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

Arie Bodek[a]

[a]Department of Physics and Astronomy, University of Rochester, Rochester, New York 14618, USA

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])

1. INTRODUCTION

In the early 1960's a large number of hadrons were discovered and studied at in proton and pion-nucleon scattering experiments. From elastic electron-nucleon scattering experiments, it was known that nucleons were composite and had a finite size. However, it did not appear that any of the hadrons were any more fundamental than all the other hadrons. There were multitude of theoretical models proposed to describe the spectroscopy of hardrons and the physics of lepton scattering from nucleons. Many of the experiments in mainstream particle physics was being done in hadron (proton) machines where new hadron resonances were being 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 various valid 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. During that period I was told by one of the leading theoretical physicist that any self-respecting theorist who actually used the quark model in any calculations, did it in the privacy of his own office. Later the calculations were translated into field-theoretic language before they were submitted for publication refereed journals. In summary prior to the MIT-SLAC electron-nucleon scattering experiments (1967-1973), many believed that quarks mathematical constructs and not be considered real particles.

Figure 1. Nobel Prize of 1990 Picture

Quarks became accepted as real particles during the 1967-74 perid 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 (1967-1974) 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)."

Figure 1 is taken from the Noble archives. It shows Richard Taylor, Jerome Friedman, Henry Kendall in the front row, and Arie Bodek, David

Coward, Michael Riordan, Elliott Bloom, James 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 those experiments can be found in a popular science book written by Michael Riodan [?]. Some of the graduate students who particpated in the the first and second generation MIT-SLAC experiments include Arie Bodek, Martin Briedenbach, Michael Riordan, Scott Poucher and R Ditzler (MIT), and Guthrie Miller and William Atwood (Stanford).

Soon thereafter the J/psi and Charm particles were discovered in hadron-nucleon and electron-positron experiments. A few years later the Upsilon and Bottom quarks in were discovered proton-nucleon and electron-positron experiments. A large number of experiments in the 1970's and 1980's were done at e+e- or hadron machines where the new charm and bottom mesons and hadrons were studied in great details. Again, a significant effort of effort in high energy physics was focussed on the study of spectroscopy, partial wave analysis, and new resonances. However, the new hadronics states that were being investigated were now composed of variety of quark flavors (up, down, strange, charm and bottom). In addition, neutral currents were discovered, the tau lepton was discovered and the standard model of electro-weak interactions became accepted. An addition, a significant of the experimental effort in particle physics is now also focused a variety of searches (non-discoveries or limit setting) for new particles such as Supersymmetry, Lepto-quarks, Higgs, Heavy Leptons.

Meawhile, in past thirty years, a segment of experimental high energy physics community continued (later joined by members of the nuclear physics community) continued to to make incremental progress in the study of nucleon structure. 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 Quantum Chromodynamics (QCD) in Next to Next to Leading Order (NNLO QCD) works very well from very low momentum tranfers (e.g. order of the proton mass) to the highest Q^2 values currently accessible in hadron colliders.[3] Like most advances in the field, progress in this area was accomplished by a combination of experiments at higher energies (e.g. accessible with new accelerators) and new experimental techniques. It was also essential to achieve higher precision in order for field to progress beyond the limitation (e.g. brick walls) of old techniques. In addition to higher Luminosities (more statistics) and experiments with different probes (new beams). new theoretical tools (better understanding of radiative corrections, QCD to higher orders) played an essential role.

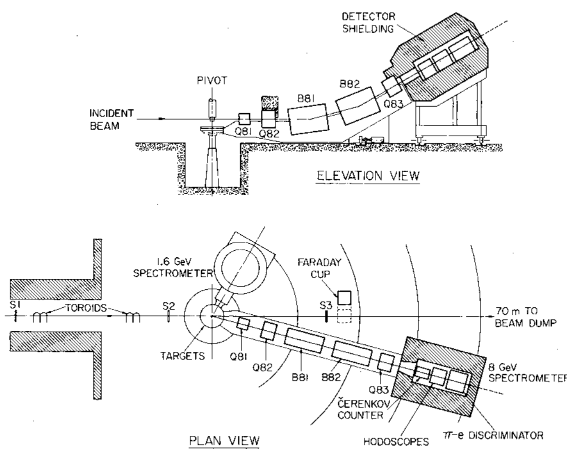

Figure 2. Experimental setup used in some of the electron-nucleon scattering experiments (e.g. E49B, E87, E139, E140) showing the SLAC 8-GeV spectrometer.

2. The MIT-SLAC Experiments

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. He said that this is because, as shown in Figure 2 the detector [8] looks very much like the Feynman diagram.

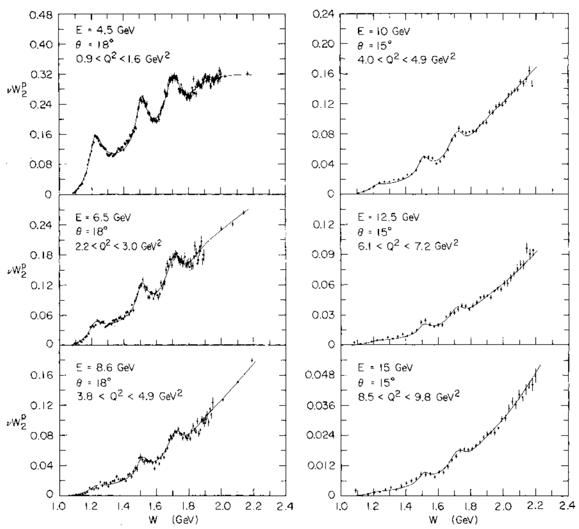

Figure 3. The Frank-Hertz and Rutherford Experiments of the Proton [8]

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

Figure 4. Current understanding of the structure of the nucleon in terms of point-like partons.

