The Structure of the Nucleon, Three Decades of Investigation (1967-2004)

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A personal historical account of three decades of experiments that led to a detailed understanding of the structure of the nucleon and the theory of Quantum Chromodynamics. (Panofsky Prize 2004 Talk, Presented at NuInt04, Mar. 2004, Laboratori Nazionali del Gran Sasso - INFN - Assergi, Italy [1])

$$p = \overbrace{\underbrace{uud}_{valence} + \underbrace{u\bar{u} + d\bar{d} + ...}_{sea} + \underbrace{g + g + ...}_{gluons}}^{partons}$$

Figure 1. Current understanding of the structure of the nucleon in terms of point-like partons.

1. INTRODUCTION

Currently, the structure of the nucleon is well understood and nucleon parton distributions have been measured with very high precision. It took about 30 years of various experiments to show that Quantum Chromodynamics (QCD) in Next to Next to Leading Order (NNLO QCD) works very well[4] from very low momentum tranfers (e.g. order of the proton mass) to the highest Q^2 values currently accessible in hadron colliders (as shown in Figure 2).

2. OVERVIEW

In the early 1960's a large number of hadron resonances were discovered and studied at in proton and pion-nucleon scattering experiments. From elastic electron-nucleon scattering experiments in the 1960's (Nobel Prize of Hofstader), it was known that nucleons are composite and have a finite size of about 1 Fermi. However, it did not appear that any of the hadrons were particularly more fundamental than other hadrons.

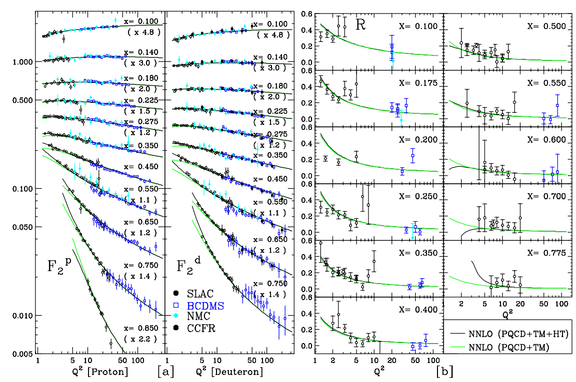

Figure 2. The Triumph of Quantum Chromodynamics in Next to Next to Leading Order. Results from a NNLO QCD analysis from Bodek and Yang [4] (2000). QCD theory in NNLO describes all the data from very low to very high Q^2 with no need for dynamical higher twist corrections. Shown are electron and muon-nucleon scattering data (SLAC, BCDMS and NMC) for F_{2p} [a] and $R = \sigma_L/\sigma_T$ [b] compared to the predictions with (NNLO modified) MRSR2 NLO PDFs including both NNLO and target mass corrections with (solid line) and without (dashed line) higher twist corrections. This analysis indicate that in QCD fits at lower order (LO or NLO fits), the extracted higher twist corrections originate from target mass effects and the missing QCD NNLO higher order terms (for $Q^2 >$ 1 GeV^2).

There were many theoretical models proposed to describe the spectroscopy of hardrons, and the physics of lepton-nucleon scattering. Much of the effort of mainstream particle physics at that time was focused on hadron-nucleon experiments where hadron resonances were discovered and categorized. It was the era of spectroscopy, group theory, partial wave analysis, resonances, regge poles, and field theory. During that period, the quark model was proposed, but quarks were only considered as one convenient way to model SU(3) symmetry.

Quarks were not considered real particles for very good reasons such as (a) no free quarks were ever observed, (b) quarks had to have fractional 1/3 charges, and (c) new quantum numbers (e.g. color) were required if the quark states were to satisfy Fermi-Dirac statistics. At that time, to illustrate this point, I was told by a leading theoretical physicist that any self-respecting theorist who actually used the quark model in any calculations, did it only in the privacy of his own office. Later, any calculations based on the quark model were translated into field-theoretic language before they were submitted for publication refereed journals. I took that advice to heart and only did quark model calculations in private. In summary prior to the MIT-SLAC electron-nucleon scattering experiments (1967-1973), many believed that quarks were mathematical constructs and could not be real particles.

Quarks became accepted as real particles during the 1967-74 period following their discovery in the MIT-SLAC inelastic electron-nucleon scattering experiments. The Nobel Prize of 1990 was awarded to Friedman, Kendall, and Taylor for: "their pioneering investigations concerning deep inelastic scattering of electrons on protons and bound neutrons, which have been of essential importance for the development of the quark model in particle physics (1967-74)."

Soon thereafter the J/ψ and Charm particles were discovered in hadron-nucleon and electron-positron experiments. A few years later the Υ and Bottom quarks were also discovered in proton-nucleon and electron-positron experiments. This led to a large number of experiments (in the 1970's and 1980's) at e+e- and hadron machines where charm and bottom hadrons were studied in great detail. Here again, attention was focused on the study of spectroscopy, partial wave analysis, and new resonances. The new hadronic states that were being investigated were now composed of larger variety of quark flavors (up, down, strange, charm and bottom). During that period, neutral-currents were discovered, the τ lepton was discovered and the standard model of electro-weak interactions was developed.

To put the previous paragraph in context, I should note that, as is the case today, a portion of the experimental effort in particle physics was focused on non-discoveries of new particles (searches and limit setting) such as Supersymmetry, Lepto-quarks, Higgs, Heavy Leptons.

However, as we have learned many times before, physics is a quantitative experimental science and precision experiments are essential to its progress. In the past thirty years, a segment of the experimental high energy physics community (later joined by members of the nuclear physics community) continued to to make incremental progress in the study of nucleon structure.

Like other advances in science, progress in this area was accomplished by a combination of experiments at higher energies (e.g. accessible with new accelerators) and new experimental techniques. New techniques were instrumental in achieving higher precision and overcoming the limitation (e.g. brick walls) of old techniques. Higher Luminosities (more statistics), experiments with different probes (new beams), new theoretical tools (better understanding of radiative corrections, QCD to higher orders) were all essential. In this review I will discuss some of my own involvement and highlight the contributions of PhD graduate students in the Rochester group over the past three decades.

3. The Nobel Prize of 1990: The MIT-SLAC Experiments

Figure 3 is taken from the 1990 Nobel Prize archives and SLAC Web Page [3]. It shows Richard Taylor, Jerome Friedman, Henry Kendall in the front row, and Arie Bodek, David Coward, Michael Riordan, Elliott Bloom, James

Figure 3. Nobel [3] Prize of 1990 (see text for details)

Bjorken, Roger (Les) Cottrell, Martin Breidenbach, Gutherie Miller, Jurgen Drees, W.K.H. (Pief) Panofsky, Luke Mo, William Atwood in the second row (not pictured was Herbert (Hobey) DeStaebler). An historical account of the experiments can also be found in a popular science book written by Michael Riodan [2].

The following is a generic summary description of the PhD Thesis topics of the graduate students who particpated in the the first and second generation MIT-SLAC experiments Arie Bodek (scaling on neutrons and protons), Martin Briedenbach (scaling on protons, Briedenbach was awarded later awarded the Panofsky Prize in Experimental Particle Physics later for his work on the SLD Experiment), Rod Ditzler (nuclear dependence), Scott Poucher (scaling on neutrons and protons), and Michael Riordan (R on protons and neutrons) all from MIT. Also Guthrie Miller (scaling on protons) and William Atwood (scaling on neutrons and protons) from SLAC.

Professor Victor Weisskopf (a former faculty member at the University of Rochester, who spent many of his later years as a faculty member at MIT) said at one of his talks at MIT that theorists like the electron scattering experiment because it is one of the few detectors that they can understand. His reasoning was that, as shown in Figure 4, the experimental setup [9] looks very

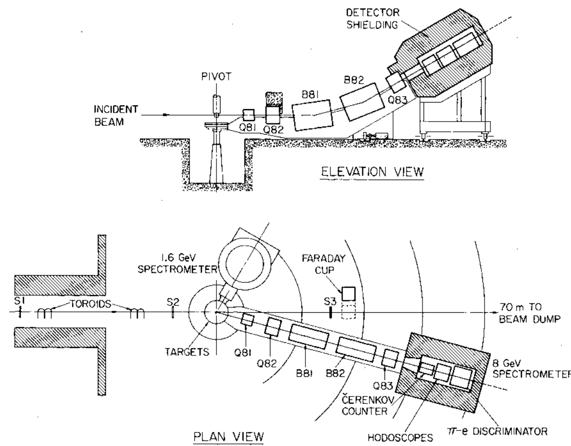

Figure 4. Experimental setup [9] used in some of the MIT-SLAC electron-nucleon scattering experiments 1967-1974 (e.g. E49B, E87) with the SLAC 8-GeV spectrometer (the Feynman Diagram Experimental Setup).

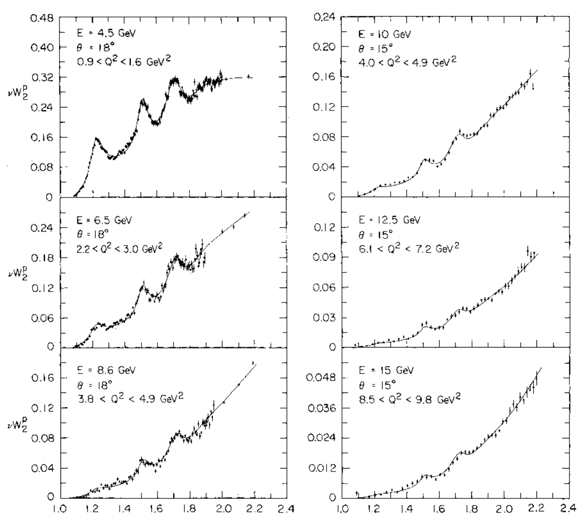

Figure 5. The MIT-SLAC data [9] (described by V. Weisskopf as the Frank-Hertz and Rutherford Experiments of the Proton and Neutron)

much like the Feynman diagram for the deep inelastic scattering process.

When he showed the MIT-SLAC results at a colloquium at MIT, (Figure 5) Weisskopf referred to the inelastic scattering region as the Rutherford Experiment of the proton, and to the resonance production region as the Frank-Hertz Experiment of the proton.

From the series of electron scattering experiments performed between 1967 and 1974, it was inferred that:

(1) The nucleon is composed of point like constituents (called *partons*, as shown in Figure 1). The evidence for this was that the data approximately *scaled* in the Bjorken variable x as shown in Figure 6.

(2) The charged partons were predominantly *spin* 1/2 since the ratio of the cross section for longitudinal and transverse virtual photons ($R = \sigma_L/\sigma_T$) was found to be small [7].

