847 \pm 0.015)/\sqrt{E_{Had}(GeV)} + (0.30 \pm 0.12)/E_{Had}$.

The muon spectrometer is located immediately down stream of the target calorimeter and consists of three toroidal magnets and nine drift chambers to provide accurate measurements of muon momenta. The momentum resolution of the spectrometer (σ/p_μ) is approximately 10.1% and the angular resolution is $\theta_\mu = 0.3 + 60/p_\mu$(mrad).

α_s from Nucleon Structure Functions

The nucleon structure functions provide important pieces of information for momentum densities of partons in nucleons. These momentum densities cannot be calculated from QCD but need to be measured experimentally. Global fits of QCD evolutions to experimental measurements of the nucleon structure functions yield the parton momentum density functions, as well as the QCD scale parameter, Λ_{QCD}. This evolution causes the scaling violations and the degree of this violation is represented by the logarithmic slopes, $d(logF)/d(logQ^2)$, of the structure functions.

There are two aspects in determining Λ_{QCD}. The first aspect is to test QCD and the second is to determine the value precisely, assuming QCD is correct. To test QCD, we have performed a fit to structure function xF_3 only and a fit to both F_2 and xF_3 combined. We used the NLO Dokshitser-Gribov-Lipatov-Altarelli-Parisi (DGLAP) evolution equation [2] and hard scattering coefficients in Ref. [3], along with the following forms of the parton density functions :

$$xq_{NS}(x, Q_0^2) = A_{NS}x^{\eta_1}(1-x)^{\eta_2} \tag{2}$$

$$xq_S(x, Q_0^2) = xq_{NS}(x, Q_0^2) + A_S(1-x)^{\eta_s} \tag{3}$$

$$xG(x, Q_0^2) = A_G(1-x)^{\eta_G} \tag{4}$$

for non-singlet, singlet, and gluon density functions, respectively.

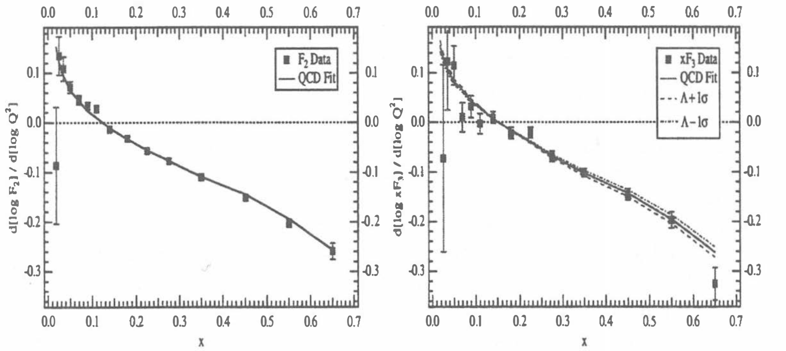

Figure 1: Logarithmic slopes of F_2 and xF_3 as a function of x. The solid lines represent the slopes for the central value of Λ_{QCD} and the dashed lines represent the one standard deviation uncertainty boundary.

We then fit the measured structure functions, using QCD, in the kinematic regions of $Q^2 > 5GeV^2$, $W^2 > 10GeV^2$, and $x < 0.7$, minimizing the χ^2, defined as :

$$\chi^2 = \Sigma_{x,Q^2}[(\mathbf{F^{data}(x, Q^2)} - \mathbf{F^{QCD}(x, Q^2)})^{\mathbf{T}}\mathbf{V^{-1}}(\mathbf{F^{data}(x, Q^2)} - \mathbf{F^{QCD}(x, Q^2)})] \tag{5}$$

where **F**'s represent structure function vectors and **V** the error matrix that takes the point-to-point statistical correlations between the structure functions, F_2 and xF_3, into account. The effects target mass [4] were included in the fit. The reference Q^2 value, Q_0^2, was set to 5GeV, in order to keep the fit in perturbative regions of QCD. The systematic errors in the fit were obtained by varying each source by one unit of error at a time and re-fitting on the structure functions over, and taking the difference between the refit result and the central value as the error due to the given source. The resulting total systematic uncertainty is obtained by adding errors from all sources in quadrature.