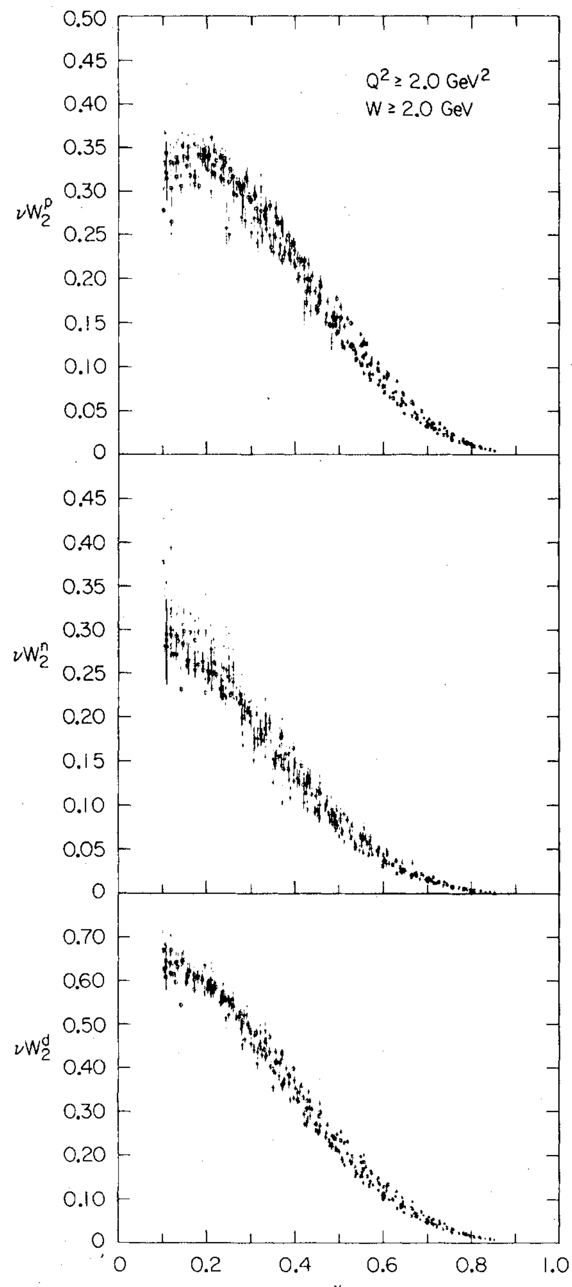

Figure 5. Approxmiate scaling of the MIT-SLAC data in the Bjorken variable x was the first evidence for point like consituents in the proton. The scatter of the points (with more precise data taken a couple of years later) also showed evidence for scaling violations. [7]

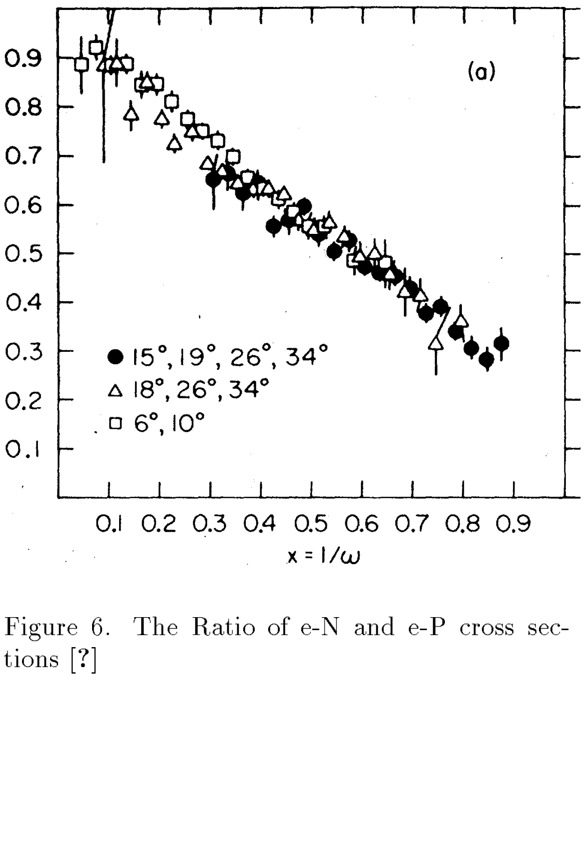

Figure 6. The Ratio of e-N and e-P cross sections [?]

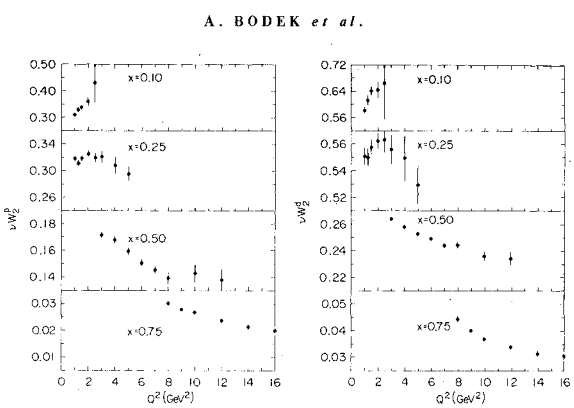

Figure 7. The x, Q^2 dependence of scaling violations first observed in the MIT-SLAC data

IN 1970 showing the MIT-SLAC data (Figure 3) 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 done between 1967 and 1974, it was inferred that: (1) The nucleon is composed of point like constituents (called partons, as shown in Figure 4). The evidence for this was that the data approximately scaled in the Bjorken variable x as shown in Figure 5.

(2) The charged partons were predominantly spin 1/2 as indicated by the fact that ratio of the cross section for longitundinal and transverse virtual photons was found to be small small. [6]

(3) The integral of the fractional momentum carried by the charged partons was about half, thus indicating that neutral particles (gluons) carried half of the nucleon momentum. [7] Therefore, gluons were actually discovered in the MIT SLAC experiments many years before the observation of three jet events at PETRA.

(4) The ratio of the cross sections from neutron and proton was about 1.0 (at small x) and went below 2/3 at large x. [4,5] Such a ratio could only be understood within a model which the partons at large x were fractionally charged valence quarks (as shown in in Figure 6.

(5) The observation that small x the neutron to proton ratio [4,5] was near 1.0 indicated that ,in addition to valence quarks, there was a sea of quark-antiquark pairs which was about the same for the neutron and proton (Figure 6 and Figure Figure 4.

(6) Experimental measurements showed that there was little nuclear dependence of the structure functions in the region near $x = 0.1$. These data ruled out the simple vector dominance models which predicted nuclear dependence similar to pion-nucleus scattering (subsequently, the vector mesons dominance models evolved to include a much larger number of vector mesons).

(6) Scaling in the Bjorken variable x was only approximate. The observed deviations [7,8] from perfect scaling could be attributed to either gluon emission in the scattering process (as predicted by the new theory of Quantum Chromodynamics) or

from binding effects of the partons in the nucleon (e.g. target mass and/or dynamical higher twist effects).