(3) The integral of the fractional momentum carried by the charged partons was only *half* of the nucleon's momentum. Therefore, neutral particles carried the other half of the nucleon momentum [8]. These neutral particles were referred to as *gluons*. Just as neutrinos were discovered from missing energy in β decays, *gluons* were discovered in the MIT-SLAC experiments around 1970, years before the observation of three jet events at PETRA.

(4) The ratio of the cross sections on neutrons and proton was below 2/3 at large x [5,6]. This could only be explained in a model in which the partons at large x are *fractionally* charged valence *quarks*. This was the clinching evidence in support of the *quark* model (as shown in in Figure 7).

(5) At small x the neutron to proton ratio [5,6] was near 1.0. This indicated that in addition to valence quarks, there was a *sea* of *quark* $-$ *antiquark* pairs which was about the same magnitude for the neutron and proton (Figure 1 and Figure 7.

(6) There was little *nuclear* dependence of the structure functions in the region near $x = 0.1$. These data ruled out simple *vector* dominance models which predicted nuclear dependence similar to *pion* $-$ *nucleus* scattering (subsequently,

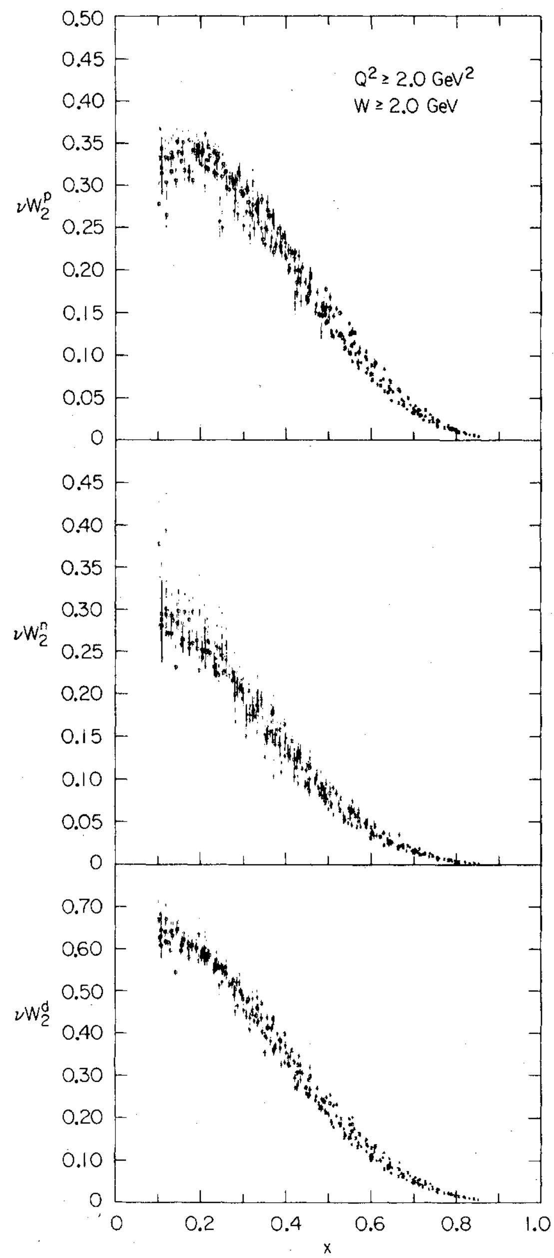

Figure 6. Approxmiate scaling of the MIT-SLAC data in the Bjorken variable x was the first evidence for point like constituents in the proton. After Rosenbluth separation of F_1 and F_2 it was clear the the scatter of the points was due to scaling [8] violations in F_2.

the vector mesons dominance models evolved to include a much larger number of vector mesons). As an aside, a decade later, we would find that nuclear effects were more important than we thought and that $x = 0.1$ is the *only* region for which there is no nuclear dependence of the structure functions.

(6) Within a couple of years, it was foudn that *scaling* in the Bjorken variable x was only *approximate*. *Rosenbluth* separations of F_1 and F_2 showed (Figure 8) that the scatter of the points was in F_2 and not from uncertainties in R [8]. The observed deviations [8,9] from scaling were investigated and were attributed to either gluon emission in the scattering process, as predicted by the new theory of Quantum-Chromodynamics (QCD), and/or to binding effects of the partons in the nucleon (e.g. target mass and/or dynamical $higher - twist$ effects). The only x value for which there were no deviations from scaling was at $x = 0.2$ (which incidentally was the first region that was investigated in 1968).

These results changed our view of the structure of the nucleon. The parton model was proposed, and by the early 1970's, the accepted view was that the nucleon is composed of point like quarks. It is interesting to note that this view was accepted quickly (especially by some of the referees for Physical Review Letters). Many of the results of the more precise second generation MIT-SLAC electron scattering experiments were not accepted for publication in Physical Review Letters (precision experiments were not as valued in those days as they are today).

Figure 7 shows both first results (E49A and E49B at 6 and 18 degrees) of the neutron to proton structure function ratio [5] which were published in Phys. Rev. Letters. Also shown are the more precise results (E87 at 15 degrees) obtained a couple of years later [6]. Since the quark model was already established, our second paper with more precise data was rejected by Physical Review Letters" as not adding much to our state of knowledge". At that time I was a young graduate student at MIT, and accepting the judgement of my elders, I re-submitted that paper to Physics Letters [6] instead.

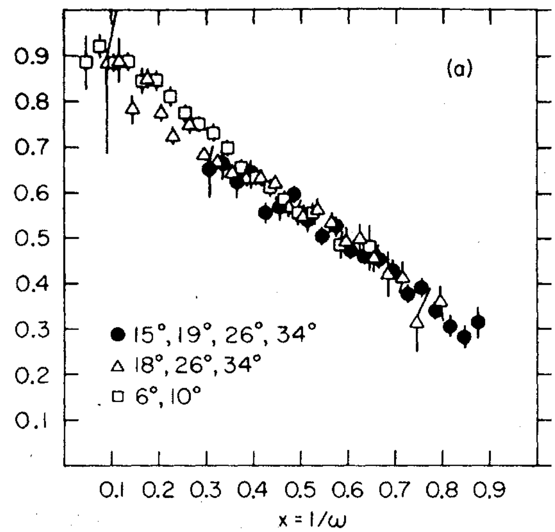

Figure 7. The Ratio of e-N and e-P cross sections. It was found to be below 2/3 at large x [5,6]. This could only be explained in a model in which the partons at large x are *fractionally* charged valence *quarks*. This was the clinching evidence in support of the quark model.

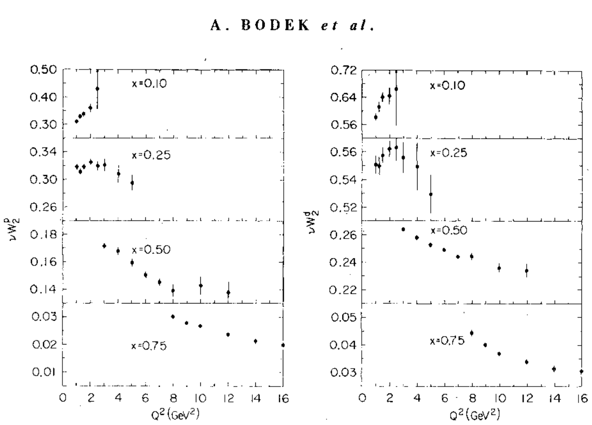

Figure 8. The x, Q^2 dependence of scaling violations first observed in Rosenbluth separated MIT-SLAC data [8].

By the early 1970's the accepted dogma was that when higher momentum transfers can be reached, scaling will become more and more exact. However, the second generation Rosenbluth separated MIT-SLAC data (E87) showed clear deviations from scaling [8] as shown in Figure 8. Note that deviations from scaling due to interactions between the quarks bound in the nucleon (target mass and dynamical higher twist effects) were expected to vanish as $(1/Q^2)$. However, there were several theories that predicted other forms of scaling violations, including models in which the quarks had a finite size (e.g. form factors) and a new theory of quantum chromodynamis (QCD) which predicted that scaling violations will only decrease as $1/\ln(Q^2)$. Nonetheless, our study comparing the measured scaling violation (extracted from Rosenbluth separated data) to various models was rejected for publication in Physical Review Letters. The referees stated that these were obviously "uninteresting higher twist effects". At time time I was a young postdoc at MIT, and accepting the judgement of my elders, I re-submitted the paper for publication in Physics Letters [8] instead.

4. The New 400 GeV Accelerator at Fermilab - Higher Energy Fixed Target Lepton-Hadron Experiments

The focus shifted to the new muon and neutrino scattering experiments at Fermilab and CERN. These experiments, though less precise, could provide data at higher values of Q^2. The primary motivation was to search for W bosons and to search for new heavy leptons. Nonetheless, the questions specific to nucleon structure that were of interest at that time were:

(1) Is QCD correct. Are there *logarithmic* scaling violations? what are those *gluons* that carry half of the momentum in the nucleon.

(2) What was the magnitude and *flavor* decomposition of the $quark - antiquark$ sea?

(3) Are there heavy quarks (e.g. *charm*) intrinsic in the nucleon?

(4) What is the x and Q^2 dependence of the nucleon *sea*.

(5) What is the value of the strong interactions *coupling* constant and does it change with Q^2 as predicted by QCD.

(6) Is there experimental evidence for the validity of a variety of Current Algebra and QCD *sum rules*.

These questions could be addressed by using new probes at higher energies such as high energy neutrino beams. In 1974 I went to Caltech as Millikan Fellow to work on the new neutrino program at Fermilab (led by Frank Sciulli and Barry Barish and H. E. Fisk). Over the years, this program evolved from the Caltech-Fermilab experiment to the Chicago (F. Merritt/M. Oreglia) - Columbia (F. Sciulli/M. Shaevitz) - Rochester(Bodek) -Fermilab (HE Fisk) - Wisconsin (W. Smith) (CCFR) neutrino program, and became NuTeV at the end. Frank Sciulli has received the APS Panofsky prize in Experimental Particle Physics for his leadership in this program.

The first results from the neutrino experiments showed that the ratio of neutrino to electron (or muon) structure functions was in agreement with the quark-parton model (assuming fractional charged quarks). The combination of neutrino and antineutrino measurements was used to separate the distributions of valence quarks from the distribution of antiquarks in the sea. The experiments were not only relevant to nucleon structure, but also led to new discoveries such neutral currents, charm production (dimuon events), and trimuon events in neutrino interactions.