From the pQCD fit, we obtain $\Lambda_{\overline{MS}}^{4,NLO} = 387 \pm 42(stat) \pm 92(syst)$MeV ($\chi^2/dof = 81.4/82$), from the fit on xF_3 only, and $\Lambda_{\overline{MS}}^{4,NLO} = 381 \pm 23(stat) \pm 58(syst)$MeV ($\chi^2/dof = 190.6/164$), from the combined fit on both F_2 and xF_3.

Figure 1 shows the logarithmic slopes from the combined fit on both F_2 and xF_3 as a function of x. The solid lines represent the logarithmic slopes corresponds to the central values of Λ_{QCD} from the fit and the dashed lines represent one standard deviation error boundary of the Λ_{QCD} from the fit. As one can see the fits agree with data, describing the logarithmic slopes of both F_2 and xF_3. This proves that pQCD describes the data well in wide kinematic ranges of measurement.

However, we estimated the total systematic uncertainty in these fits, assuming that the sources of the systematic error are not correlated to each other. Thus, the systematic error in Λ_{QCD} may be overestimated due to the possible correlations between the sources.

Since we have verified that pQCD describes data well, we then decided to determine the value of Λ_{QCD} as precisely as possible. In order to do this, we assume that QCD is correct and treat the systematic errors from all sources, as free parameters whose sizes get determined by QCD. This is reasonable to do, because the scale parameter $\Lambda_{QCD}^{4,NLO}$ is only meaningful in the context of NLO QCD. For this fit, we slightly modified the definition of χ^2 in order to constraint wild variation of systematic uncertainties :

$$\chi^2 = \Sigma_{x,Q^2}[(\mathbf{F^{diff}})^{\mathbf{T}}\mathbf{V}^{-1}(\mathbf{F^{diff}})] + \Sigma_{\mathbf{k}}\delta_{\mathbf{k}}^2, \tag{6}$$

where $\mathbf{F^{diff}} = \mathbf{F^{data}} - \mathbf{F^{Theory}} + \Sigma_{\mathbf{k}}\delta_{\mathbf{k}}(\mathbf{F^k} - \mathbf{F^{data}})$ and the term δ_k is the fractional shift of $\mathbf{F}$ for source k which adds additional units to the value of χ^2 as it gets varied from the central value by one unit of uncertainties, every time the error of a source gets varied. $\mathbf{F^k}$ represents the structure function vectors with the source k varied by one unit of error. Using this method, we find that the total experimental uncertainties get reduced, retaining the sizes of the uncertainties of sources mostly the same.

Again two fits were performed. From the fit on xF_3 only, we obtain : $\Lambda_{\overline{MS}}^{4,NLO} = 381 \pm 53(combined)$MeV ($\chi^2/dof = 69/82$), and from the combined fit on both F_2 and xF_3 : $\Lambda_{\overline{MS}}^{4,NLO} = 337 \pm 28(combined)$MeV ($\chi^2/dof = 158/164$). Thus, we chose to quote the final value of four flavor, Next-to-Leading order, Λ_{QCD} to be : $\Lambda_{\overline{MS}}^{4,NLO} = 337 \pm 28(exp) \pm 13(HT)$ where the error HT represents uncertainties due to the higher twist effects [5]. The corresponding value of α_s^{NLO} at the mass of Z boson is: $\alpha_s^{NLO}(M_Z^2) = 0.119 \pm 0.002(exp) \pm 0.001(HT) \pm 0.004(scale)$, where the scale error is estimated from Ref. [6].