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 so widely shared, that in the early 1970's the results of the more precise second generation of electron scattering experiments at SLAC were not accepted for publication in Physical Review Letters. Figure 6 shows both the first results (E49B) of the ratio of neutron to proton ratio [4], as well as the more precise results (E87) a couple of years later [5]. Since the quark model was already established, the paper reporting on the more precise results was rejected by Physical Review Letters as not adding much to our state of knowledge. Being a graduate student at the time and accepting the judgement of my elders, I submitted that paper to Physics Letters [5](a European Journal) instead.

In the early 1970's the accepted dogma was that as we go to higher momentum transfers, scaling will become more exact. However the second generation MIT-SLAC experiments (E87) showed clear deviations from scaling [7] as shown in Figure 7. 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 $(1/Q^2)$ at higher values of Q^2. There were several theories that predicted other forms of scaling violations. These included theories in which the quarks had a finite size (e.g. form factors) and also the new theory of quantum chromodynamis (QCD) which predicted that scaling violations will only decrease as $1/\ln(Q^2)$. It is interesting that these more precise results on scaling violation were also rejected for publication in Physical Review Letters (refrees stated that these were obviously uninteresting higher twist effects). Now still being only a postdoc at the time, and accepting the judgement of my elders, I resubmitted the paper for publication in Physics Letters [7] instead.

3. Higher Energy Fixed Target Lepton-Hadron and Hadron-Hadron Experiments

The focus shifted to the new muon and neutrino scattering experiments at Fermilab and CERN. There experiments, though much less precise than electron scattering data, provided results at higher values of Q^2. The questions specific to nucleon structure that were of interest at that time were:

(1) Is QCD really 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,

(6) Is there experimental evidence for the validity of Current Algegra and QCD sum rules.

The answers to some of these questions could be determined by using new probes at higher energy. For example high energy neutrino beams. Therefore, I joined the Caltech-Fermilab neutrino experiments (first led by Frank Sciulli and Barry Barish) which later became the Chicago-Columbia-Rochester-Fermilab (CCFR) neutrino experimetal 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). A combination of neutrino and antineutrino measured could be used to separate the distributions quarks from the distribution of antiquarks in the sea. Around the same time, neutral currents and dimuon events were also discovered.

Dimuon events in neutrino interactions originated from charm states produced in charged current events. These dimuon events allowed 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 several PhD theses that focussed on the determination of the strange-quark content of the sea was done by Rochester PhD student, Karol Lang [10], who is now a faculty member at UT Austin (I will occasionally mention the names of some of my students and postdocs with whom I have worked on some of topics. This list is no meant to be complete. It should be recognized that high energy physics is a group effort, and a large number of people from many institutions made major contributions that were essential to the success of the many experiments).

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, some experiments at the CERN Instersecting Storage Ring reported the observation of copious production of forward production of charm states proton-proton collisions. This was rather surprising because it implied that there were intrinsic charm quarks 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 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 as observed open production of charm in hadron collisions. Adding to the confusing, leading order QCD calculations predicted that the production of charm states in the central (via the gluon-fusion mechanism process) was very small (e.g. 1-3 microbrans). Another result that was not understood hadron ollisions was the observation of the production of prompt muons (i.e. not from long lived pion decays) in hadron collisions. It was not clear if these prompt muons orginated from dimuon pairs (e.g. vector meson and Drell Yan events) or from the decays of new states. It turns out that the new large acceptance neutrino detectors, when 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 promt muons in proton-nucleon and pion-nucleon collisions (FNAL experiments E379/E595).

The results from the FNAL E398/E595 data 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. (b) The production of forward charm particles in proton-nucleon collisions was very small. A limit was placed on the intrinsic charm in the nucleon wave function (the large forward cross section reported by the ISR experiemnts were not observed). (c) The hadronic charm production cross section in the central region was about 20 microbarns (much higher than the earlier emulsion limit, thus implying large higher order corrections (K factor) to the QCD calculations). (d) Investigation of the double leptonic decays of charm mesons (to muons and missing energy) put a limit on the mixing of D0 and D0bar mesons. Some of these results (published in Physics Letters) are reported in the PhD Theses of Rochester graduate student Jack Ritchie [14], who is currently a faculty member at UT Austin.

Over the next 20 years, both the muon and neutrino experiments at CERN and Fermilab were upgraded and evolved to became high statistics programs. (accumuilating samples of order of millions of charged current events). In the neutrino program, 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 [?, ?]. Over the course of time, QCD has become the accepted theory of strong interations.

Because of the coarse sampling in the massive neutrino target calorimeter and the multiple scattering of muons in the large acceptance magnetized iron muon spectrometers, both the hadron energy and muon energy were measured with much poorer resolutions than could be achieved in the lower energy electron-nucleon experiments. This was partially compensated for by carefully calibrating the detectors with hadron and muon beams [9], and by accumulating large statistical samples [13]. These second generation neutrino and muon experiments yielded information on detailed distributions of the various types of quarks 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 [11]. These were used by several groups to provide parametrizations of the various parton distribution functions (PDFs) in nucleon.

Around that period it became clear that precise knowledge of nucleon PDFs was crucially needed in order to be able to do physics in the new proton-antiproton colliders. In the the early 1980's PDFs describing the valence, sea, strange quark and gluon distributions were extrated from fits to all muon and neutrino scattering data taken during previous decade. 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 in the new proton-antiproton colliders.

It did not take long for the second generation (more precise) proton-antiproton collider experiments to become limited by systematic errors on the parton distribution functions. The systematic errors on the PDFs also limited the precision on extraction of precise parameters (such as electroweak mixing angle) from high statistics neutrino experiments.

These systematic errors in the PDFs came from the following sources.