5. The strange-sea is cut in half

Dimuon events in neutrino interactions originated from charm-particles produced in charged current events. The discovery of dimuon events allowed for a separate determination of the strange-quark content of the quark-antiquark sea. It was found that the quark-antiquark sea was not SU(3) Symmetric. The strange-sea carried about 1/2 of of the average momentum carried by the sea of up or down quarks. One of first PhD theses that focused on the determination of the strange-quark content of the sea (in leading order QCD) was done by Rochester PhD student, Karol Lang [11], who is now a faculty member at

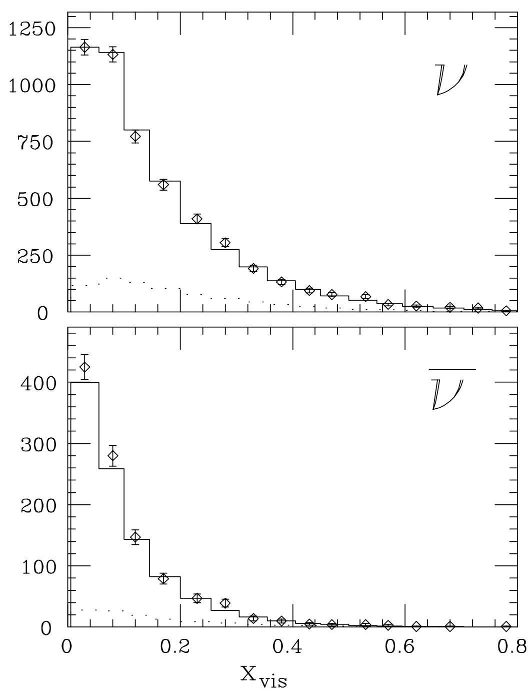

Figure 9. The magnitude and x distribution of the strange sea (in NLO QCD) was extracted from the x distribution of dimuon events in both neutrino and antineutrino interactions [11] at CCFR.

UT Austin. As more data were accumulated, the x distribution of the strange sea (in NLO QCD) was extracted from the x distribution of dimuon events in both neutrino and antineutrino interactions [11] as shown in Figure 9.

6. Intrinsic charm comes and goes

With the discovery of charm states, a significant fraction of the high energy physics community was involved in looking for charm-particles in electron-positron, proton-proton and neutrino-nucleon interactions. At that time, two experiments at the CERN Intersecting Storage Ring (ISR) observed copious production of charm states in the forward direction proton-proton collisions. This was surprising because it implied that there were intrinsic charm quarks in the nucleon wave function (of order one to three percent), and that these charm quarks carried a very large fraction of the momentum of the proton.

In contrast, an emulsion experiment which searched for charm particle production in proton-proton collisions in the central region, reported that for 400 GeV protons the cross section for the production of charm particles was less than 3 microbarns. At that time, aside from the reported results by the ISR, not a single experiment has observed the production of open charm in hadron collisions. Adding to the confusion, QCD calculations in leading order predicted that the production of charm states in the central region (via the gluon-fusion mechanism process) was very small (e.g. 1-3 microbrans) in agreement with the emulsion limits. It turned out that all of the experimental results as well as the theoretical calculations were incorrect.

There was another unresolved mystery at that time. The source of prompt muons (i.e. not from long lived pion decays) produced in hadron collisions was not understood. It was not clear if the prompt muons originated from dimuon pairs (e.g. vector meson and Drell Yan events) or from weak decays of single states such as charm particles. The new large acceptance neutrino detectors, if placed in a hadron beam, could be used to answer some of these questions.

In order to calibrate the new neutrino detectors at Fermilab, the Lab E neutrino facility had access to both a neutrino beam (in the center) and a hadron/muon calibration beam (on the side). The neutrino target/calorimeter modules and muon spectrometers are ideal muon detectors. Therefore, one of the first experiments in Lab E was actually a high intensity hadron experiment to investigate the production of prompt muons in proton-nucleon and pion-nucleon collisions (FNAL experiments E379/E595). This experiment was a collaborative effort between Caltech (B. Barish), Fermilab (HE Fisk), Stanford (S.Wojcicki) and Rochester. The results from FNAL E379/E595 were:

(a) About 3/4 of the prompt muons originate from dimuon events and about 1/4 of the prompt muons originate from the production of charm particles.

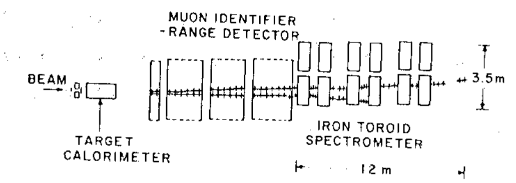

Fig. 1

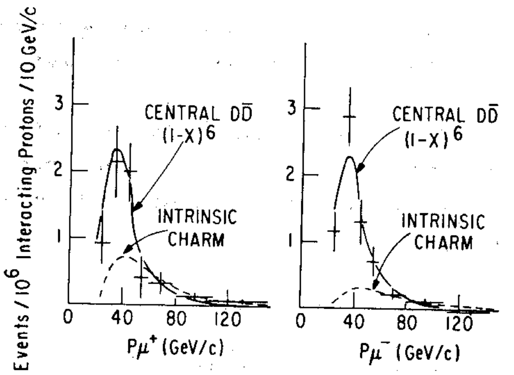

Fig. 2

Figure 10. The apparatus and results from experiment [15] E595. A limit of 2x10^{-4} was placed on the intrinsic charm in the nucleon wave function. The experiment also measured tha hadronic charm production cross section for the first time (20 microbarns) from single charm decay events), and placed the best limit on D0-D0bar mixing (from double charm decay events).

(b) The production of forward charm particles in proton-nucleon collisions was very small. A limit of 2x10^{-4} was placed on the intrinsic charm in the nucleon wave function (which is a factor of 100 lower than what was needed to explain the large forward cross sections reported). Later experiments at the ISR (which much larger acceptance) did not confirm the original ISR results.

(c) The hadronic charm production cross section in the central region was about 20 microbarns (much higher than the earlier emulsion limit). This implied that large higher order corrections (K factors) were necessary to improve on the Leading Order QCD calculations of hadroproduction cross sections.

(d) Investigation of the double leptonic decays of charm mesons (to muons and missing energy) place the most stringent limit on the mixing of D0 and D0bar mesons.

Some of the published results [15] are reported in the PhD Thesis of Rochester graduate student Jack Ritchie [15] (who is currently a faculty member at UT Austin). The apparatus and one of the plots from the papers is shown in Figure 10.

7. The Era of High Statistics Neutrino and Muon Experiments

Over the following 20 years, the muon and neutrino-nucleon experiments at CERN and at Fermilab were slowly upgraded. The programs have matured to become high statistics experiments. Data samples of order of millions of charged current events were collected. In the neutrino case, this was accomplished by the use of massive targets (about 600 tons of iron) and higher fluxes of neutrinos made possible by higher proton intensities. In these higher energy experiments, logarithmic scaling violations was observed at higher values Q^2, in agreement with QCD [12–14]. During that period, QCD became the accepted theory of strong interactions.

Because of the coarse sampling in the massive neutrino target-calorimeters, and the multiple scattering of muons in the large acceptance magnetized iron muon spectrometers, both the hadron energy and muon energy were measured with worse resolutions than was standard in the lower energy electron-nucleon experiments. Better uniformity at lower cost was accomplished by the CCFR Neutrino collaboration by the invention of large area scintillation counters with wavelength shifter bar readout. In addition CCFR constructed a compensating calorimeter by using thick active sampling layers. Still, the worse resolutions in those experiments had to be compensated for by carefully calibrating the detectors with hadron and muon beams [10], and by accumulating large statistical samples [14].

The second generation neutrino and muon experiments yielded information on detailed distributions of the various types of quarks and antiquarks in the nucleon. The higher energies allowed determination of the parton distribution functions at small values of x. In addition, values of the strong interaction coupling constant and the x and Q^2 dependence of the gluon distributions were extracted from the x and Q^2 dependence of the scaling violations [12]. These data were used in global parametrizations of the various parton distribution functions PDFs in nucleon (by CTEQ, MRST, GRV) for the benefit of other experiments.

8. High Statistics but poor systematics - new mysteries

Precise knowledge of nucleon PDFs is crucial in order to be able to do physics in the new proton-antiproton colliders. In the early 1980's PDFs describing the valence, sea, strange quark and gluon distributions were extracted from fits to all available high Q^2 muon and neutrino scattering data. The PDFs were known sufficiently well for the first generation proton-antiproton experiments. New particles including the W and Z bosons and the Top quark were subsequently discovered and studied in the new high energy proton-antiproton machines at CERN and then at Fermilab.

With time, the proton-antiproton collider experiments at Fermilab have become more precise and started accumulating large statistical samples. Some of the most important measurements have become limited by the systematic errors on the parton distribution functions. The systematic errors on the PDFs (and especially $R = \sigma_L/\sigma_T$) also limited the extraction of precise parameters (such as the electro-weak mixing angle) from high statistics neutrino experiments.

Systematic errors in the PDFs originated from the following sources.

(1) The high statistics muon and neutrino experiments are mostly done on iron targets. The PDFs are corrected for nuclear binding effects using theoretical models. Early results reported by the European Muon Collaboration (EMC) on the ratio of iron to deuterium structure functions showed a large discrepancy from the Fermi-Motion calculations of Bodek and Ritchie [16]. The ratio of iron to deuterium was observed to be different than 1.0 with a 20 % slope as a function of Bjorken x, as shown in Figure 11. Here, since the results were also in disagreement with my calculations [16], I was further motivated to try to find out if it was correct.

(2) The systematic errors in calibration and flux normalizations in the neutrino and muon experiments were significant. These high energy experiments were not yet precise enough to separate the contribution of the longitudinal and transverse components of the cross sections. Therefore unless $R = \sigma_L/\sigma_T$ could be measured to better precision, there was a limit on how well the structure function F_2 (which has contributions from both longitudinal and transverse components) could be extracted from muon and neutrino data at high energies.

(3) There were differences at small x between the PDFs extracted from muon and neutrino experiments. If those differences were attributed to the strange sea, it implied a factor of 2 increase in the magnitude of the strange sea, in contradiction with results from the dimuon neutrino data. This also implied that there was more than a 10% uncertainty in the level of the PDFs at small x (a very important region for collider experiments).

(4) There were normalization uncertainties in the various muon and neutrino experiments, as well as Q^2 dependent errors from the the remaining uncertainties in the calibration of muon and hadron energies. As we later found out the systematic errors in the muon energy calibration (in some muon experiments), and in the hadron energy calibration (in some neutrino experiments) were larger then initially estimated.

(5) A smaller value of the strong interaction coupling α_S was extracted from DIS muon and neutrino experiments, when compared to α_S extracted from e+e- experiments. The origin of difference was not understood since it was outside the quoted systematic errors. Models with low mass supersymetric gluinos were proposed to account for this difference. Since I was involved in both the AMY e+e- experiment and the CCFR Neutrino experiment, I was caught in the middle between the two results and had strong motivations to try resolve this issue.

(6) The relative contribution to the scaling violations from QCD evolution and from higher twist effect was not understood. Therefore, more precise lower energy electron scattering data from SLAC was not included in the PDF fits. This resulted in uncertainties in the evolution of the PDFs from fixed target energies to the energies at hadron colliders, and led to uncertainties in the extraction of the strong interaction constant α_S.

