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Fixed Target Electroweak and Hard Scattering Physics*

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Editors representing the
Fixed Target Electroweak and Hard Scattering Group[1]

Abstract

The possibilities for future physics and experiments involving weak and electromagnetic interactions, neutrino oscillations, general hard scattering and experiments involving nuclear targets were explored. The studies were limited to the physics accessible using fixed target experimentation. While some of the avenues explored turn out to be relatively unrewarding in the light of competition elsewhere in the world, there are a number of positive conclusions reached about experimentation in the energy range available to the Main Injector and Tevatron. Some of the experiments would benefit from the increased intensity available from the Tevatron utilizing the Main Injector, while some require this increase. Finally, some of the experiments would use the Main Injector low energy, high intensity extracted beams directly. A program of electroweak and hard scattering experiments at fixed target energies retains the potential for important contributions to physics. The key to major parts of this program would appear to be the existence of the Main Injector.

1 INTRODUCTION

All physics is interlaced; nevertheless, for the purposes of a Workshop such as this it is necessary to divide in order to conquer in a finite time. A loose overall relationship was maintained in the subject field, and this report is an attempt at a coherent

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representation of the work done. Nevertheless for the most part of the 10 days people worked in small subgroups on rather specific questions. The subgroups were as follows:

Neutrino Oscillations
Electroweak Interactions
Structure Function and Parton Distribution Phenomenology
Prompt Photon Experiments
Muon Scattering Experiments
Spin and Polarized Parton Distributions
Nuclear Effects

The typical daily format involved a meeting for about 45 minutes in the morning for each of the subgroups, a number in parallel, followed on some afternoons by a plenary meeting with presentations (References 1-10) judged to be of interest to the group as a whole. There had been a workshop on Main Injector Physics[11] in the Spring of 1989 and for some of the working subgroups, particularly that concerned with ν oscillations, the meeting at Breckenridge was a natural continuation. This is reflected in the maturity of their discussions. This summary of the work was prepared by the leaders of the groups with the active electronic participation of the whole group. Conclusions are those of the editors.

2 FIXED TARGET ELECTROWEAK INTERACTIONS

2.1 Introduction

The Fixed Target Electroweak Group was almost evenly split between those interested in neutrino oscillation phenomena and those interested in more conventional measurements of electroweak model parameters such as the Weinberg angle and Kobayashi-Maskawa matrix elements. Accordingly, there were two subgroups formed which studied improvements in these areas. The subgroups were an Oscillation Subgroup and an Electroweak Parameter Subgroup.

2.2 Oscillations

The possibility of neutrino oscillations is quite old and has been motivated by mostly theoretical influences[12]. If it should be the case that there are at least two families of neutrinos in which there is a mass difference, then there is expected to be quantum mechanical mixing among those states. For two family mixing, the familiar expression for the probability of mixing is expressed as

$$\mathcal{P}(\nu_i \rightarrow \nu_j) = \sin^2 2\vartheta \sin^2(1.27\Delta m^2 \frac{L}{E_\nu}). \quad (1)$$

There have been a number of experimental tests which have been performed at reactors and accelerators which fall into one of two categories:

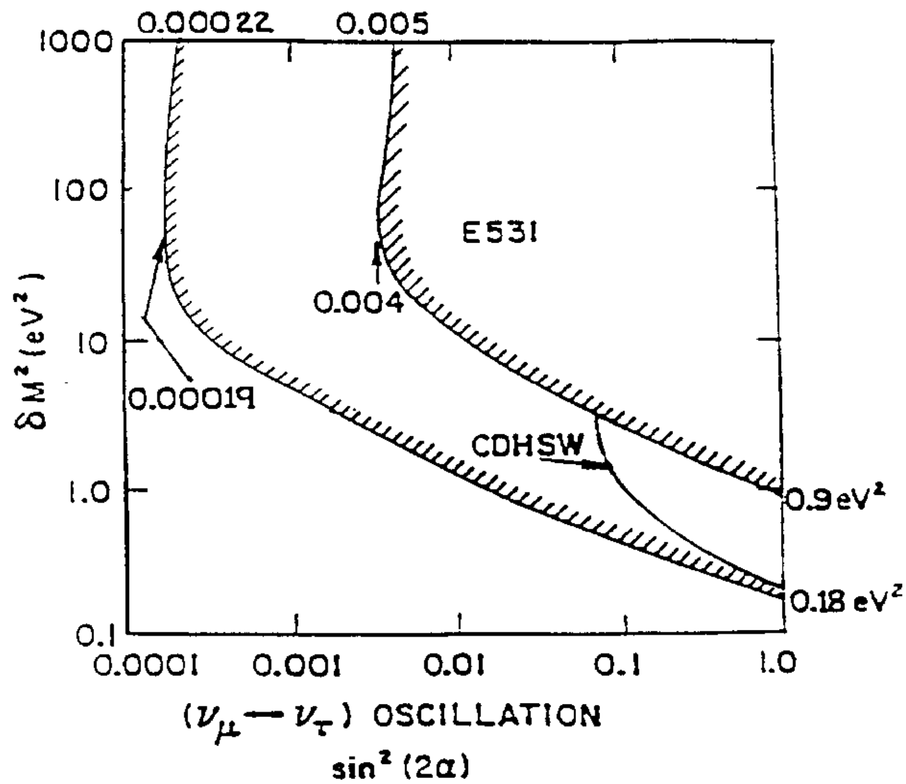


Figure 1: ν Oscillation Experimental Limits

Appearance experiments in which a beam of neutrinos appears to contain a flavor of neutrino not expected to exist from conventional sources. The measurement in an appearance experiment is reported as $\mathcal{P}(\nu_\mu \to \nu_x) = \frac{N_x}{N_\mu}$.