(1) The high statistics muon and neutrino experiments were mostly done on iron targets. The PDFs were corrected for nuclear binding effects using theoretical models. Early results reported

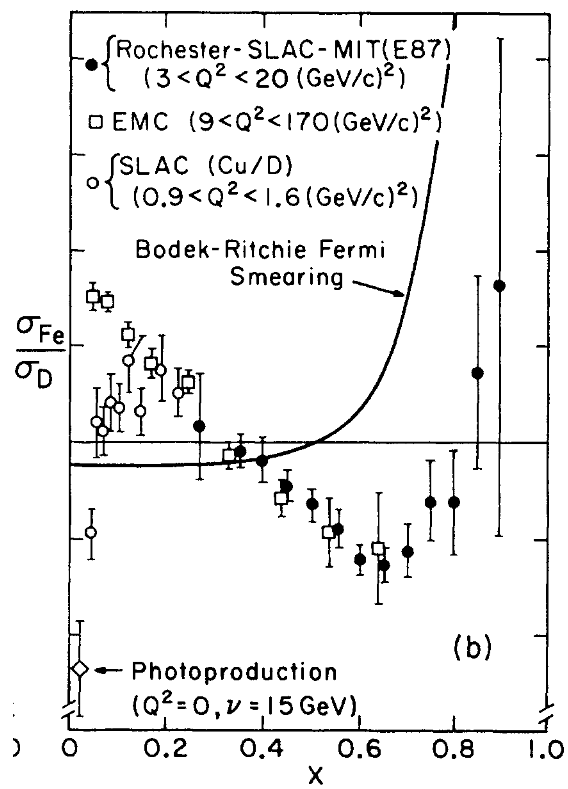

Figure 8. The x dependence of iron to deuterium ratio extracted from MIT-SLAC Empty Target Data compared to the results initially reported by the EMC collaboration

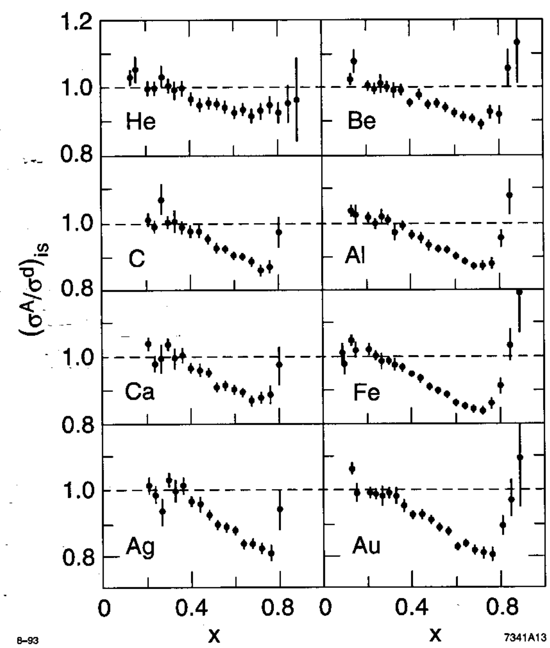

Figure 9. A determination of the ratio of electron scattering on various nuclear targets to that measured on deutrium in SLAC experiment E139

by the European Muon Collaboration (EMC) showed that of the ratio of structure functions for iron and deutrium showed a large discrepancy from the Fermi-Motion calculations of Bodek and Ritchie. The ratio of iron to deuterium was observed as having a 20 % slope as a function of Bjorken x, as shown in Figure 8.

(2) The systematic errors in calibration and flux in the neutrino and muon experiments were significant. Therefore, these experiments were not yet precise enough to separate the contribution of the longitudinal and transverse component of the cross sections. This resulted in a fundamental limit on how well the structure function F_2 (which has contributions from both longitudinal and transverse component) could be extracted from muon and neutrino data at high energies.

(3) There were differences 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.

(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. For a while, these errors resulted in a smaller alue of the strong interaction coupling constant as extracted from DIS versus that extracted from e+e- experiments.

(5) In addition, the relative contribution to the scaling violations from QCD evolution and from higher twist effect was not understood. Therefore, this also resulted in uncertainties in the evolution of the PDFs from fixed target energies to energies at hadron colliders.

(6) The high energy muon and neutrino experiments could not determine the PDFs at high values of x, because of resolution smearing effects. Since the structure functions evolve from high x to low x, with increasing Q^2, the poor of knowledge of the PDFs at high x and low Q^2 low contribute to the PDF uncertainties at intermediate x and high Q^2. Searches for new physics in high energy electron-proton and proton-antiproton collisions are in turn limited by these PDF uncertainties.

(7) The ratio of the d and u quark distributions was 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.

During the twenty year period from 1980 to 2000, a part of the experimental effor of my group at Rochester was directed towards finding solutions to each of the limitations listed above. The solutions involved a combination of new measurments at different laboratories, different beams, new experimental detectors and techniques, higher precision, and better theoretical tools.

The first issue that we tackled was to resolve the large difference between the iron and deutrium structure functions as reported by the EMC (muon) collaboration. It turns out that a check of this result was possible by going back and doing an analysis of the empty target data of the orginal MIT-SLAC Experiments (E849 and E87). The extraction of the old data MIT-SLAC empty target data [15] (after more than a decade) was an excecise in Physics Archeology (or a study of the shifting standards and media of computer technology). In a couple of months, the results on the ratio of iron to deutreium [16] and on the aluminum to deuterium [17] structure fucntions were submitted for publication to Physical Review Letter by the Rochester-MIT-SLAC group. 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 8. At small x, the electron data showed a ratio of iron to deuetrium that was actually less than 1.0, which indicated shadowing (while the EMC muon data 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 large x, the electron data showed that ratio became less than 1.0. Finally, for x greater than 0.7, Fermi motion effects took over and the ratio was larger than 1.0. The initial EMC results at small x were found to come from a tracking inefficiecy from extra hits for the lower density deuterium target. Subsequent data with taken with muon was in good agreement with the electron scattering results.

The nuclear binding effects were found to much more complicated than just simple Fermi motion, and included contributions from shadowing, antishadowing, binding energy effect and Fermi motion. Therefore, the simple model of Bodek and Ritchie was also incomplete.

I submitted the first paper on the ratio of iron to deuterium [?] to Physical Review Letters. To my surprise the paper was first rejected by Physical Review Letters. One referee said that there was no evidence for quarks in nuclei, and the other 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 got the editors to ignore the suggestions of the referees, and the results were published in Physical Review Letters [16,17].