(7) Because of poor resolution smearing in muon and neutrino experiments, these experiments could not reliably measure the the PDFs at high values of x. Conversely, the lower energy high x data from SLAC was not considered reliable, because the higher twist effects were not understood. As the structure functions are evolved to very high Q^2, the poor of knowledge of the PDFs at high x and low Q^2 contributed significantly to the PDF uncertainties at intermediate x and high Q^2 at CDF and HERA. Searches for new physics in high energy electron-proton and proton-antiproton collisions were limited by these PDF uncertainties, since some cross sections could be accounted for by introducing Toy Model PDFs which are higher at larger x.

(8) The ratio of the d and u quark distributions was only extracted from the ratio of muon and electron scattering on neutrons and protons. Since the neutrons are bound in deuterium, the uncertainty in deuteron binding corrections results in an uncertainty in the ratio of d and u PDFs. This uncertainty led to an irreducible uncertainty of 75 MeV (from PDF errors) in the measurement of the mass of the W boson when extracted from data in high energy proton-antiproton collisions.

9. Physics Archeology -Lepton Scattering on Nuclear Targets

During the twenty year period from 1980 to 2000, much of my efforts were directed towards the construction of new detectors (e.g. the Lab E Neutrino facility at Fermilab, the AMY muon detector, SLAC E140, the CDF plug upgrade calorimeter and the CMS HCAL calorimeter. However, one of my physics hobbies was

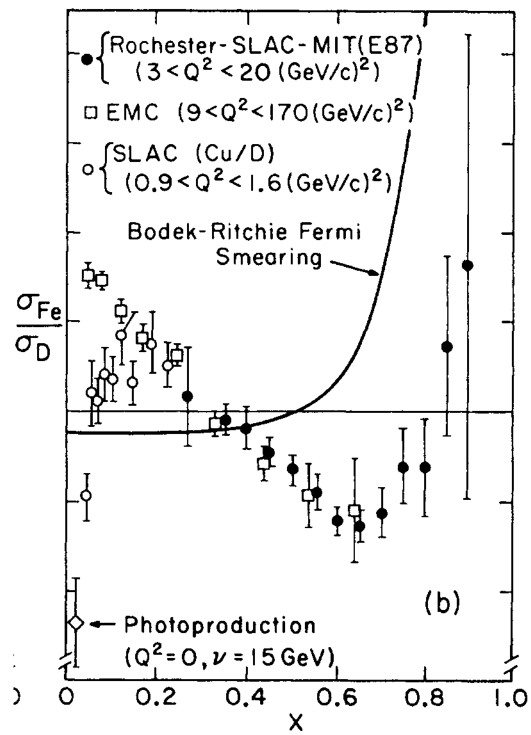

Figure 11. The x dependence of iron to deuterium ratio extracted from MIT-SLAC Empty Target Data [18] compared to the results initially reported by the EMC collaboration.

to resolve experimental discrepancies by improving on the precision of experiments. It is known that techniques used in one subfield of high energy physics can sometimes make a large impact whey introduced to another subfield. The solutions frequently involved a combination of new measurements at different laboratories, different beams, new experimental detectors and techniques, higher precision, better theoretical tools, and some phenomenology.

First, I tried get an independent measurement of the ratio of iron and deuterium structure functions, in view of the surprising results reported by the EMC muon collaboration. I called the members Group A at SLAC and asked if they could look at their more recent empty target data. It turned out that that data was not readily available. Since I could not convince somebody else to do the measurement, I decided to do it myself. I went back and did a re-analysis of my own empty target data taken in the original MIT-SLAC Experiments (E849 and E87). The extraction of the MIT-SLAC empty target data [17] (after more than a decade) was an exercise in Physics Archeology (or a study of the quickly changing standards and media of computer technology). The analysis was greatly simplified by the fact that in the 1970's (at my suggestion [17]), the H and D empty target replicas at SLAC were made six times thicker. The thicker empty replicas had the same radiation length as the D and H targets. This meant that to first order, the radiative corrections for the full and empty targets were the same. In addition, more statistics could be taken with the thicker replicas. This re-analysis was completed within a few months of the announcement of the EMC results. New electron scattering results on the ratio of iron to deuterium [18] (and also on the ratio of aluminum to deuterium [19]) structure functions were submitted for publication to Physical Review Letters. This ratio, which has since become known as the EMC effect, was actually found to be in disagreement with the initial results reported by EMC, as shown in figure Figure 11. At small x, the electron data showed a ratio of iron to deuterium that was actually less than 1.0, which indicated effects of shadowing (in contrast to the EMC muon data which showed a ratio of 1.1). At x values between 0.1 to 0.2, the electron data showed a small amount of antishadowing (of order a couple of percent). At larger x, the electron data showed that ratio became less than 1.0. Finally, for x greater than 0.7, Fermi motion effects take over and the ratio is larger than 1.0. It is interesting to note that the only reason this was not noticed in the early MIT-SLAC data was that the first experiment to look for nuclear effects was performed near x=0.1, where the effect just happened to be small (at the time, vector dominance model predicted a large effect at x=0.1). Similarly, the first test of scaling was done at SLAC at x=0.2, which also happens to be the region where the scaling violations are also the smallest.

The mistake in the EMC data at small x was later found to originate from a tracking inefficiency for deuterium running. This was from extra hits in the forward chambers that were less shielded when the lower density deuterium target was used. Later measurements taken by EMC, BCDMS and NMC (New Muon Collaboration) were in good agreement with our new electron scattering results.

We discovered that the nuclear binding effects were more complicated than calculations which only include the effects of Fermi motion. We have found out that there are contributions from shadowing, anti-shadowing, binding energy effect and Fermi motion, all contributing in different regions of x. Therefore, both the initial EMC experimental results, and the Fermi motion model of Bodek and Ritchie were found to be incorrect.

We submitted the first paper on the extraction of the ratio of iron to deuterium [18] from the MIT-SLAC data to Physical Review Letters. To my surprise the paper was first rejected. One referee said that there was no evidence for quarks in nuclei (contrary to the referees in 1973 who rejected a paper because the evidence for quarks was already overwhelming). The second referee said that the effect was expected from the multiple scattering of the electron beam in the nucleus. By that time I was an seasoned faculty member, and I convinced the editors to ignore the comments of both referees. The results were published in Physical Review Letters [18,19].

10. The End Station A SLAC/NPAS E139/E140 Program - a new collaborative effort between the High Energy and Nuclear Physics Community

To the high energy physics community, it was important to understand nuclear corrections in order to convert data for lepton scattering on nuclear targets to data for free nucleons (or at least deuterium). To the nuclear physics community, it presented a new tool to investigate a new type nuclear effects.

By that time, aside from Parity Violation experiments (for which Charlie Prescott received the Panofsky Prize) the high energy physics community was not heavily involved the electron scat-

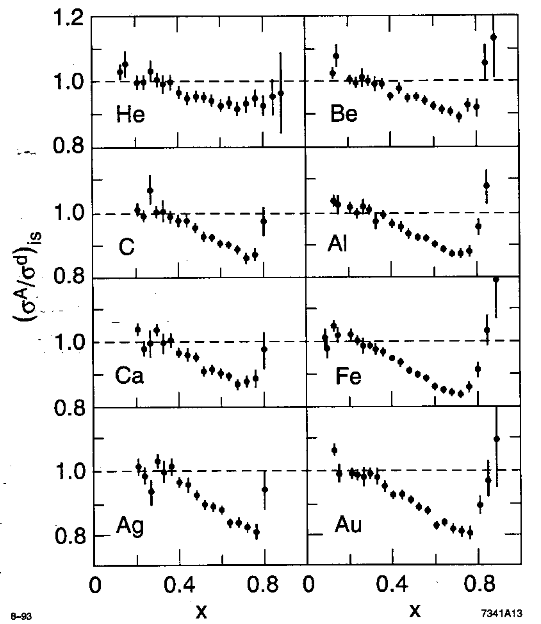

Figure 12. A determination of the ratio of cross sections on various nuclear targets to deuterium [20] from SLAC experiment E139.

tering program at End Station A. However, electron scattering experiments by members of the nuclear physics community continued. The SLAC station A electron scattering facility at SLAC was used to do a variety of nuclear physics experiments (e.g. measurement of elastic form factors of deuterium and other nuclei). This program was supported by the Nuclear Physics Divisions of DOE and NSF. A dedicated lower energy nuclear physics (NPAS) injector was built to provide low energy beams for nuclear physics applications. The NPAS nuclear physics program was managed by Ray Arnold, Steve Rock and Peter Bosted from American University. (Ray Arnold received the APS Bonner Prize in Experimental Nuclear Physics for his leadership of the NPAS program.)

The publication of the results of the re-analysis of the SLAC empty target data presented a new opportunity (for both the nuclear physics and high energy communities) to embark on a collaborative program of third generation precision electron scattering experiments. As discussed below, measurements that were not possible before could now be done with much better precision. These new higher precision electron scattering experiments would lead to a better understanding of both nucleon and nuclear structure.

At first, the End Station A SLAC 8-GeV spectrometer was used for a new SLAC experiment E139 without major modifications. Experiment E139 performed a survey of the ratio of structure functions taken on a variety of nuclear targets to that of deuterium [20]. In parallel we proposed SLAC experiment E140 for a new precision electron scattering deep inelastic scattering program on both nucleons and nuclear targets.

As part of the new SLAC E140 program (Arie Bodek and Steve Rock, co-spokespersons) the SLAC end station A 8 GeV spectrometer was upgraded for better electron/pion discrimnation using a new lead glass segmented shower counters, and an improved Cerenkov counter with UV wavelength shifting phototobes. We also upgraded the electronics improved monitoring to control beam systematics. Since beam time at SLAC was very costly, we introduced the technique (previously used in the CCFR neutrino experiment at Fermilab), to check out and time-in the detectors (in place) using cosmic ray muons.

In parallel, we undertook both an experimental and theoretical program to improve the radiative corrections. The external radiative corrections were investigated with radiation length targets ranging from 2% to 12%. It took a while to improve the radiative corrections to obtain agreement for the data from all target thickness, and the use of thicker (higher statistics) 6% radiation length target became routine. (we also had to bo back and re-correct the results of SLAC E139 by one percent, as a results of the improved radiative corrections).