Disappearance experiments in which one attempts to determine that a component of a beam of known composition disappears or changes into something else. The measurement in a disappearance experiment is reported as $\mathcal{P}(\nu_x \to \nu_x) = 1 - \mathcal{P}(\nu_x \to \nu_y)$, where typically $x = e, \mu$ and $y \neq x$.

The first type of experiment is typically performed with one detector downstream of a conventional source of neutrinos or a special beam (such as a beam dump). The second type of search is sometimes performed with two detectors or one detector at more than one distance from the source. Search limits are typically represented as exclusion plots such as that of Figure 1 for various channels.

The ability to reach to low mass and mixing angles is dependent upon a number of factors. In order to push to small mass, one finds that the sensitivity is maximized (both with and without the presence of backgrounds) by minimizing the ratio E_ν/L and by maximizing the number of events. In order to push to small mixing angle at moderate Δm^2, the sensitivity is nearly independent of E/L and depends on $\sqrt{\frac{b}{N_s}}$ where b is the fractional background.

Models which anticipate neutrino oscillations are typically rather short on specific predictions. However, with some plausible assumptions regarding the possible family-hierarchy of masses for the lepton and quark masses, such as the see-saw mechanism[13)], plus the unsupported but not unreasonable possibility that the mixing of leptons might be related in strength to the mixing of quarks, one could conclude that an optimum channel in which to search might be

$$\nu_\mu \rightarrow \nu_\tau. \tag{2}$$

Harari has suggested that such a possibility might lead to lepton mixing of the order of 4×10^{-4} or more and that a mass difference of < 70eV might be sufficient to close the universe[14)]. It has been noted[15)] that a strict interpretation of this would have suggested that the limit has already been reached.

A prediction for where to search in the relevant space of Figure 1 is an important guide. Further, the search strategy for $\nu_\mu \rightarrow \nu_\tau$ is straightforward for the following chain:

$$\nu_\mu \rightarrow \nu_\tau + N \rightarrow \tau + X \tag{3}$$

$$\tau \rightarrow \text{muonless final states.}$$

The search for the interaction of a ν_τ would result in a final state τ^- for deep inelastic charged current scattering. The τ^-, in turn, would signify its presence by decaying within its characteristic distance of $c\tau = 90$microns, which might be detectable. Almost 90% of τ decays would result in a single kink, and since there would be no muon in the final state, the event would appear to be a neutral current. With track signing, the kink could be identified as the negative track required for an incoming ν_τ.

This match of a detectable final state, a prediction for an oscillation scenario which is independent of E/L, and the recent discussion of the Fermilab Phase II upgrade (the so-called Main Injector) led an experienced group from Ohio State, Fermilab, Nagoya University, Kobe University, and Osaka City University to consider the possibility of searching for $\nu_\mu \rightarrow \nu_\tau$ oscillations using a high-rate neutrino beam. The basis of this new plan is the possibility of using the proposed proton synchrotron, the Main Injector, which is the centerpiece of the Phase II upgrade proposal. With this device the proton beam would be extracted every 3 seconds at 150 GeV at intensities which are potentially many times 10^{13} protons. This idea has been discussed by this group in various fora [16)], previously led to a Fermilab Letter of Intent (P803), and was the center of attention in the Oscillation Subgroup within the Electroweak Group. The essential element of this design, as in the earlier E531, is an emulsion vertex detector with downstream tracking. The entire device would be immersed in a magnetic field supplied by the now surplus 15' bubble chamber superconducting magnet.

The results of these discussions were:

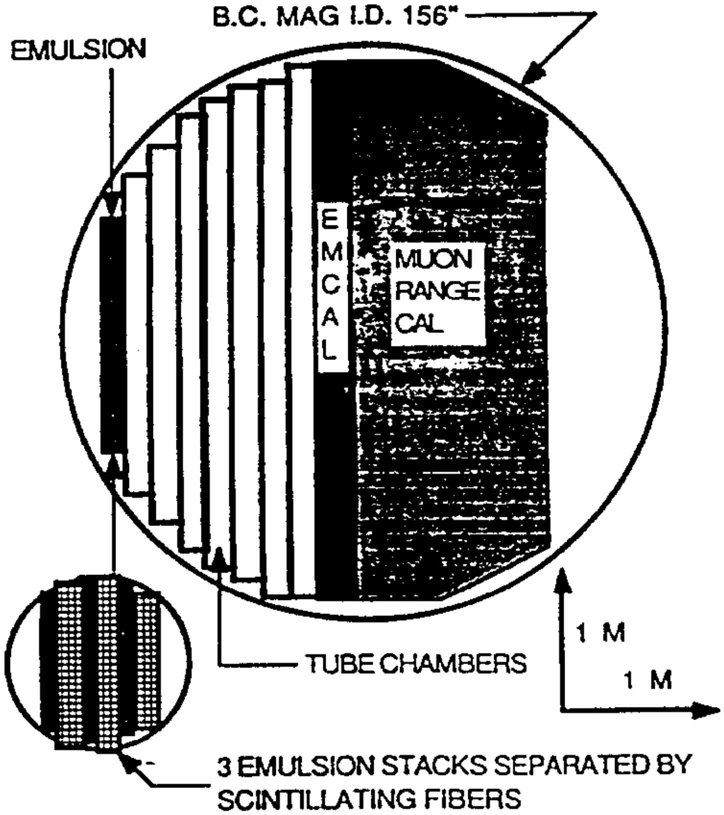


Figure 2: ν_τ P803 Experimental Layout

1. fundamental decisions regarding a final design for the detector,
2. progress on kinematical cuts which would significantly reduce the scanning time, and
3. progress on supplementary physics measurements of importance (see below).