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

To the high energy physics community, these nuclear corrections were important in order to convert data on nuclear targets to data on free nucleons (or at least deuterium). To the nuclear physics community, it presented a new tool to investigate a new type nuclear effects. It also happened that by the 1980's, the SLAC station A electron scattering facility at SLAC was already being in a variety of nuclear physics experiments (e.g. in the measurement of elastic form factors of deutrium an other nuclei). A dedicated lower energy nuclear physics (NPAS) injector that provided 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. The results of the re-analysis of the SLAC empty target data presented a new oppotunity (for both the nuclear physics community and for the high energy community) to embark on a collaborative program

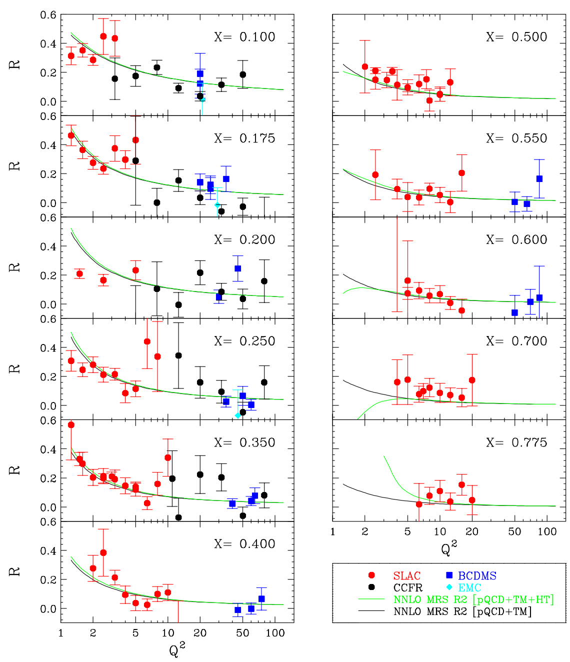

Figure 10. Precise data [19] on R taken by SLAC E140 as compared to subsequent data taken by third generation neutrino (CCFR/NuTeV) [13] and muon experiments

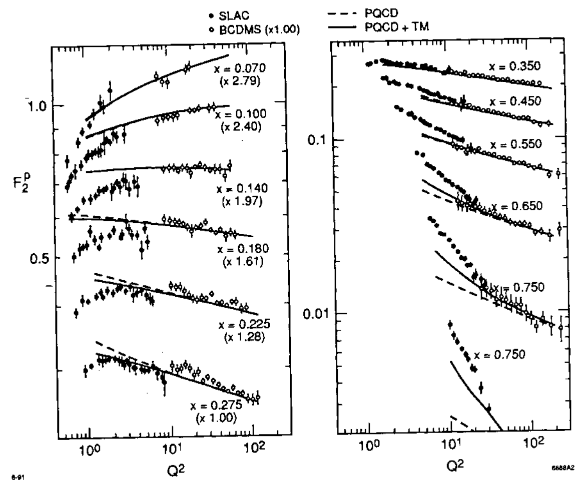

Figure 11. The initial results from the SLAC E140/combined SLAC analysis indicating the the systematic errors in QCD fits that only included the data from the higher energy experiments (compare these fits to the improved analysis the next figure).

of third generation precision electron scattering experiments. As discussed below, measurements that were not possible before, could now be done with much better precision. Thesenew higher precision experiments would lead to a better understanding of both nucleon and nuclear structure.

At first, the existing End Station A SLAC 8-GeV spectrometer was used for a new SLAC experiment E139. This experiment performed a survey of the ratio of structure functions taken on a variety of nuclear targets to that of deuterium [18]. In parallel we proposed SLAC experiment E140 for a precision electron scattering deep inelastic scattering on nucleons and nuclei.

As part of the new SLAC E140 program (Arie Bodek and Steve Rock, cospokepersons) 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, upgraded electronics and a better monitoring to control beam

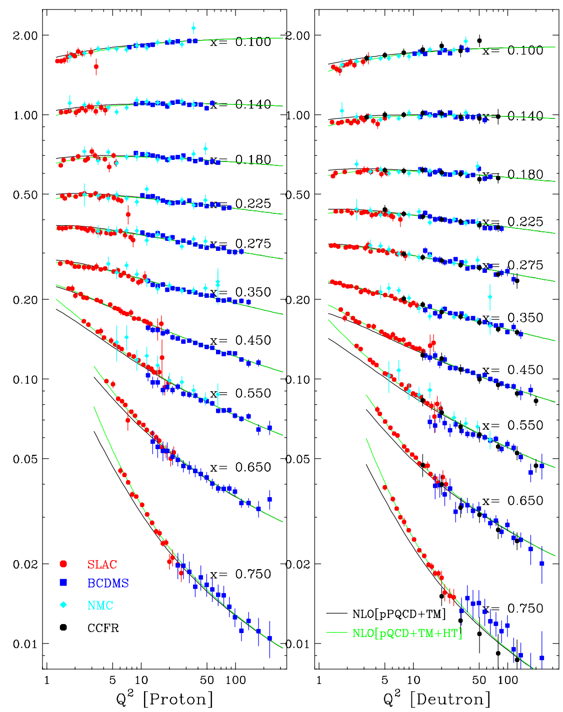

Figure 12. Post SLAC E140 status. The NLO QCD plus target mass fits (with and without renormalon higher twist corrections, by Bodek and Yang. The new determinations of R from the SLAC E140 program are now used by the higher energy experimentsl In additluion, the normalizations of the higher energy experiments 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 the previous figure).

systematics. Since beam time at SLAC was very costly, we introduced the technique (used in the neutrino experiment at Fermilab), to check out and time-in the detectors (in place) using cosmic rays. In addition, we have undertaken both an experimental and theoretical program to improve the radiative corrections. The external radiative corrections were invetigated 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. The internal radiative corrections were also improved by comparing two very different approaches (the Mo-Tsai procedure and the Bardin procedure). By investiating the similarities and difference between the two approaches, improvements were made and agreement was between the two approaches was achieved. Since the Bardin calculation also included electro-weak corrections (important 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 new and much more precise measurements [19] of R 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 data additional data in regions that overlapped with previous electron scattering experiments at SLAC. These previous SLAC experiments were then re-analyed with the improved radiative corrections program (for both external and internal radiation), and cross normalized to SLAC E140. The results from the SLAC E139/E140 program and new combined reanalysis of the previous data were:

(1) Provided precise ratios of structure functions for heavy targets to that of deuterium [?] (see Figure 9). Now all data taken with nuclear targets could be used in PDF fits.

(1) Extracted the first precise determinations of the x and Q^2 dependence of R, the ration of longitudinal and transverse structure functions [19]. The parametrization of these and other data (called Rwolrd) was subsequently used for

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

$$x_1 - x_2 = x_W,$$

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

Figure 13.

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. Figure 10.

(2) Established that the nuclear dependence of R 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.

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

(3) Provided a high precision anchor for the 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 11 (before) and Figure 12 (after)).

(4) 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.

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

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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 worked on improved modeling of the nuclear binding effects in the deutreon (the reader is referred our publication [25]). Even higher precision on PDFs can 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 [20] the d and u quark distributions without the complication of nuclear effects.

Figure 13 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 14 shows the 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 15. 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 16.