The internal radiative corrections were also improved by comparing two very different approaches (the Mo-Tsai procedure and the Bardin procedure). By investigating the similarities and differences between the two approaches, improvements were made and agreement between the two approaches was achieved. Since the Bardin calculation also included electro-weak corrections (im-

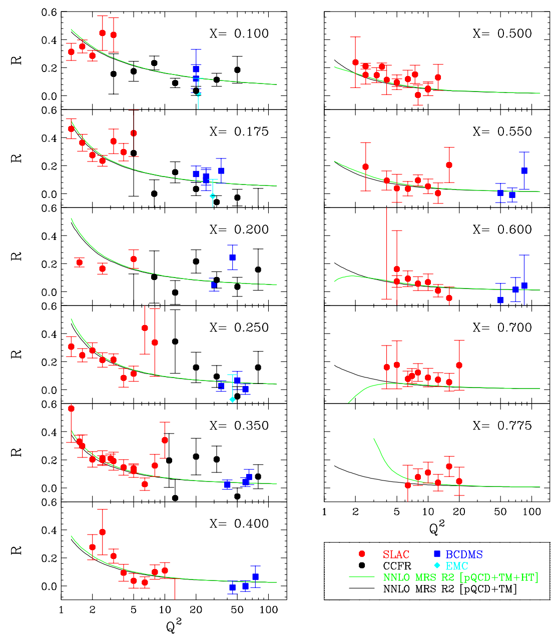

Figure 13. Precise data [21] on $R = \sigma_L/\sigma_T$ taken by SLAC E140 as compared to subsequent data taken by third generation neutrino (CCFR/NuTeV) [14] and muon experiments

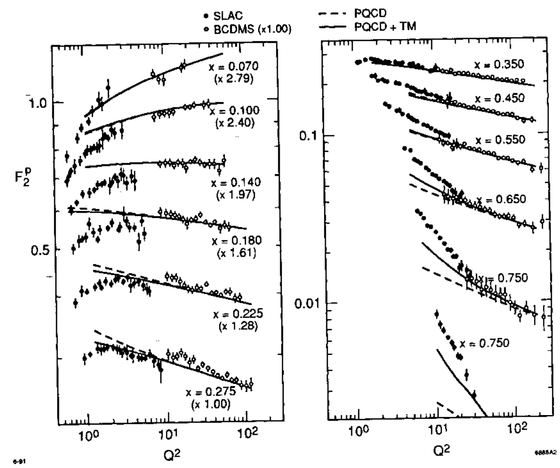

Figure 14. The initial results from the SLAC E140/combined SLAC analysis [21] indicating the the systematic errors in QCD fits that only included the data from the higher energy experiments (compare these fits to the improved post-E140 analysis in Figure 18.

portant for neutrino and higher energy muon experiment) it became the standard for all of the next generation electron, muon and neutrino scattering experiments.

In SLAC experiment E140 we preformed much more precise measurements [21] of $R = \sigma_L/\sigma_T$ and F_2. These data were the PhD thesis topic of Rochester graduate student S. Dasu (now a faculty member at Madison). SLAC Experiment E140 also took additional data in regions that overlapped with previous electron scattering experiments at SLAC. These previous SLAC experiments were then re-analyzed with the improved radiative corrections program (for both external and internal radiation), and cross normalized to SLAC E140. This was the PhD thesis topic of W. Whittlow, from Stanford. The following are highlights of results from the SLAC E139/E140 program and the new combined re-analysis of all previous data:

(1) Provided precise ratios of structure functions for heavy targets to that of deuterium [20] (see Figure 12). Now all data taken with nuclear targets could be used in PDF fits.

(2) Extracted the first precise determinations of the x and Q^2 dependence of $R = \sigma_L/\sigma_T$, the ration of longitudinal and transverse structure functions [21]. The parametrization of these and other data (called R_{wolrd}) was subsequently used for the extraction of the structure function F_2 by higher energy muon and neutrino scattering experiments. This greatly reduced the errors on the extracted structure functions from the previously poor knowledge of R (see Figure 13).

(3) Established that the nuclear dependence of $R = \sigma_L/\sigma_T$ was small, and provided the nuclear corrections for the structure function F_2 for a wide range of nuclear targets used in muon and neutrino experiments.

(4) Provided a better understanding of radiative corrections for both nucleon and nuclear targets for both past (E49, E87, E139) and future lepton scattering experiments.

(5) Provided a high precision anchor for the

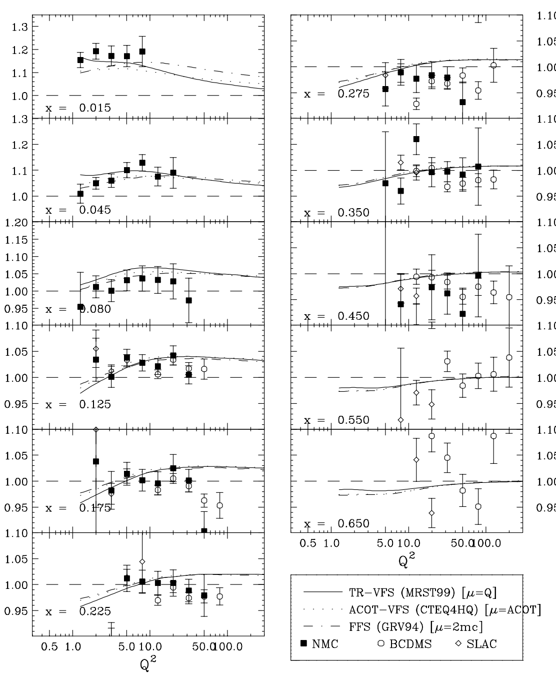

Figure 15. The ratio of neutrino [14] and muon structure functions as compared to the expectations from NLO QCD.

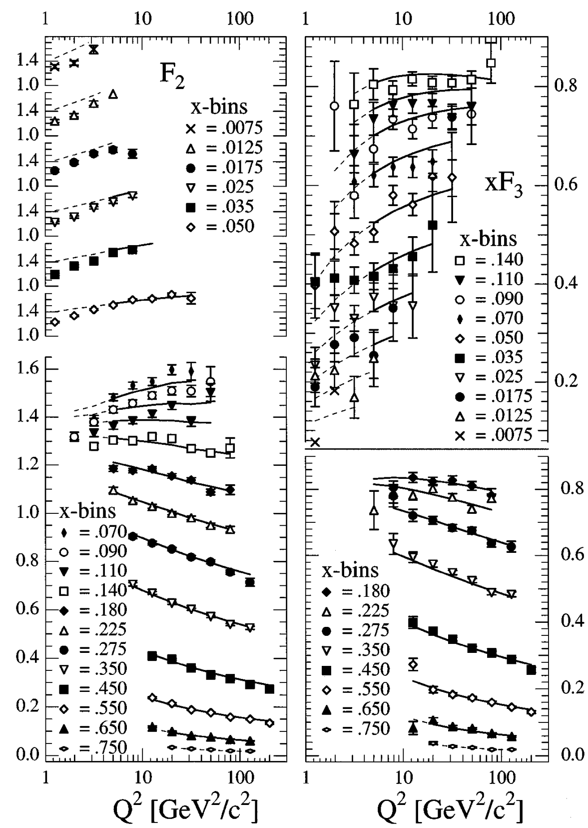

Figure 16. The QCD fit for the improved extraction [12] of the strong interaction coupling α_S from CCFR structure function F_2.

normalized F_2 structure functions at low Q^2 for a wide range of x. By matching the structure functions between SLAC and the higher energy muon and neutrino experiments in the overlap region, better determinations of the normalizations and systematic errors of the higher energy experiments could be done (see a comparison of Figure 14 (before) and Figure 18 (after)). This resulted in greatly improved determination of α_S and help resolve the difference between the value of α_S from DIS (electron/Muon) and e+e- experiments (the e+e- results were correct).

(6) Led to new program of precision electron scattering experiments at End Station A at SLAC in advance of the construction of the facilities at Jefferson Lab.

11. Reducing Systematics

A comparison between the precise SLAC data and the high energy muon scattering data showed that there was a larger systematic error in the BCDMS magnetic field. Once this was corrected, there was better agreement between the BCDMS data and other experiments (both for the structure function and for the value of the extracted strong interaction coupling constant α_S). With improved hadron energy calibrations and by extracting structure functions from the CCFR neutrino data in a more model independent way (e.g. Rosenbluth separation), the difference in the structure functions in muon and neutrino experiments at low values of x has been resolved, and new measurements of R at higher values of Q^2 became available. This work is reported in the PhD thesis of Rochester graduate student Un Ki Yang [14] (now at the University of Chicago). The ratio of neutrino [14] and muon structure functions now agrees with the expectations from NLO QCD (as shown in figure 15. Figure 13 shows both our new Rosenbluth separated CCFR measurement of R with neutrinos as compared to our previous measurements with electrons [21] from the combined SLAC/E140 analysis.

With additional improvements in the hadron energy calibration [10] for the CCFR detector (thanks to Un Ki Yang, Willis Sakumoto, Debbie Harris and J. Yu) the strong interaction coupling constant was extracted from the Q^2 dependence CCFR neutrino [12] data on F_2 and xF_3 (at large Q^2) shown in figure 16. The extracted value is $\alpha_S(M_z)$= 0.119 ± 0.002(expt) ± 0.004(theory). In addition, an independent measurement $\alpha_S(M_z)$ =0.114 ± 0.009 was extracted from the Q^2 dependence (at low Q^2) of the GLS sum rule, using the CCFR data on the structure function [13] F_3 shown in figure 17. Both of these measurements are in agreement with data from electron-positron colliders (the e+e- results were correct).

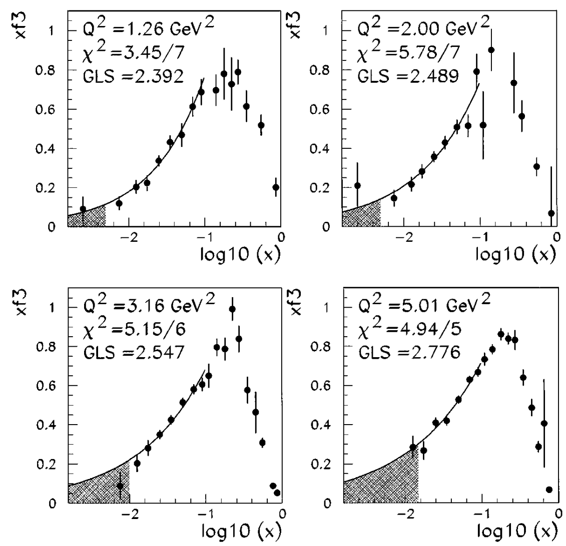

Figure 17. An independent extraction of the strong interaction coupling α_S from the Q^2 dependence of the GLS sum rule evaluated [13] using the CCFR structure function F_3.

12. The High Energy Frontier, d/u, W Charge Assymmetry and Production of W, Z bosons and Drell-Yan pairs in Proton-Antiproton Collisions at 2 TeV

As mentioned earlier, the ratio of the d and u quark distributions is extracted from the ratio of muon and electron scattering on neutrons and protons. Since the neutrons are bound in deuterium, the uncertainty in deuteron binding corrections leads to an uncertainty in the ratio of d and u PDFs. This uncertainty led to an irreducible uncertainty of 75 MeV (from PDF errors) in the measurement of the mass of the W boson when extracted from data in high energy proton-antiproton collisions.