The design discussions led to a new layout which retained emulsion as the central feature but enhanced the muon detection. Vertex-pointing would now be facilitated with scintillating fibers which would surround the 3 upstream emulsion layers. The new design is shown in Figure 2.

Among the kinematical cuts which were discussed was a simple $E_{visible}$ cut. Figure 3 shows Monte Carlo predictions for resolution-smeared distributions of this quantity for ν_μ deep inelastic neutral current events as compared with ν_τ deep inelastic charged current events. A cut of 5 Gev on $E_{visible}$ removes nearly 40% of the neutral current background at negligible cost in τ's. Other promising cuts include a requirement of at least one small-angle ($\leq$ 200 mrad) track, stiff enough to be reconstructed, which is effective against neutral current events, and demanding a transverse momentum imbalance of 0.2 GeV in the event as a whole, which is effective against charged-current events with an untagged muon. These conservative cuts reduce the total scan effort by more than a factor 2.

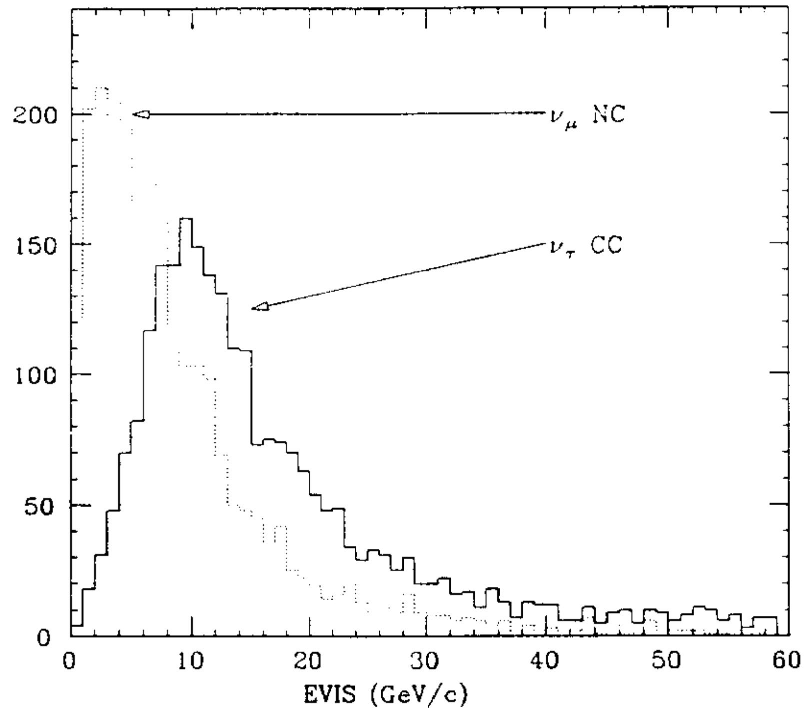


Figure 3: Monte Carlo Distributions of the variable E_{vis} for both charged current ν_τ events with τ final states and inclusive ν_μ neutral current events

The present status of the prospects for an experiment of this sort rely completely on the successful completion of the Main Injector and the construction of a horn-focussed wide band beam. With a run of 6-7 months and 1 ton of emulsion the number of events which would be scanned for oscillation after cuts would be less than 40k. In this sample, it is expected that there might be a background remaining of 1-1.5 events which would lead to a limit of 2.2×10^{-4} in mixing angle. This expectation is also shown on Figure 1. The number of "regular" ν_μ charged current events with a tagged negative muon would be roughly 250k. The most serious background to the oscillation search is one in which contaminant antineutrinos in the neutrino beam produce charged current events containing a hidden muon and negative charmed particles which themselves decay with an observed kink. In order to study this background, it is estimated that roughly two months of devoted antineutrino running would be required.

Another background source in this high rate beam might include the direct production of ν_τ in the beam stop. Obviously, such an occurrence would lead to events with precisely the same characteristics as those of the oscillation signal. This background from real ν_τ's can be virtually eliminated by the addition of dipole magnets in the neutrino beam decay space to deflect the uninteracted proton beam; this would cause most ν_τ's of detectable energy to miss the emulsion target.

However, what is often not emphasized, is that while the appearance technique does serve as an oscillation strategy, an experiment of this sort could also, if desired, be uniquely and automatically optimized as a discovery device for new neutrino species: Observation of final states containing (the background) τ leptons qualifies as the discovery of the ν_τ!

Other activities of the Oscillation Subgroup included discussions of other experimental possibilities at Fermilab and CERN. The group from INS University of Tokyo, Tokai University, Kobe University, and Tokyo University of Technology which is presently involved with the successful Kamiokande water Cerenkov detector, presented ideas for a long baseline detector, again proposed for exposure to the Main Injector wide band beam. This too would be a search for the oscillation channel $\nu_\mu \to \nu_\tau$, except through the quasi elastic reaction

$$\nu_\mu \to \nu_\tau + n \to \tau + p \tag{4}$$

$$\tau \to e + \nu_\tau + \nu_e$$

The effort would be to detect the electron final state with high accuracy relying on the experience gained in the previous experiment. The goal would be to eventually construct a 1 Mton water detector 500-1000km from the source of neutrinos. With such a device the mass limit could be improved in a disappearance experiment to $\Delta m^2 > 10^{-3} eV^2$ for $\nu_\mu \to \nu_e$ and $\Delta m^2 > 3 \times 10^{-3} eV^2$ for $\nu_\mu \to \nu_\tau$.

Finally, a report was given by R. Santacesaria on a Letter of Intent from the CHARM II at the CERN PS collaboration to study neutrino oscillations over a long baseline.