In order to have sensitivity d and u quark distribution contributing to 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 directon not possible in CDF, since the central tracker covered a limited range of rapidity around the central region. We therefore introduced a new technique [22] to measure both the charge and energy of electrons and positrons in the forward plug calorimeter with

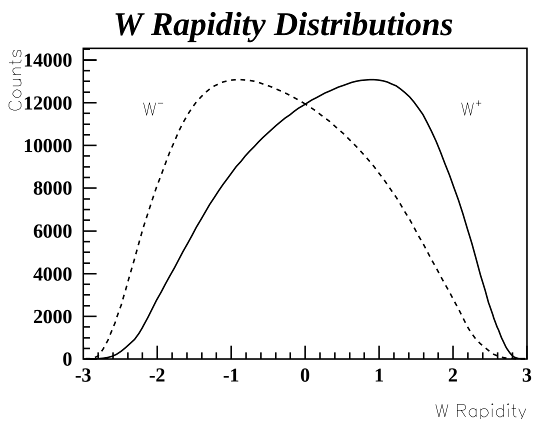

Figure 14.

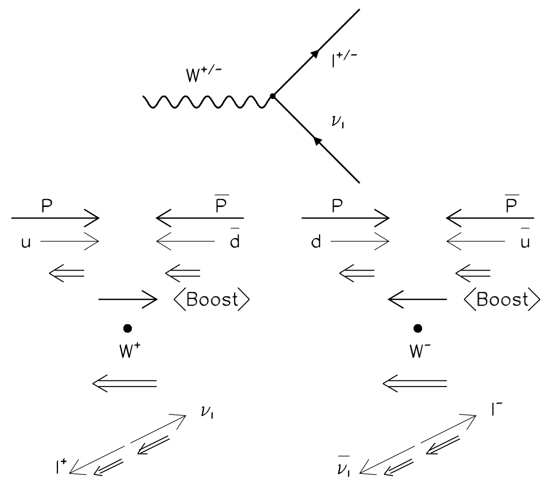

Figure 15.

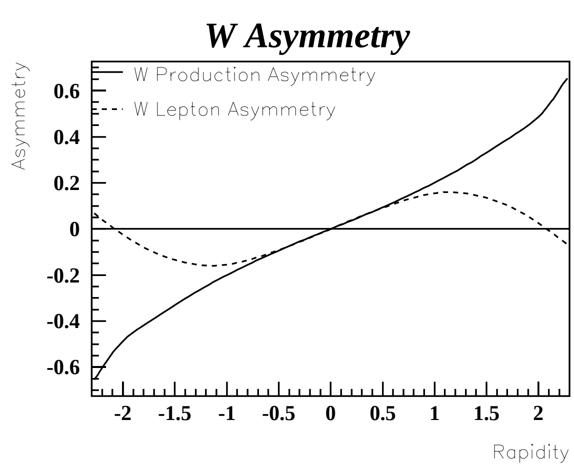

Figure 16.

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 left or right of the extrapolated track from the vertex silicon tracker. This resulted in a measurement of the W decay lepton assymetry [?] as shown in Figure 18. The new data indicated that the d/u ratio in the proton was lower than that from the best PDF fits avilable at the time. The ratio was in better agreement with d/u ratio extracted from deutrium data with improved corrections for nuclear binding effets. Susequently, both the W asymmetry data and deutron binding effects are used in modern fits to PDFs. Therefore, the uncertainties in the d/u ratio are small and allow for a more precise measurement of the W mass. The analysis of the W assymetry data was the subject of the PhD Theses [?] of two Rochester graduate students, Mark Dickson (now at MIT Lincoln Lab) and Qun Fan (now at Tencor corp).

As a matter of fact, it was found that in order to do physics with electrons and positrons in hadron collider, using silicon vertex track-

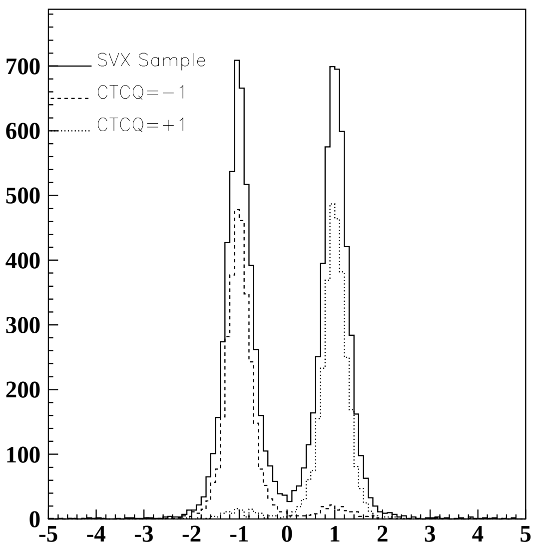

Figure 17.

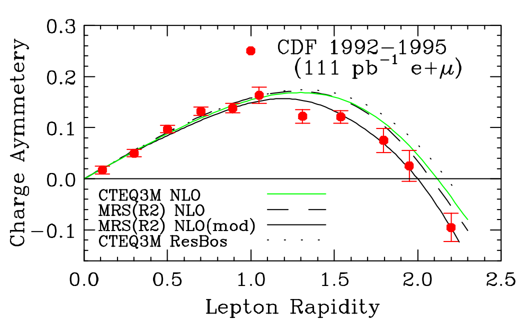

Figure 18.

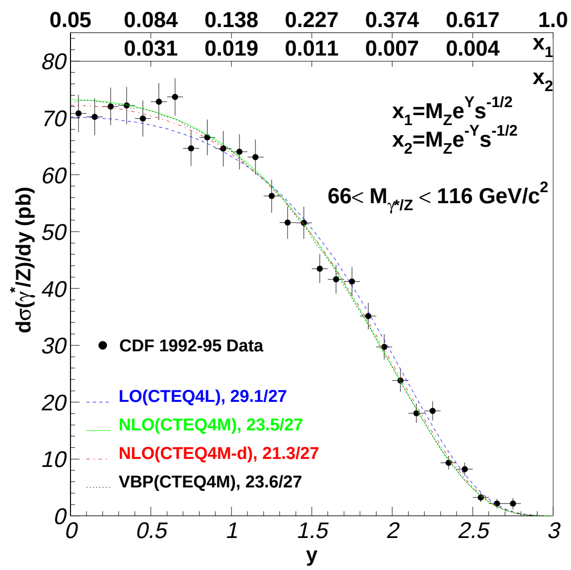

Figure 19.

ing in conjunction with segmented electromagnetic calorimetry is better than using a central tracker [22] (the central tracker has a higher charge misidentification rate because it is sensitive conversions of gamma rays). This new technique also allowed for the measurement of the rapidity distributions of Z Bosons at high rapidity as shown in Figure 19. This was the PhD thesis topic of Rochester graduate student Jinbo Liu [23] (now at Lucent). The technique is now also used to greatly reduce the jet background and measure the mass and forward-backward charge asymmetry of Z Bosons and high mass Drell-Yan dilepton pairs. The asymmetry is sensitive way to search for new physics beyond the standard model (e.g. high mass Z' Bosons). Figure 20 shows the CDF Drell-Yan data from run 1, compared to a calculation by Baur and Bodek [24] (with and without a hypothetical Z' Boson. (The CDF analysis for the forward-backward asymmetry was done by Rochester postdoc Yonsei-Chung [24]).