This issue was resolved in two different ways. First we have done some work on improved modeling of the nuclear binding effects in the deuteron [29]. More importantly, we also embarked on a new experimental approach. Higher precision on PDFs can be achieved by introducing new techniques and new measurements in proton-antiproton collisions. Since proton and antiprotons are free nucleons, the production of W and Z Bosons measures and constrains [22] the d and u quark distributions without the complication of nuclear effects.

Figure 19 shows the relationship between the kinematic variables for production of W and Z Bosons and the initial fraction of the proton and antiproton momentum carried by the interacting quark and antiquark. Figure 21 shows that since the d quark distribution falls more steeply with x than the u quark distribution, the positive and negatively charged W bosons are boosted in opposite directions with respect to the beam axis. However, only the W decay final state leptons are detected, as shown in Figure 20. The well-understood V-A asymmetry in the decay of the W Boson tends to partially cancel and convolute the asymmetry from the production process as shown in Figure 22.

In order to have sensitivity to the d and u quark distribution which contribute to initial W production asymmetry, the electrons and positrons from W decays must be measured over a wide range of rapidity, including the very forward direction. Initially, a measurement in the forward direction was not possible in CDF, since the central tracker covered a limited range of rapidity around the central region. We therefore introduced a new technique [25] (which we first used in the AMY e+e- exxperiment) to measure both the charge and energy of electrons and positrons in the forward plug calorimeter with very high precision. This was accomplished by doing a combined analysis between the track of the electron in the silicon tracker (SVX) and the location of the centroid of the electromagnetic shower in the plug calorimeter. The energy of the electron or positron was measured very well by the calorimeter. The sign of the lepton was determined by seeing if the shower centroid in plug calorimeter was to the left or right of the extrapolated track from the vertex silicon tracker. This resulted in a measurement of the W decay lepton asymmetry [23] as shown in Figure 24. The new data indicated that the d/u ratio in the proton was lower than that from the best PDF fits available

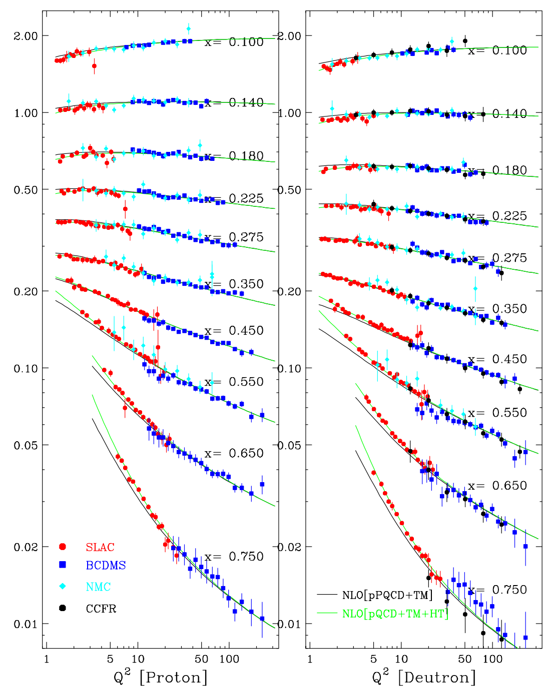

Figure 18. Post SLAC E140 status. [29] The NLO QCD plus target mass fits (with and without renormalon higher twist correction) by Bodek and Yang. The new determinations of R from the SLAC E140 program are now used by the higher energy experiments. In addition, the normalizations of the higher energy experiments and the BCDMS systematic error on the magnetic field were allowed to float and be constrained by the overall fit. (Compare these improved fits to the pre-SLAC E140 fits shown in Figure 14).

$$x_1 x_2 = \frac{M_W^2}{s}$$

$$x_1 - x_2 = x_W,$$

$$x_{1,2} = \frac{M_W}{\sqrt{s}} e^{\pm y}.$$

Figure 19. Kinematics of W production in proton-antiproton collisions. [23]

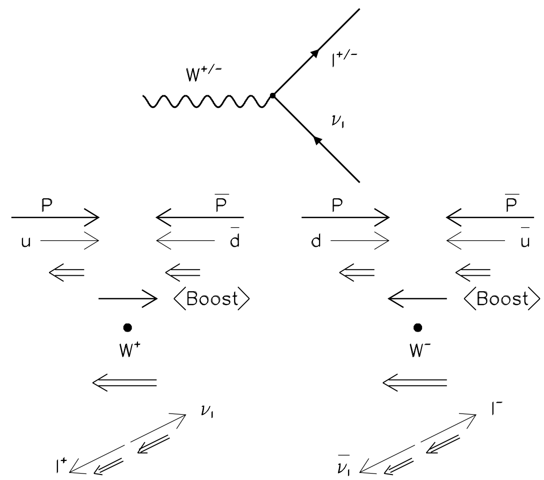

Figure 20. Kinematics of W Production and Decay

at the time.

In addition, the improved deuteron binding corrections and the re-extraction of $d/$ by Bodek and Yang from muon scattering data at high Q^2 were in agreement with previously improved re-extraction of (d/u) from the lower Q^2 MIT-SLAC H and D electron scattering data (A. Thomas and collaborators). Both of these re-extractions indicated that at large values of x, d/u approaches a value of 0.2 (in agreement with expectations from QCD), instead of a value of 0 which has been assumed by previous PDF prametrizations. Some hints this (though with large errors) are also found in neutrino data on hydrogen and charged current data at HERAc̃itelargex

The d/u ratio extracted from the W asymmetry data was in better agreement with d/u ratio extracted from deuterium data with improved corrections for nuclear binding effects [29]. Subsequently, both the W asymmetry data and deutron binding effects are used in modern fits to PDFs. The uncertainties in the d/u ratio are greatly reduced and allow for a more precise measurement of the W mass. The analysis of the W asymmetry data was the subject of the PhD Theses [23] of two Rochester graduate students, Mark Dickson (now at MIT Lincoln Lab) and Qun Fan (now at KLA-Tenor in California).

The W charge asymmetry was also used to put stringent limits on models which proposed isospin charge symmetry violation in the nucleon PDFs [24] as shown in Figure 25.

We have also found that doing physics with electrons and positrons in hadron collider by using only silicon vertex tracking in conjunction with segmented electromagnetic calorimetry is actually better than using a central tracker [25]. We found that the the central tracker has a higher charge misidentification rate because it is more sensitive to conversions of gamma rays. It is interesting to note that the CMS collaboration at the LHC has decided to eliminate their central tracker and use a pure silicon system instead.

This new technique also allowed for the measurement of the rapidity distributions of Z Bosons at high rapidity as shown in Figure 26. This was the PhD thesis topic of Rochester graduate student Jinbo Liu [26] (now at Lucent).

We have since used this technique to greatly reduce the jet background and measure the mass and forward-backward charge asymmetry of Z

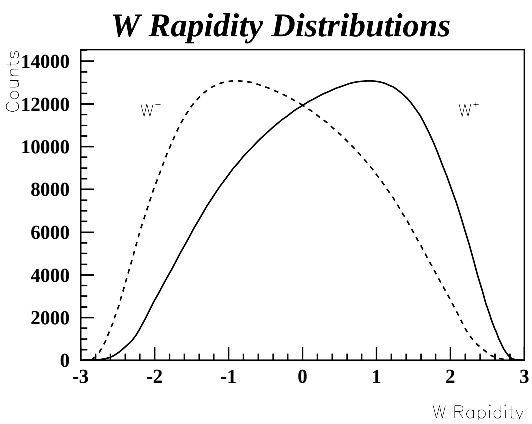

Figure 21. The expected asymmetry in the rapidity distribution for the production of positive and negative W boson in proton-antiproton collisions at CDF [23].

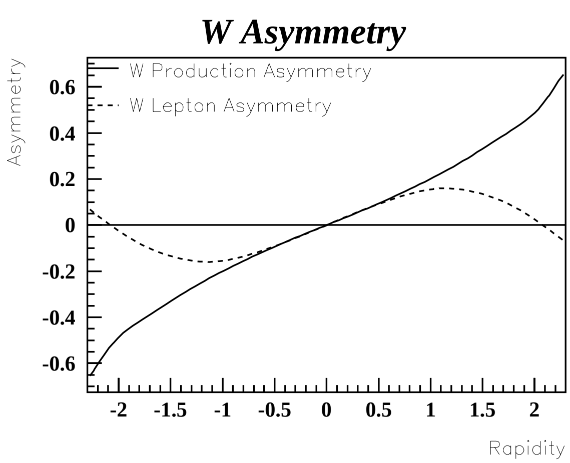

Figure 22. A comparison of the W production Asymmetry and the assymetry of the W decay leptons [23]

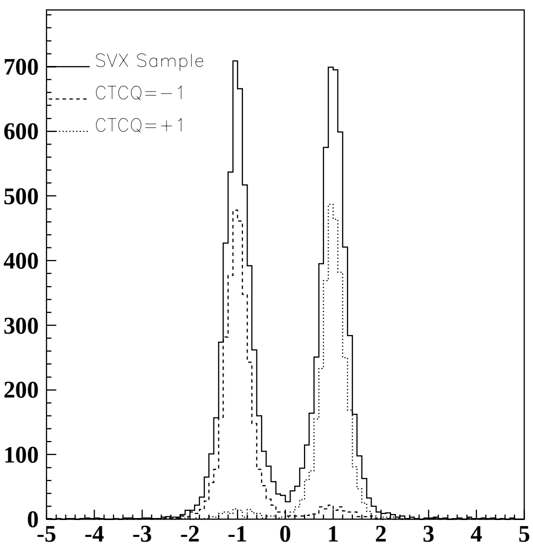

Figure 23. A comparison between the extrapolated track in the CDF Silicon SVX vertex detector and the location of the centroid of the electromangetic shower in the CDF electromagnetic calorimeter. This illustrates the discrimination between positive and negative electrons (from A. Bodek and Qun Fan, Frascati Calorimetry Conference [25]).

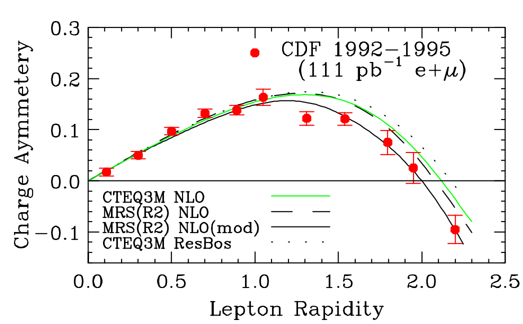

Figure 24. A comparison of the CDF W Asymmetry data [23] with the prediction of PDFs with different assumptions for the d/u ratio.