In summary, we have measured the nucleon structure functions $F_2(x,Q^2)$ and $xF_3(x,Q^2)$. We have determined the value of four flavor, Next-to-Leading order Λ_{QCD} to test QCD. The resulting fits describe data well in all kinematic ranges of the fit, proving that pQCD describes data well. The global systematic fits on both F_2 and xF_3 provided a precise determination of $\Lambda_{QCD}^{4,NLO}$:

$$\Lambda_{\overline{MS}}^{4,NLO} = 337 \pm 28(exp) \pm 13(HT)\text{MeV}. \tag{7}$$

The corresponding value of α_s^{NLO} at the mass of the Z boson :

$$\alpha_s^{NLO}(M_Z^2) = 0.119 \pm 0.002(exp) \pm 0.001(HT) \pm 0.004(scale). \tag{8}$$

This value of α_s is higher than the previously reported value [7] where $\alpha_s(M_Z^2) = 0.111 \pm 0.002(stat.) \pm 0.003(syst.)$. The most significant changes, compared to the previous measurement, are 1) hadron and muon energy calibrations, determined from an extensive analysis of the test beam data, 2) more regorous muon energy loss correction, 3) higher order calculation of radiative correction [8], 4) better parameterization of low x $R(x,Q^2)$ [9].

α_s from GLS sum rule

Once the structure function xF_3 is measured, one can use the Gross-Llewellyn-Smith (GLS) sum rule [10] that states that the number of valence quarks in the nucleon is 3 up to QCD corrections. Since in simple quark-parton model, the structure function xF_3 is $xq - x\overline{q}$, the valence quark distributions, integrating xF_3 over x give total number of valence quarks, 3.

The GLS sum rule is a fundamental predictions of QCD and since the integral only depends on valence quark distributions, the α_s can be determined without affected by less

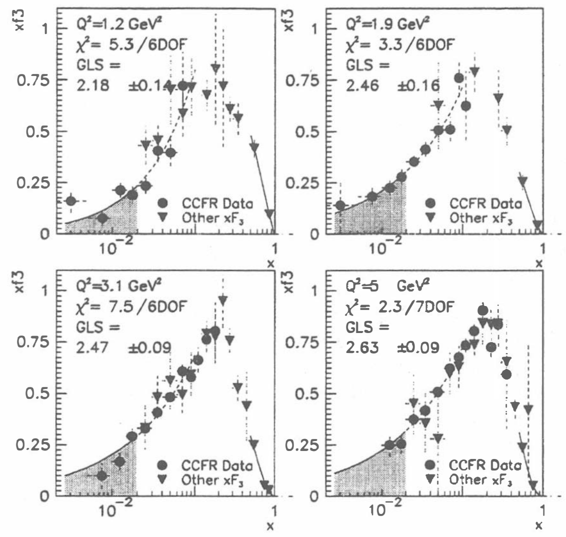

Figure 2: xF_3 vs x for four lowest Q^2 bins. The solid circles represent the CCFR xF_3 data and the inverse triangle represent the data from other experimental measurements.

known gluon distributions. Moreover, since there are many measurements of xF_3 in wide range of Q^2, one can measure α_s as a function of Q^2.

With the next-to-next-to-leading order QCD corrections [11], the GLS integral takes the form :

$$\int_0^1 xF_3(x,Q^2)\frac{dx}{x} = 3(1-\frac{\alpha_s}{\pi} - a(n_f)(\frac{\alpha_s}{\pi})^2 - b(n_f)(\frac{\alpha_s}{\pi})^3) - \Delta HT \tag{9}$$

where the term ΔHT is the corrections from higher twist effects from Ref. [12], $(0.27 \pm 0.14)/Q^2$.

In order to perform the integration of xF_3 in the entire ranges of x, we use the data from other ν-N DIS measurements, as well, to cover the x what are not covered by CCFR. We then fit xF_3 to power law in the range of $x < 0.02$ and $x > 0.5$ and use the fit functions to extrapolate xF_3 to the region without data for integration.

Figure 2 shows xF_3 for four Q^2 bins as a function of x. The solid lines represent the regions of x that uses the fitted functional forms to perform the integration. The shaded area in each plot shows the region of x that the fit functional forms are used for the integration. The solid circles represent the CCFR data and the inversed solid triangles represent the xF_3 from other experiments : WA59, WA25, SKAT, FNAL-E180, and BEBC-Gargamelle [13]. The plots also show the values of χ^2 of the fits, as well as the results of the GLS integrals in each Q^2 bin. The dashed lines represent the extrapolation of the fit function which describe the data very well. This agreement gives us confidence in using these functions for the integration.