With a factor of 10 data expected in CDF run II, the W Asymmetry data and the Z rapidity distribution will make a significant contribution to constrain the PDFs with even higher precisions.

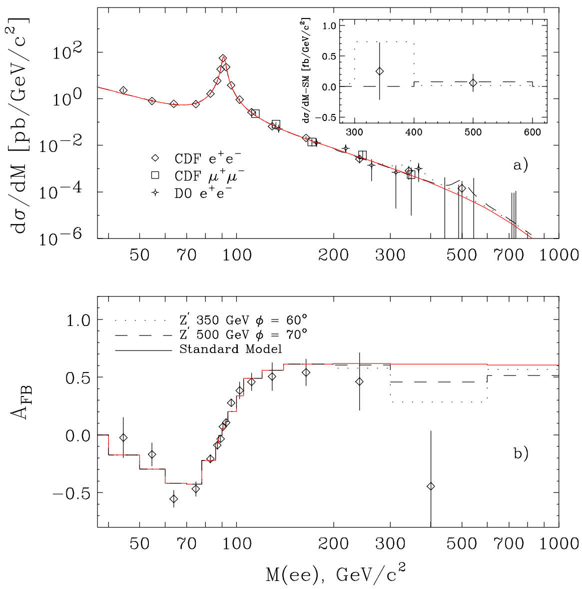

Figure 20. High mass Drell-Yan events and the forward-backward asymmetry measured at CDF.

Precise PDFs determine the expected level of high mass Drell-Yan events, so that searches for new states are possible in both the differential cross section (versus mass) and the forward-backward asymmetry.

6. Putting It all Together - 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 available at large x was 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 know 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. 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 (in LO, NLO and NNLO) to the data would allow one to extract the magnitude of higher twist multiplative factors a_2 and a_4. This work was done in a series of papers by Bodek and Un-Ki Yang, a Rochester graduate student who also completed his thesis on CCFR/NuTeV (Yang is now at the University of Chicago). Figure 12 shows the fits in NLO, and the extracted higher twist coeficients. Figure 21 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 [25] 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 [26] the study in NNLO QCD. Figure 22 shows the comparison of the NNLO QCD fits (including target mass) to the data. It appears that NNLO QCD works very well for all data above $Q^2 = 1\ GeV/C^2$ without the need for any dynamnical higher twist correction. We have shown that NNLO QCD works very well, and the need for higher twist corrections in the NLO QCD case are mostly from dropping the higher order NNLO terms.

Note that although the Q^2 of the structure functions has been calculated to NNLO in QCD, NNLO PDFs were not yet available for the calculations. Figure 23 shows the small correction factors that were neede to fit the data in the NLO and NNLO analyses. The ratio of the factors for NNLO and NLO is the ratio of NNLO to NLO PDFs. This was the first extraction of NNLO PDFs. Subsequently the work on NNLO PDFs

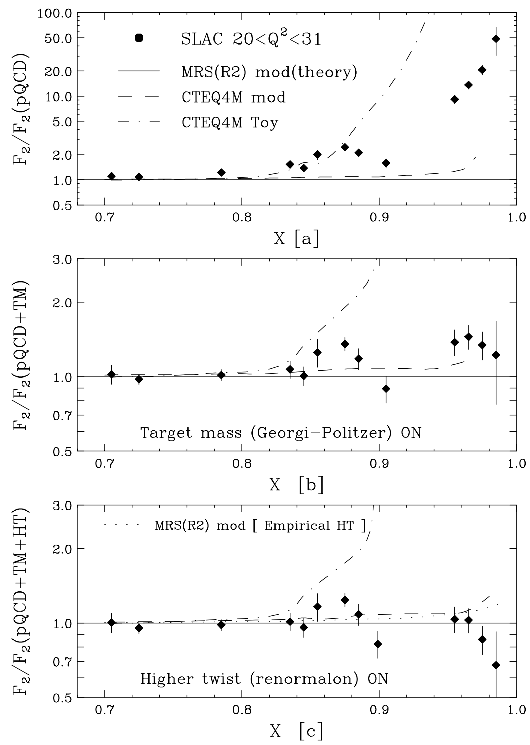

Figure 21.

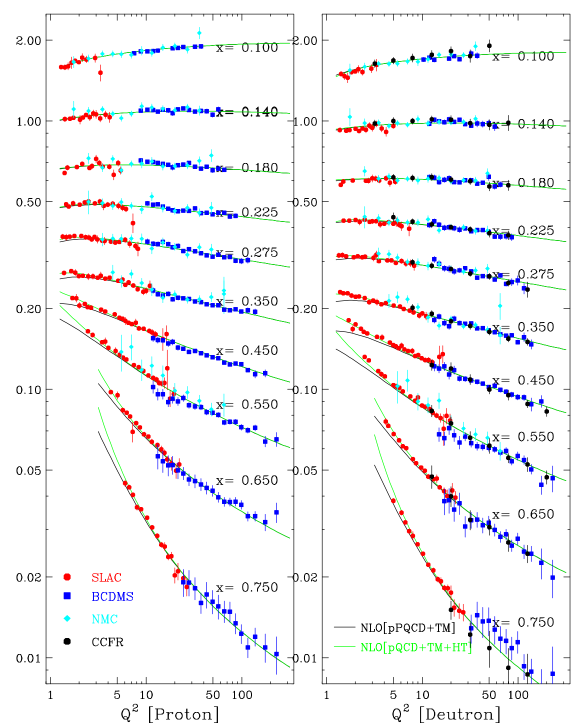

Figure 22.

was continued by the MRST PDF group. In summary, our conclusions are that QCD NNLO calculations should work well 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.