2.3 Electroweak Parameters Subgroup

The majority of effort in the Fixed Target Electroweak Parameters Subgroup was expended in discussions of the neutrino determination of $\sin^2 \vartheta_W$. The timing of this discussion was particularly important for a number of reasons:

1. The first truly precise measurements of the mass of the Z^0 had just been announced in the preceeding few weeks and summarized the previous week at the Lepton Photon Conference[17)] at Stanford. The results as presented at that meeting are:

CDF[18)]	M_Z	$= 90.9 \pm 0.3(stat + syst) \pm 0.2(scale)$GeV
MarkII[19)]		$= 91.17 \pm 0.18$GeV
UA2[20)]		$= 90.2 \pm 0.6 \pm 1.6$GeV

as to be compared with the previous results from the CERN Collider [21)]:

UA2	M_Z	$= 91.5 \pm 1.2 \pm 1.7$GeV
UA1		$= 93.1 \pm 1.0 \pm 3.1$GeV

2. CHARM II reported[22)] on their first determination (for no radiative corrections) of $\sin^2 \vartheta_W$ with very high statistics running over the last few years in which they

have a sample of 762 ± 43 $\nu_\mu e$ and 1017 ± 51 $\overline{\nu}_\mu e$ events:

$$\sin^2 \vartheta_W|_{\nu e_{CHARM}} = 0.233 \pm 0.012 \pm 0.008. \tag{5}$$

The world's data to date from deep inelastic measurements (DIS) result in the following combined determination [23]:

$$\sin^2 \vartheta_W|_{\nu N_{WORLD}} = 0.233 \pm 0.003(stat + syst) \pm 0.007(theory), \tag{6}$$

where the last error is the combined theoretical uncertainty in the extraction of the derived $\sin^2 \vartheta_W$ from the determined $R = NC/CC$. These uncertainties are almost completely dominated by parton model uncertainties.

3. Two Tevatron experiments (E733 and E770) are within a year of completing high energy determinations of this quantity. This is significant since much of the theoretical uncertainty in the world average above derives from the relatively low energies of the older DIS neutrino beams.

There are two significant questions regarding the importance of high precision comparisons among different reactions of $sin^2\vartheta_W$. First, the measurements are nearly precise enough to begin to probe the underlying electroweak field theory, the so-called test of radiative corrections. This tests the basic Standard Model; the theory should be well-behaved to all orders.

Second, given the reasonableness of those assumptions and the calculational tools, precision experiments become probes for new physics. This new physics could either take the form of observations which could be accounted for by natural extensions to the model, but also new physics which could only be admitted through radical extensions. Among the most popular and straightforward of the natural extensions is the bracketing of the mass of the presumed-to-exist top quark and Higgs boson.

The language used almost exclusively today to parameterize the answers to the above questions was formulated a number of years ago by Mariciano and Sirlin [24]. In their proposal, the *defining* relation for $\sin^2 \vartheta_W$ is:

$$sin^2\vartheta_W \equiv 1 - \frac{M_W^2}{M_Z^2}, \tag{7}$$

where M_W and M_Z refer to the physical masses. With this scheme, any other determination beyond the ratio of the physical boson masses requires corrections for high order contributions.

In the Standard Model, the Fermi coupling constant can be represented in terms of the mass of the W-boson and the coupling constant for the $SU(2)_L$ gauge boson, g as

$$\frac{G_\mu}{\sqrt{2}} = \frac{g^2}{8M_W^2}. \tag{8}$$

The Sirlin and Marciano scheme causes the high order corrections to be absorbed by g modifying it into $\hat{g}$ which is then defined in terms of a single parameter, Δr, as $\hat{g}^2 = g^2 + \Delta r$. In this way, apart from the *defining* relationship above, other measurements of $\sin^2\vartheta_W$ become dependent on the high order corrections through the parameter, Δr. For example, the mass of the W (and hence, Z) depends upon Δr in the following way:

$$M_W^2 = \frac{A^2}{(1-\Delta r)\sin^2\vartheta_W} \tag{9}$$

where $A = \sqrt{\frac{\pi\alpha}{\sqrt{2}G_\mu}} = 37.2810 \pm 0.0003\text{GeV}$ and is determined from low energy, precision experiments. In this way, the determination of $\sin^2\vartheta_W$ can be made through a measurement of the W or Z masses alone.

The radiative correction parameter, Δr will depend upon the masses of the electroweak theory (such as the top quark and Higgs boson) mostly due to vacuum polarization loops. Hence, extraction of $\sin^2\vartheta_W$ will result in different values depending on the choices of those masses. In this manner, determination of $\sin^2\vartheta_W$ can point the way toward new physics or help to constrain the values allowed for presumed-to-exist particles like the top quark.

The variation of $\sin^2\vartheta_W$ with top quark or Higgs mass is different, depending upon the general reaction chosen and the specific observable used. For example, the choice of $R = NC/CC$ in deep inelastic scattering contains contributions from higher order effects which largely cancel in the ratio. On the other hand, the determination of $\sin^2\vartheta_W$ in νe scattering as measured in the ratio $\frac{\sigma(\bar{\nu}e)}{\sigma(\nu e)}$ is fairly sensitive to the masses of heavy quarks. In comparison, the direct measurement of the intermediate vector boson mass (IVB) is similarly sensitive as well as being quite precise and it is the intersection of the allowed regions of this measurement with deep inelastic neutrino measurements which is presently the best discriminator on the top mass. The recent results are shown in Figure 4 for various reactions. Shown is the m_{top} dependence for the recent Z^0 mass measurement from the average of the CDF and Mark II determinations as presented recently [17)]; world-averaged neutrino deep-inelastic scattering neutral current data[23)]; CHARM II results for $\nu_\mu e$ elastic scattering[22)]; and the definitional relationship for the ratio of the IVB masses from CDF[17)]. The bands show the evolution of the heavy fermion sensitivity[17)] while the points are the specific top quark mass for which public values $\sin^2\vartheta_W$ were quoted. The square data point is the expectation for deep inelastic scattering at a precision of $\pm 2\%$, centered at the current mean value. For the first time, the mass of the top quark is clearly bounded from above and below through this (not uncorrelated) comparison among the Z^0 mass measurement, the definitional IVB mass ratio, and the deep-inelastic neutrino measurement and appears to lie between about 90 and 200GeV/c^2.