After integrating xF_3 in all six Q^2 bins, we solve the Eq. 9 to obtain the value of α_s at the given Q^2. We evolve each measured value of α_s, using two loop expression of α_s, to the mass of Z boson, M_Z. We take the average value of α_s at the mass of Z boson as the result of the measurement. The preliminary value from α_s at the mass of Z boson is:

$$\alpha_s^{NNLO}(M_Z^2) = 0.112^{+0.004}_{-0.005}(stat.)^{+0.006}_{-0.008}(syst.) \pm 0.008(model)^{+0.004}_{-0.005}(HT) \quad (10)$$

where model error is due to our modelling of low x acceptances and HT represents the uncertainty due to higher twist effects. We expect this measurement to improve due to better modelling of our low-x acceptances. Currently more regorous estimate of systematic uncertainties is in progress.

Prospects in the NuTeV experiment

The NuTeV experiment is the successor of the CCFR experiment which uses the Sign-Selected-Quadrupole-Train (SSQT) in the neutrino beamline. This beamline enables the experiment to select the sign of pions and kaons to select either neutrinos or anti-neutrinos at a given time. The selection of the neutrino sign provides many advantages over the previous experiment, such as, 1) increased anti-neutrino statistics that would reduce statistical uncertainties in xF_3 measurements and 2) reduction of the wrong sign background that contributed to the systematic uncertainties in the previous measurements.

In addition to the SSQT, the NuTeV experiment has an ability of continuous in-situ calibration of the detector. This calibration beam enables the experiment to acquire better knowledge on hadron and muon energy scale and resolution, and to track systematic variation of the detector responses as a function of time and temperature. This ability would ultimately reduce the calibration error to 0.3% which is a factor of 3 better than the previous experiment that would reduce experimental systematic errors of Λ_{QCD} significantly.

References

[1] W.Seligman, Ph.D. Thesis, Columbia University, New York, Nevis Report 292 (1997).

[2] G.Altarelli & G.Parisi, *Nucl. Phys.* **B126**, 298 (1977); V.N.Gribov & N.Lipatov, *Sov. J. Nucl. Phys.* **15**, 438 (1972); Yu.L.Dokshitzer, *Sov. Phys. JETP* **46**, 641 (1977).

[3] R.T.Herrod & S.Wada, *Phys. Lett* **B96**, 295 (1980).

[4] M.Dasgupta & B.R.Webber, HEP-PH-9604388 (Apr. 1996).

[5] H.Georgi & H.D.Politzer, *Phys.Rev*D**14**, 1829 (1976).

[6] M.Virchaux&A.Milsztajn, *Phys. Lett.* **B274**, 221 (1992).

[7] P.Z.Quintas *et. al.*, *Phys. Rev. Lett.* **71**, 1307 (1993).

[8] D.Yu,Bardin & V.A.Dokuchaeva, JINR-E2-86-260 (1986).

[9] L.W.Whitlow *et. al*, *Phys. Lett.* **B250**, 193 (1990).

[10] D.J.Gross & C.H.Llewellyn Smith, *Nucl. Phys.* **B14**, 337 (1969).

[11] S.A.Larin & J.A.M.Vermarseren, *Phys. Lett.* **B274**, 221 (1991).

[12] V.M.Braun & A.V.Kolesnichenko, *Nucl. Phys* **B283**, 723 (1987).

[13] K.Varvell *et al.*, *Z. Phys.* **C36**, 1 (1987) D.Allasia *et al.*, *Z. Phys.* **C28**, 321 (1985); V.V.Ammosov *et al.*, *Z. Phys.* **C30**, 175 (1986); V.V.Ammosov *et al.*, JETP **36**, 300 (1982); P.C. Bosetti *et al.*, *Nucl. Phys.* **B142**, 1 (1978)