7. Back to the Future, Neutrino Physics and the Low Energy Frontier

Well, we thoguht 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 genaration 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

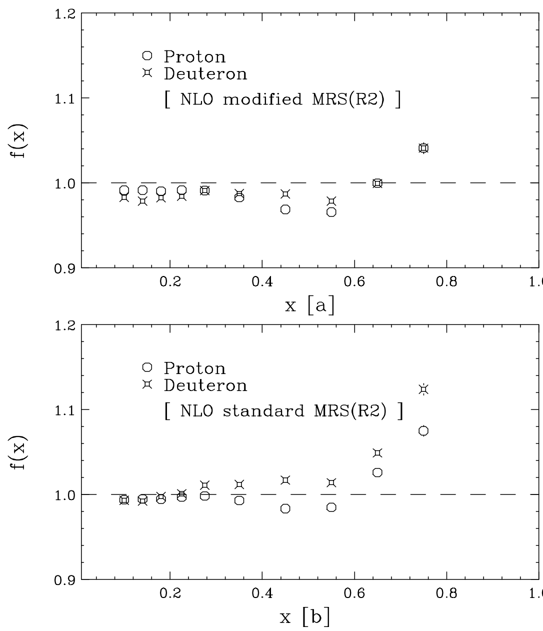

Figure 23.

mixing can only be investigated with low energy neutrino beams. Current and next generation neutrino experiments in the future require the understanding of quasielastic, resonance and the deep inelastic regions for incident neutrino energies in 0.4 to 5 GeV range. However perturbative QCD NLO and NNLO calculations are not valid very low Q^2.

Therefore, I have embarked on a phenomenolical study of this energy region using existing neutrino and electron scattrering data in this energy region. 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 [27].

In parallel, I have continued to work with Un Ki Yang on modeling [28] vector and axial structure functions for resonance and production and inelastic scattering at low energies. In the low energy region we have reversed the model. Previously, we worked hard to remove all higher twist corrections by using NNLO QCD. The approach at low energies is to use QCD PDFs in leading order and model the non-perturbative effects with a new scaling variable, and with effective target mass and higher twist corrections that work all the way down to $Q^2 = 0$. This approach has worked very well. We have derived a new scaling variable to account for 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 24, 25, and 26 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.

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 in the resonance region (for nuclear targets) need to be measured beter. At present, two experimental programs (at Jefferson Laboratory [30] and at Fermilab [29]) have been approved for a collaborative effort in measuring vector and axial form factors and structure functions at low energies. These experiments will provide the understading of neutrino cross sections at low energies, which is essential for the next generation neutrino oscillations experiments at Fermilab, Japan and Europe.

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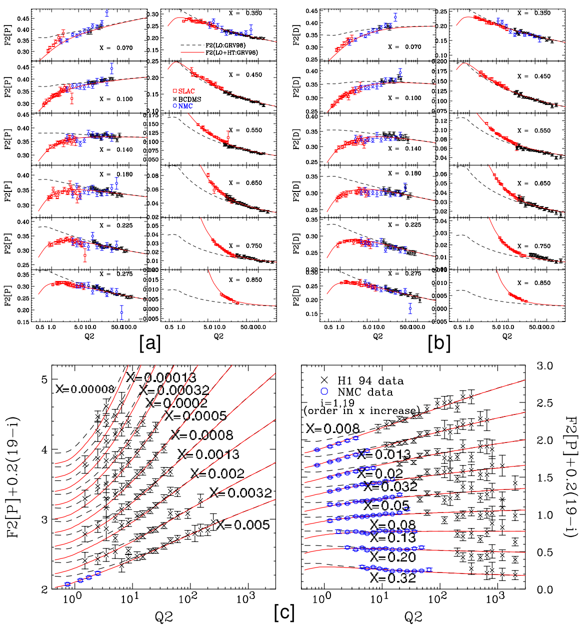

Figure 24.

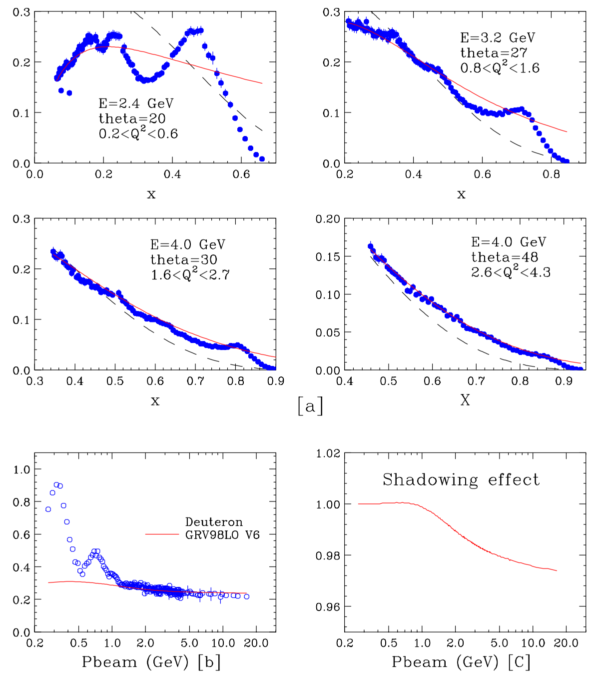

Figure 26.

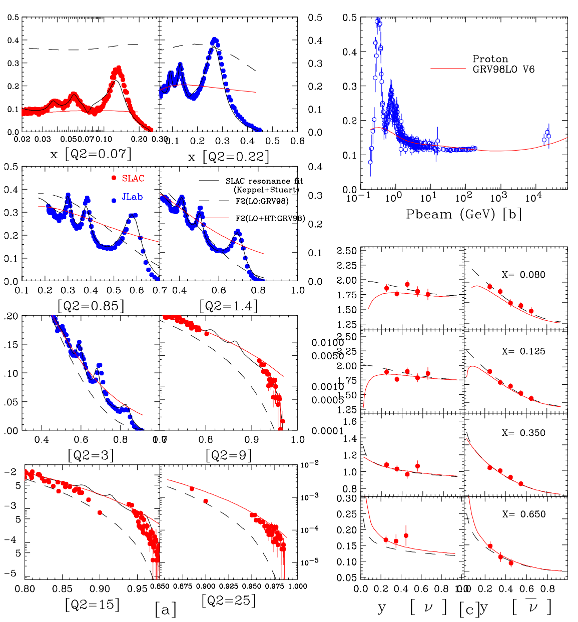

Figure 25.

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