From this Figure it is plain that considerable benefit could be derived from more precision in the statistically potent deep inelastic scattering measurement and

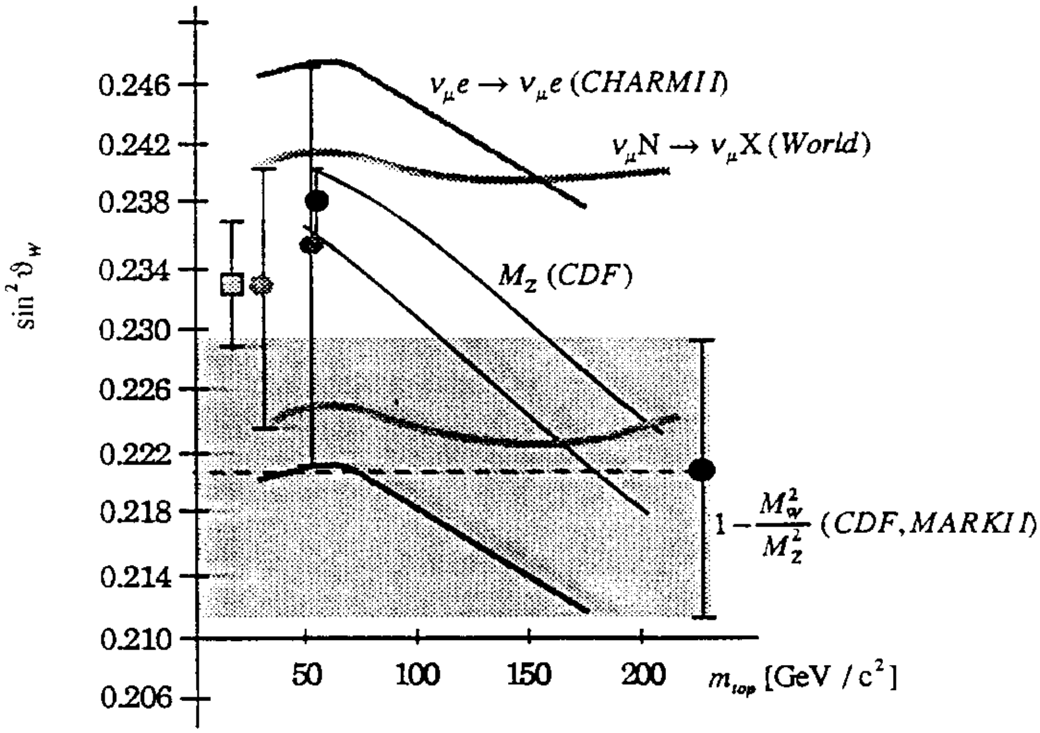


Figure 4: $\sin^2\vartheta_W$ vs. m_t for various processes.

it is to the question of what might be possible at Fermilab in this regard that the Electroweak Parameters addressed itself.

At stake is the advisability or feasibility of another deep inelastic experiment at the Tevatron with at least a partial purpose of remeasuring $\sin^2\vartheta_W$. In order to focus the discussion it is necessary to understand the roadblocks which stand in the way of a completely satisfactory acceptance of the data to date. In order to understand the contributions to the uncertainty, it is useful to note that much of the unpleasantness of neutrino physics cancels in a ratio such as R. The corrections and errors in this measurement are from:

1. Statistics. Here, a rule of thumb is that the statistical precision in $\sin^2\vartheta_W$ is 1%, 2%, and 3% for charged current event samples of roughly 170K, 40K, and 20K events respectively. Data sets of these sizes can be achieved.

2. Experimental systematics. For the ratio, no flux determination is required, only a proper counting of events. A useful rule-of-thumb is to note that approximately

$$\frac{\delta \sin^2\vartheta_W}{\sin^2\vartheta_W} \approx \frac{2\delta R}{R}, \tag{10}$$

suggesting that a small error in the ratio is seriously magnified in the propagation toward the derived quantity, $\sin^2\vartheta_W$. Uncertainties of a fraction of a percent in R are mandatory. There are two methods employed to distinguish the number of neutral and charged current events which are employed separately by the large iron calorimeter detectors such as CDHS and CCFR and the lighter, fine grained detectors such as CHARM and FMMF. The former experiments employ a statistical subtraction based on the observed length of events where high energy charged current muons always lead to long events. The latter experiments employ pattern recognition algorithms to distinguish the nature of the final states on an event-by-event basis. Experiments employing the statistical subtraction make corrections which are substantial (of order 20% in R) unless the exclusion of uncertain regions is undertaken. CDHS does not cut their data but CCFR does employ a y cut which reduces the correction substantially. The fine-grained experiments typically make corrections which are smaller (of order less than 10%). One experiment, CHARM, does not cut the data for cleanliness and the other, FMMF, does cut in y.