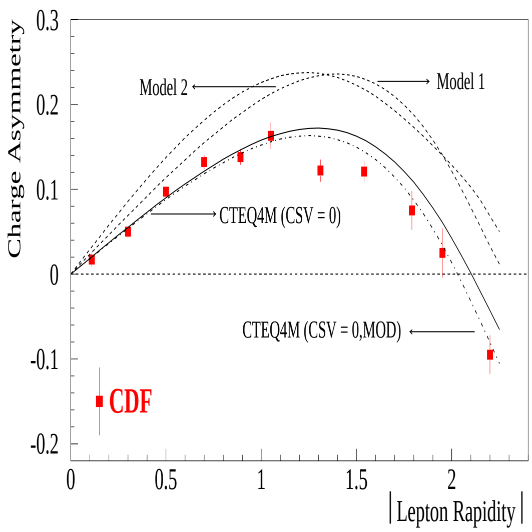

Figure 25. A comparison of the CDF W Asymmetry data [23] with prediction from models proposing PDFs with Isospin Charge Symmetry Violation (CSV) in the nucleon. These models were ruled out [24].

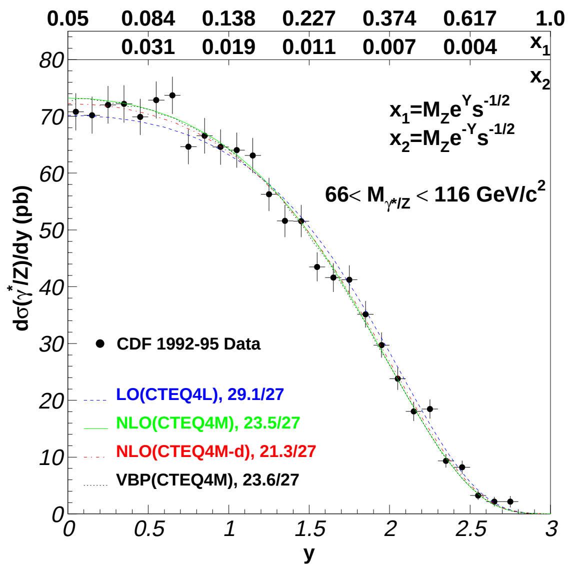

Figure 26. A measurement of the full rapidity distribution [26] of Z bosons by including final states with both electrons detected the CDF plug calorimeter.

Bosons and high mass Drell-Yan dilepton pairs. The Drell-Yan asymmetry is a sensitive way to search for new physics beyond the standard model (e.g. high mass Z' Bosons). Figure 27 shows the CDF Drell-Yan data from run I, compared to a calculation by Baur and Bodek [27] (with and without a hypothetical Z' Boson. (The CDF analysis for the forward-backward asymmetry was done by Rochester postdoc Yonsei-Chung [28].

With a factor of 10 more data currently being accumulated in Tevatron II, the W Asymmetry data and the Z rapidity distribution will make a significant contribution to constrain the PDFs with even higher precision. Precise PDFs are used to predict the expected level of high mass Drell-Yan events. Therefore, searches for new states are possible in both the differential cross section (versus mass) and the forward-backward asymmetry for Drell-Yan dilepton pairs.

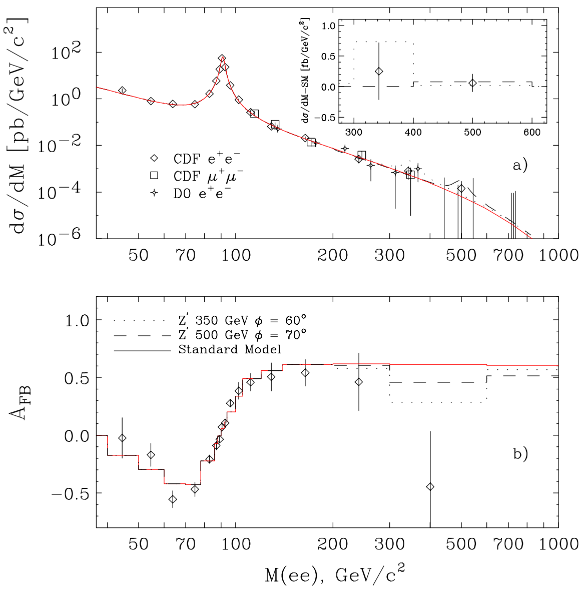

Figure 27. The mass and forward-backward asymmetry of Drell-Yan lepton pairs at CDF [27](including events with one electron in the forward plug calorimeter) as compared to the predictions of the standard model and a model with an extra Z boson.

13. More Phenomenology- The Triumph of NNLO QCD, Origin Twist Effects, and PDFs at large x

Although the lower energy electron scattering data was very precise, it was clear that in order to use it in the overall PDF QCD fits, one must account for effects such as target mass and dynamical higher twist. In particular, the only data available at large x is the electron-scattering data from SLAC.

The effects of target mass could be included using the formalism of Georgi and Politzer. The dynamical higher twist effects was another issue. It was known that some dynamical higher twist effects (power corrections) originate from the truncation of the QCD calculations to finite orders; i.e. the sum of the missing higher order QCD corrections adds up to a power series in $1/Q^2$. The x dependence of the $1/Q^2$ and $1/Q^4$ QCD renormalon power corrections was calculated, but the overall multiplative factors a_2 and a_4 were not predicted. However, the factors were expected to become smaller as one goes from LO to NLO to NNLO. Therefore, if the target-mass and higher order QCD terms were included, parton distribution functions extracted from high Q^2 data could be evolved backwards and compared to the lower energy SLAC data. A comparison of the QCD predictions for F_2 and $R = \sigma_L/\sigma_T$ (in LO, NLO and NNLO) to the data would allow one to extract the magnitude of higher twist multiplicative factors a_2 and a_4. This work was done in a series of papers [29,4] by A. Bodek and Un-Ki Yang, a Rochester graduate student who completed his thesis on CCFR/NuTeV and included some of this work in his PhD thesis [14]. Figure 18 shows the fits in NLO, and the extracted higher twist coeficients. Figure 28 shows the comparison of QCD in NLO, QCD plus target mass, and QCD plus target mass and higher twist to SLAC data at very high x for $Q^2 = 20\ GeV/C^2$. These very high x data were not included in the fits that extracted the higher twist coefficients in NLO. These results [29] show that at high x, the target mass corrections must be applied, and that the contribution of higher twists is much smaller. It appears that NLO QCD PDFs with target mass and a small higher twist term describe all of the data up to x=0.9. The high x PDFs are now constrained by these very high x SLAC data. We repeated [4] the study in NNLO QCD. Figure 2 shows the comparison of the NNLO QCD fits (including target mass) to the data. It appears that NNLO QCD (with the addition of target mass corrections) works very well for all data above $Q^2 = 1\ GeV/C^2$ without the need for any dynamical higher twist correction. In summary, we expect NNLO QCD to work very well, and the need for higher twist corrections in the NLO QCD case came mostly from dropping the higher order NNLO terms.

Note that although the Q^2 dependence of structure functions has been calculated to NNLO in QCD, NNLO PDFs were not yet available for the calculations. Figure 29 shows the small correction factors that were needed to fit the data in the NLO and NNLO analyses. The ratio of

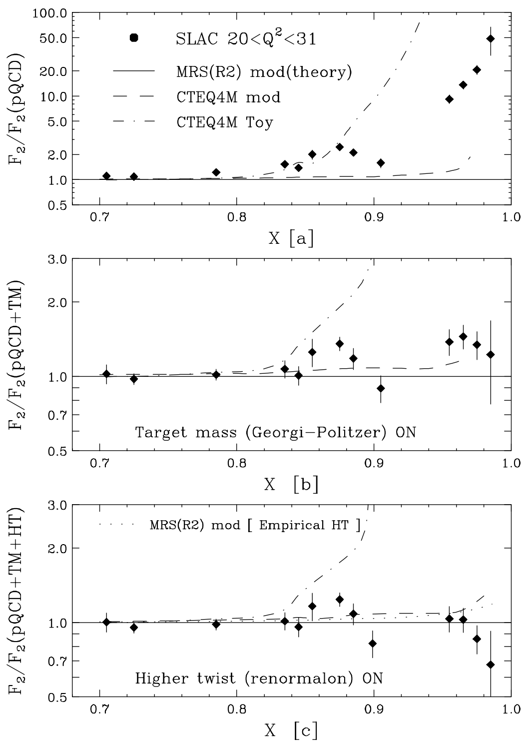

Figure 28. Comparison of SLAC F_{2p} data at high x with the NLO QCD predictions using the modied MRS(R2), CTEQ4M and the CTEQ toy model at high x and higher Q^2 ($20 < Q^2 < 31 GeV^2$). (a) Ratio to pQCD only, (b) ratio to pQCD with TM effects only, and (c) ratio to pQCD with TM and Renormalon higher twist contributions (the ratio of empirical to renormalon higher twist is also shown) [29].

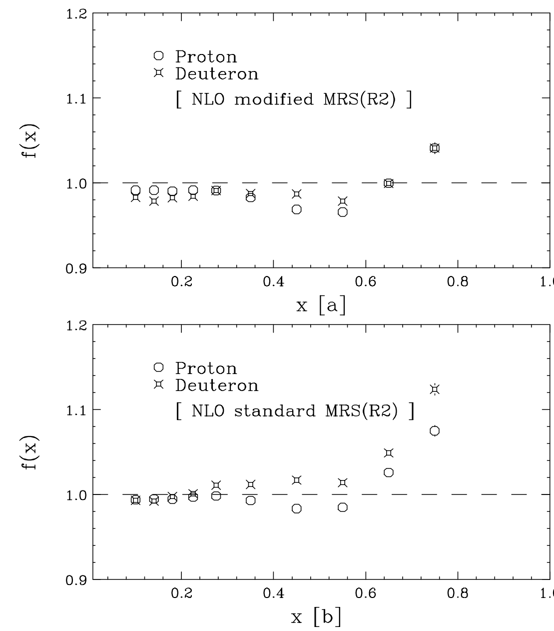

Figure 29. (a) The floating factor $f^{NLO}(x)$ as a function of x extracted from the NLO analysis with the d-quark modifed MRS(R2) PDFs, (b) The floating factor$f^{NNLO}(x)$) extracted with the standard MRS(R2) PDFs. The larger extracted floating factors for the deuteron than for the proton indicate that the d quark distribution at high x is underestimated in the standard MRS(R2) PDFs. The ratio of the floating factors in NNLO to NLO gives the ratio of NNLO to NLO PDFs. [4]

the fitted floating factors for NNLO and NLO is identified with the ratio of NNLO to NLO PDFs. Therefore, this was the first estimate of NNLO PDFs. Subsequently the work on NNLO PDFs was continued by the MRST PDF group (who obtained similar results). In summary, our conclusions are that QCD NNLO calculations should work quite well in hadron colliders, and current PDFs are well understood over a very large range in x and Q^2. This is indeed very good news for the next generation hadron colliders at Fermilab and CERN.