3. Theoretical uncertainties. The steps required to go from the measurable, R, to the desired quantity $\sin^2\vartheta_W$ involve a number of theoretical and phenomenological assumptions and parameters. This issue has recently received some comment[23)] and will only be sketched here. The major uncertainties in the ratio come from the assumptions in the charged current denominator in R. Further, there is considerable uncertainty in the modifications of the parton model which are required in order to account for the transition of light quark to charmed quark. Finally, there is some uncertainty in the quark mixing parameters (the Kobayashi-Maskawa matrix elements).

Were the Q^2 values higher in the older data, the length scale associated with the charmed quark mass would not be so large compared with that of the probe. However, the charm quark mass must be large, as considerable threshold behavior is seen in the neutrino production of charm. There is some experimental information on this process from the neutrino production of charm as observed by measuring the characteristics of dimuons. All that is known about the strength of the strange sea comes from the dimuon analyses.

As it was a subject for discussion in a number of sessions, a brief review of the phenomenology of "slow rescaling" is in order here. Charm production in neutrino interactions can occur from either the valence down quarks or the ocean strange quarks. The most immediate consequence of the necessity of overcoming a threshold of this sort is that the normal variable which describes the fraction of the nucleon's momentum carried by the struck quark,

$$x_{Bj} \equiv \frac{Q^2}{2MyE_\nu} \tag{11}$$

is replaced by the so-called slow-rescaling variable,

$$\xi \equiv x_{Bj} + \frac{m_c^2}{2MyE_\nu}. \tag{12}$$

The general transition term in the cross section for the conversion of a light quark $q \to c$ is

$$[U_{qc}] \cdot [(1 - y + \frac{xy}{\xi})] \cdot [\xi q(\xi)] \cdot [\sum_i \{D_c^{h_i}] \cdot [BR_i(h_i \to \mu)\}], \tag{13}$$

where the first factor is a Kobayashi-Maskawa mixing factor; the second factor is a kinematical suppression factor which comes from the V,A character of the interaction; the third factor is the parton momentum distribution of the light quark which is struck; the fourth factor is the fragmentation function of the produced charm quark for becoming a charmed hadron, h_i; and the last factor is the branching ratio for the *ith* charmed hadron to decay into a muon. For dimuon production, there are considerable uncertainties inherent in the last two factors which influence the degree to which this slow rescaling idea can be deemed successful [25)].

Figure 5. shows a graphical representation of various of the theoretical uncertainties in the neutral current measurements and their influence on the determination of $\sin^2\vartheta_W$. In this Figure, the severity of the correction's influence on the designated measurement is indicated by the gray-shade of the arrow. For example the determination of the amount of strange sea is heavily influenced by the assumptions inherent in the threshold calculational scheme. The important thing to note here is that the correlation between the determination of the strange sea and assumptions about the slow rescaling strategy are very strong. These assumptions generally involve an acceptance of the method and leave as a single parameter, the so-called charm mass (an unfortunate name, as its relationship to the actual mass of a quark is tenuous at best) m_c. Many of the new experimental ideas of the last year which address the determination of $\sin^2\vartheta_W$ have dealt with this issue of the theoretical uncertainties and those proponents were present for the discussions in this group.

2.4 Specific Research Options

With the advent of precision measurements of the IVB masses, and the announcement of the CHARM II preliminary results[26)], the emphasis was on DIS measurements of $\sin^2\vartheta_W$. There was one presentation of a new idea for a Main Injector νe elastic scattering experiment[27)]. This idea was to construct a water Cerenkov detector optimized for the precise measurement of the angle of the outgoing electron, and hence a precision determination of y. By using a narrow band beam, determination of y can be made in two nearly independent ways[28)]. Then, by fitting the y distribution, $\sin^2\vartheta_W$ can be determined in a flux-independent manner[29)].

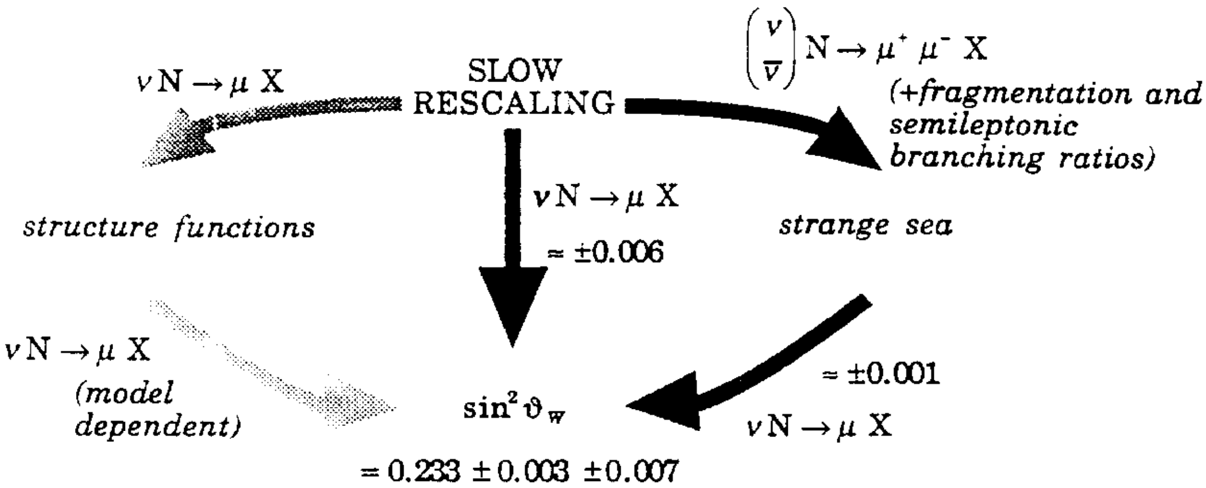


Figure 5: Contributions of theoretical error components to the determination of $\sin^2 \vartheta_W$.

The main discussion was to attempt to determine what should be the entry-level precision for any new DIS neutrino experiment proposing to determine $\sin^2 \vartheta_W$. Figure 6 shows the uncertainty, $\delta(\Delta r)$ versus $\delta(\sin^2 \vartheta_W)$ including the best expectations for the measurement of the IVB masses. The lines are for the world's deep-inelastic average value of $\sin^2 \vartheta_W$, combined with the present uncertainty of roughly ± 300MeV and expected uncertainty of roughly 50MeV in Z^0 mass. The data-point shown as an open circle is the expectation from a 50MeV determination of the mass of the Z^0 and the determination of $\sin^2 \vartheta_W$ from Eq. 7. From this type of consideration, plus the very different sensitivities in higher order to heavy fermions between the neutrino deep-inelastic and IVB mass determinations, the group concluded that any new experiment should be capable of determining $\sin^2 \vartheta_W$ to $\pm 2\%$ or ± 0.004.

There were four different research projects discussed which impact this issue of precisely determining $\sin^2 \vartheta_W$. They range from a more accurate calculation for the phenomenological process to selected determinations of the parametric ingredients of the slow rescaling process to actual proposals for completely new and unique measurements. They are:

1. Determination of the slow rescaling parameters via measurement of inclusive charm production to all final states in a low energy, high intensity neutrino beam. [6)]

2. Reliable calculation of the light-to-heavy quark transition including the "next-to-leading order" contributions from the gluon. [30)]

3. Determination of $\sin^2 \vartheta_W$ without the complication of any charged cur-

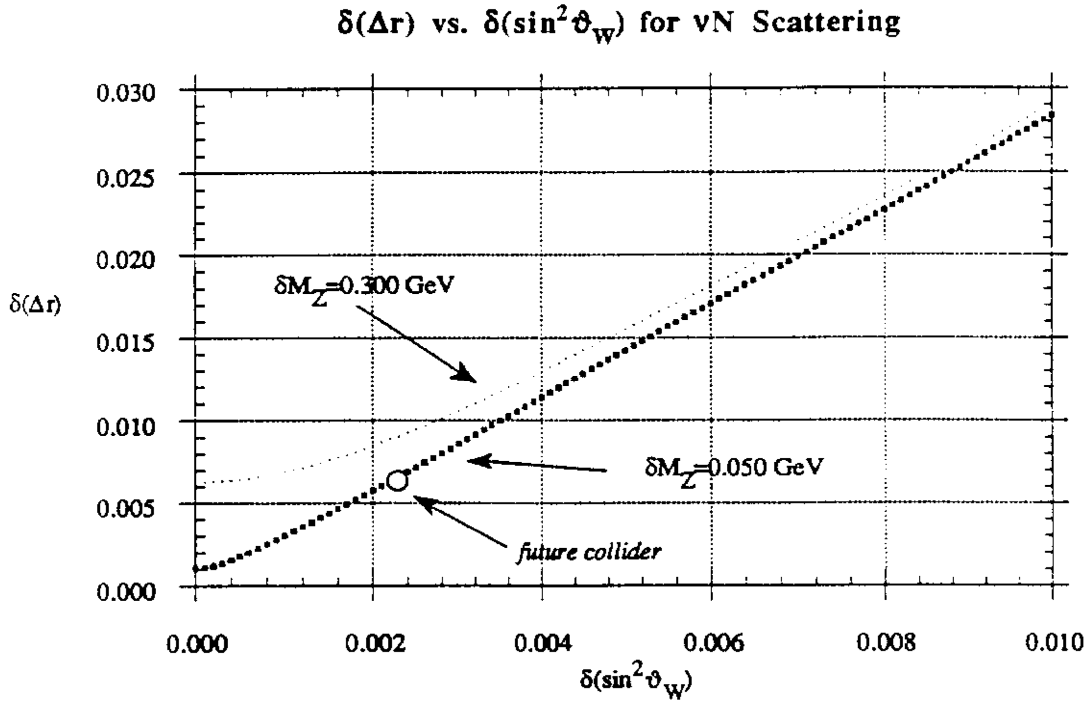


Figure 6: Uncertainty in the Δr parameter as a function of the uncertainty in $\sin^2 \vartheta_W$ according to Equation 9.

rent normalization at the Tevatron (900GeV) where the charm threshold effects are much reduced. [31]

4. Determination of $\sin^2 \vartheta_W$ with a normalization utilizing the inverse muon scattering process, also at the Tevatron. [32]

2.4.1 Determination of U_{cd} and m_c

A by-product of the emulsion oscillation search described in section 2.2 is a detailed investigation of the production of charmed hadrons by neutrinos. This is important for the primary physics issue of correctly determining the backgrounds to τ signals, as D^- decays from contaminant $\overline{\nu}$ are potentially significant. However, the collection of a significant sample of charmed hadrons of known type might provide a measure of some of the parameters which lead to the theoretical uncertainty in the neutral current measurements. If all charmed hadrons are observed and if all decay processes are counted, then normalization requirements for fragmentation would cause the last two bracketed factors to disappear in Eq. 13.