14. Back to the Future, Neutrino Physics, Phenomenology and the Low Energy Frontier at NUMI and Jefferson Lab

Well, we thought we had everything covered, i.e. all we need to do was QCD calculations in NNLO, and look for physics beyond the standard model in the next generation of hadron colliders. However, the energy frontier in particle physics is currently also at low energies.

Because the neutrino masses are so small, neutrino oscillations, neutrino mass and neutrino mixing can only be investigated with low energy neutrino beams. Current (K2K, SuperK,MiniBoone, MINOS) and future (next generation) neutrino oscillations experiments (JPARC, NOvA,Grand Sasso) require the understanding of quasielastic, resonance and the deep inelastic regions for incident neutrino energies in the 0.4 to 5 GeV range. However perturbative QCD NLO and NNLO calculations are not valid very low Q^2.

Therefore, we first embarked on a phenomenological study of this energy region using existing neutrino and electron scattering data. For quasielastic scattering, I have recently been working with Howard Budd (Rochester) and John Arrington (Argonne) on improved understanding of elastic vector and axial form factors [30]. We found that the old extractions of the axial form factor of the nucleon from neutrino data used outdated vector form factors. We recently completed a re-analysis of the old neutrino results using up to date modern vector form factors.

Most recently, I have continued to work with Yang on the modeling [31] of vector and axial structure functions for resonance and production and inelastic scattering at low energies. In our previous work we managed to finally remove all higher twist corrections by using NNLO QCD (plus target mass) calculations at higher energy.

In contrast, in the very low energy region we need to do the reverse (since the NNLO terms just blow up). Our approach at low energies is to use *leading order* QCD PDFs and include higher twist efforts. Here we model the non-perturbative effects with a new scaling variable, and with effective target-mass and higher twist corrections.

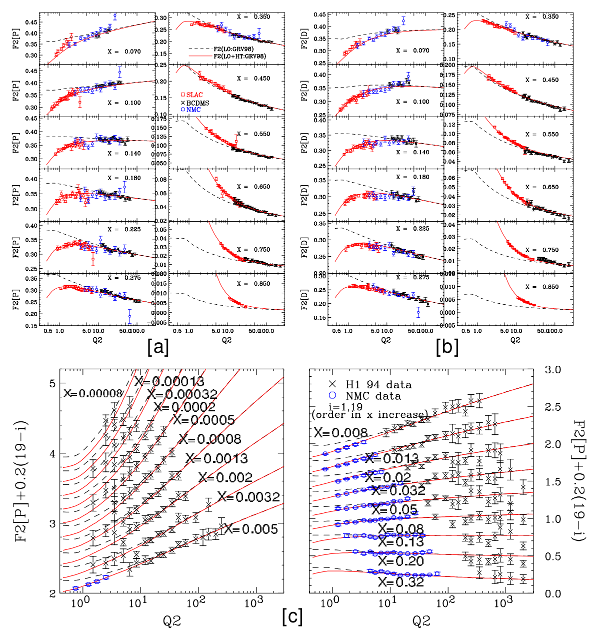

Figure 30. Electron and muon F_2 data (SLAC, BCDMS, NMC, H1 94) used in our [31] GRV98 ξ_w fit compared to the predictions of the unmodified GRV98 PDFs (LO, dashed line) and the modified GRV98 PDFs fits (LO+HT, solid line); [a] for F_2 proton, [b] for F_2 deuteron, and [c] for the H1 and NMC proton data at low x.

This approach works well all the way down to $Q^2 = 0$.

We have derived a new scaling variable to effectively account for both target-mass effects and higher-twist effects. In addition, we have applied additional corrections to the PDF which are motivated by the Adler Sum rule. The Adler sum rule is a current algebra sum rule that is valid at all values of Q^2, down to $Q^2 = 0$. Figures 30, 31, and 32 show a comparison of how these modifications to the standard GRV98 PDFs describe existing electron scattering data both at very high and at very low energies. In addition, from duality arguments, the modified PDFs also describe electron scattering data in the resonance region on average.

Although we have had good success in modeling vector structure functions at low energies, the axial structure functions at low energies are not well known. In addition, the vector structure functions and $R = \sigma_L/\sigma_T$ in the resonance region (for nuclear targets, which are used in neutrino experiments) need to be better measured.

At present, two experimental programs at Jefferson Laboratory [33] and at Fermilab [32]) have been approved for a collaborative effort in measuring vector and axial form factors and structure functions at low energies (with both electron and neutrino beams on nuclear targets. The experiments will investigate current algebra sum rules, QCD sum rules, duality, resonance production and axial form factors and structure functions. The JUPITER (A. Bodek and C. Keppel, spokespersons) and MINERvA (K. McFarland and J. Morfin, spokespersons) experiments will improve the understanding of neutrino cross sections at low energies, which is essential for the next generation neutrino oscillations experiments at Fermilab, Japan and Europe.

15. Final comments and outlook for the future

There is an increasing misapplication of a technique known as "Blind Analysis". None of the physics in the field of nucleon structure was ever discovered or resolved in a *blind* analysis. Understanding the physics of nucleon structure *looking*

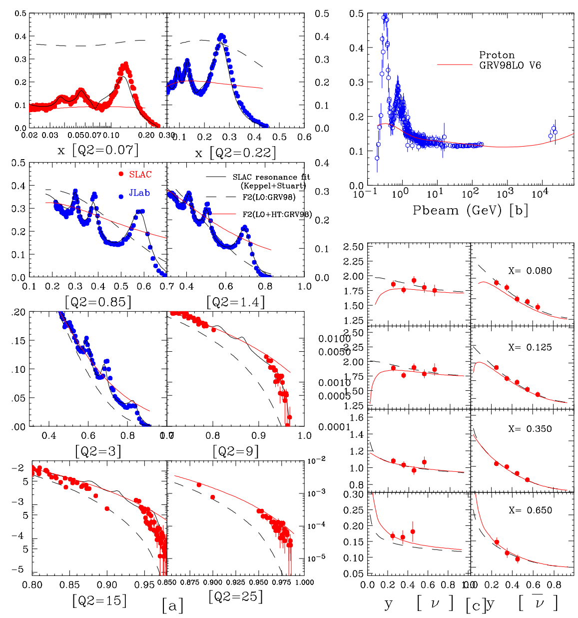

Figure 31. Comparisons to proton and iron data not included in our [31] GRV98 ξ_w fit. (a) Comparison of SLAC and JLab (electron) F_{2p} data in the resonance region (or fits to these data) and the predictions of the GRV98 PDFs with (LO+HT, solid) and without (LO, dashed) our modifications. (b) Comparison of photoproduction data on protons to predictions using our modified GRV98 PDFs. (c) Comparison of representative CCFR ν_μ and $\overline{\nu}_\mu$ charged-current differential cross sections [14] on iron at 55 GeV and the predictions of the GRV98 PDFs with (LO+HT, solid) and without (LO, dashed) our modifications.

at all kinds of data, with different beams and different probes and different final states. Most of the time the effects that are important have not been thought of (and are not in the Monte Carlo). If one uses "blind analysis" as a standard when one is looking at new data for the first time, the mostly likely outcomes are that new insights are missed (since not all the data is being looked at), or poor limits are obtained (when one was not clever enough to put all backrounds in the Monte Carlo in advance). A blind analysis should only be used on very rare occasions (e.g. in a fourth generation experiment, when one has already done the experiment several times, has results, and is now running for the last time). As long as more data is being accumulated (e.g. in Tevatron run II), there will always be another independent data set six months later.

There is a bright outlook for the future. Spending time on one's physics hobbies can be very productive. Whatever appears to have been impossible, can become possible with a new idea. A complete understanding of all the physics processes involved in a measurement is a must (i.e. we have to understand what we are measuring). This requires a collaborative effort between experiment and theory/phenomenology (in four dimensions and here on earth). Both depth and breadth are important, and high precision is just as important as higher energies (especially as higher energy machines become more and more expensive). The good news is that there is a lot of of physics to be done using both the accelerators which are currently available, and accelerators which are currently under construction. New insights and techniques will surely be introduced in response to the challenges posed by new data.

The frontier in particle physics is open on both ends, at low energies and at high energies.

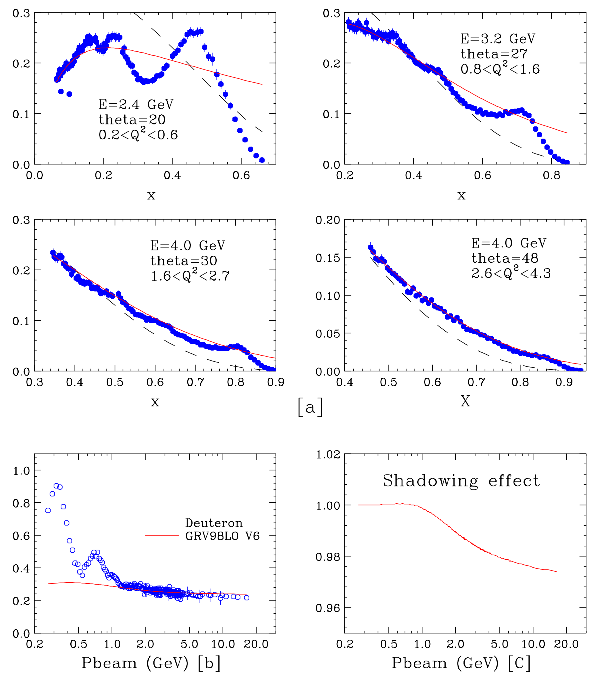

Figure 32. Comparisons to data on deuterium which were not included in our [31] GRV98 ξ_w fit. (a) Comparison of SLAC and JLab (electron) F_{2d} data in the resonance region and the predictions of the GRV98 PDFs with (LO+HT, solid) and without (LO, dashed) our modifications. (b) Comparison of photoproduction data on deuterium to predictions using our modified GRV98 PDFs (including shadowing corrections). (c) The shadowing corrections that were applied to the PDFs for predicting the photoproduction cross section on deuterium.

Since this is not meant to be a review of the field, I have only mentioned the topics in the area of nuclear structure to which I have personally contributed, and only the names of the Rochester PhD students with whom I have closely worked in those specific area. The list is not meant to be complete. I would also like to thank Rochester Senior Scientists Howard Budd, Pawel de Barbaro and Willis Sakumoto for their numerous contributions.

High energy physics is a collaborative group effort requiring the contributions of a large number of scientists from many institutions. I would like to take this opportunity to thank all other faculty, graduate students, and postdocs from a large number of institutions who made significant contributions to this important field.

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