There are two general questions that might impact the question of the theoretical uncertainty in the neutral current analyses due to the $q \to c$ transition in the CC denominator of R[33]:

1. Does slow rescaling work at all?

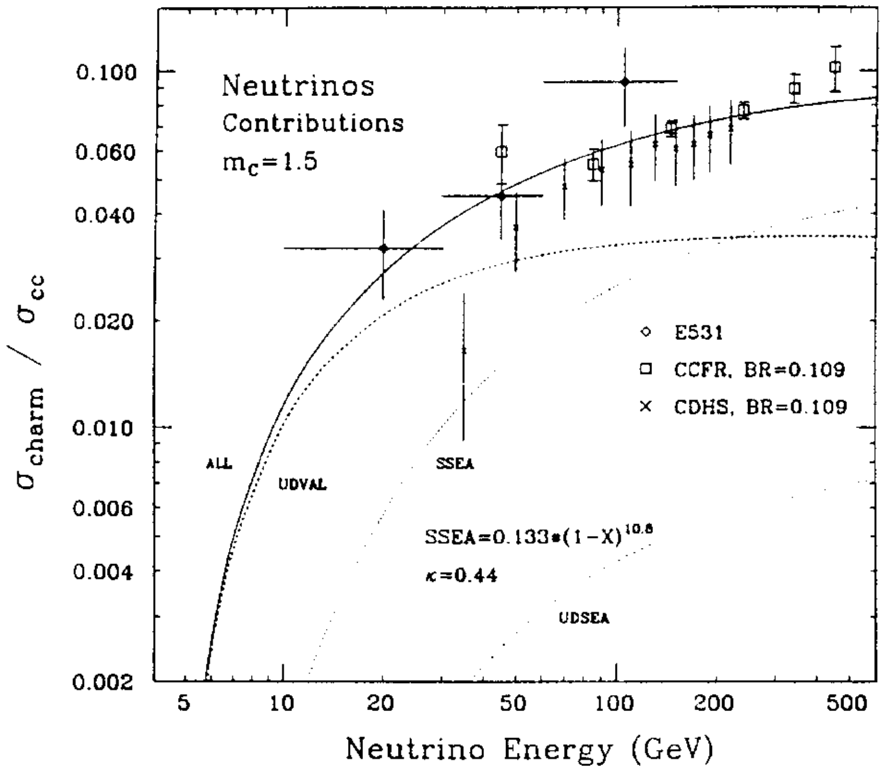


Figure 7: Quark and gluon contributions to charm production by neutrinos

2. If slow rescaling is reasonable, what is the value of the parameter, m_c?

By measuring the relative production of charmed hadron production to all charged current interactions as a function of reconstructed neutrino energy, it appears that significant progress could be made in this direction. In order to fully exploit the available sensitivity, the running of this experiment would be at both neutrino and antineutrino settings. Figure 7 shows the various contributions to charm production for neutrinos from the strange and down distributions where the data are from dimuons [34)] and hybrid emulsion [35)] experiments. The strange sea is represented in these curves by the form

$$\xi s(\xi) = 0.133(1-\xi)^{10.8} \tag{14}$$

as suggested by preliminary results from E744[25)]. Figure 8 shows results of a conservative simulation of the proposed Main Injector neutrino experiment for neutrinos and antineutrinos which indicates the sensitivity to the charmed quark "mass", m_c. Since the Main Injector horn neutrino beam is right at the kinematical threshold for charm production, the turn-on is rather pronounced. It is evident from this exercise that the antineutrino charm production is a good discriminator of m_c if the strange sea distribution is known. In order to understand the sensitivity to this poorly measured quantity, three models were tested which span the uncertainties from existing experiments with the following results. When a fit is done for 3 parameters ($|U_{cd}|$, the amount of strange sea, and m_c) the result gives ranges of $\pm 2.4\%$ to $\pm 2.7\%$ for $|U_{cd}|$ and ± 0.031 to ± 0.037 on m_c for each fit. The maximum variation among the parameterizations was $\pm 5\%$ for $|U_{cd}|$ and ± 0.10GeV on m_c. Clearly, the best available pararmeterization of the strange sea shape from higher-energy experiments will be required, and extrapolation of this shape to low energies must be checked with low-energy antineutrino data. However, even ± 100MeV is 25% of an optimistic estimate of the allowable m_c range. Because higher statistics analyses from dimuon experiments will be forthcoming from E770 and E733, it is anticipated that significant progress will be made in understanding the shape of the strange sea by the time the low-energy data are available.

Given the differences in the kinematical regimes covered by the older neutrino experiments and the Main Injector experiment, complications may arise in utilizing these results. In the former, the average neutrino energies and Q^2 are roughly 60GeV and 20GeV^2/c^2 respectively. For the Main Injector experiment these quantities are closer to 15GeV and 5GeV^2/c^2. The possibility exists, but was not yet addressed, that the emulsion experiment might be capable of directly determining $\sin^2\vartheta_W$ with the 200,000 charged current events that it would collect in the course of the oscillation running, thereby creating the attractive possibility of being able to measure $\sin^2\vartheta_W$ and determine the systematics within the same detector.

2.4.2 *Next-to-leading order calculation of $q \to c$.*

Should there be a high precision run of a detector such as the oscillation experiment, the language necessary to extrapolate the low Q^2 results to higher regions must be created. Therefore, a next-to-leading order calculation is being done [30]. Figure 9 shows the lowest order (LO) and the two next to leading order (NLO) Feynman diagrams for the production of charm by neutrinos. All of the dimuon and neutral current analyses to date have relied on the LO graph. However, experience with other kinematically suppressed processes show that rather severe corrections may be required when the process is calculated to NLO [36]. An order of magnitude calculation shows that the contribution of the inclusion of NLO terms will be negligible for the third graph (the quark process) but might be of the same order as the LO for the second graph, (the gluon contribution). This is easy to see, as the large gluon to sea-quark ratio (~ 10) can easily overcome the extra power of α_S (~ 0.1) associated with the NLO term. The calculation is being undertaken at IIT and is straightforward, but technically involved. The results, if seriously different from the LO contribution, will have far-reaching consequences for the dimuon determination of $xs(x)$.

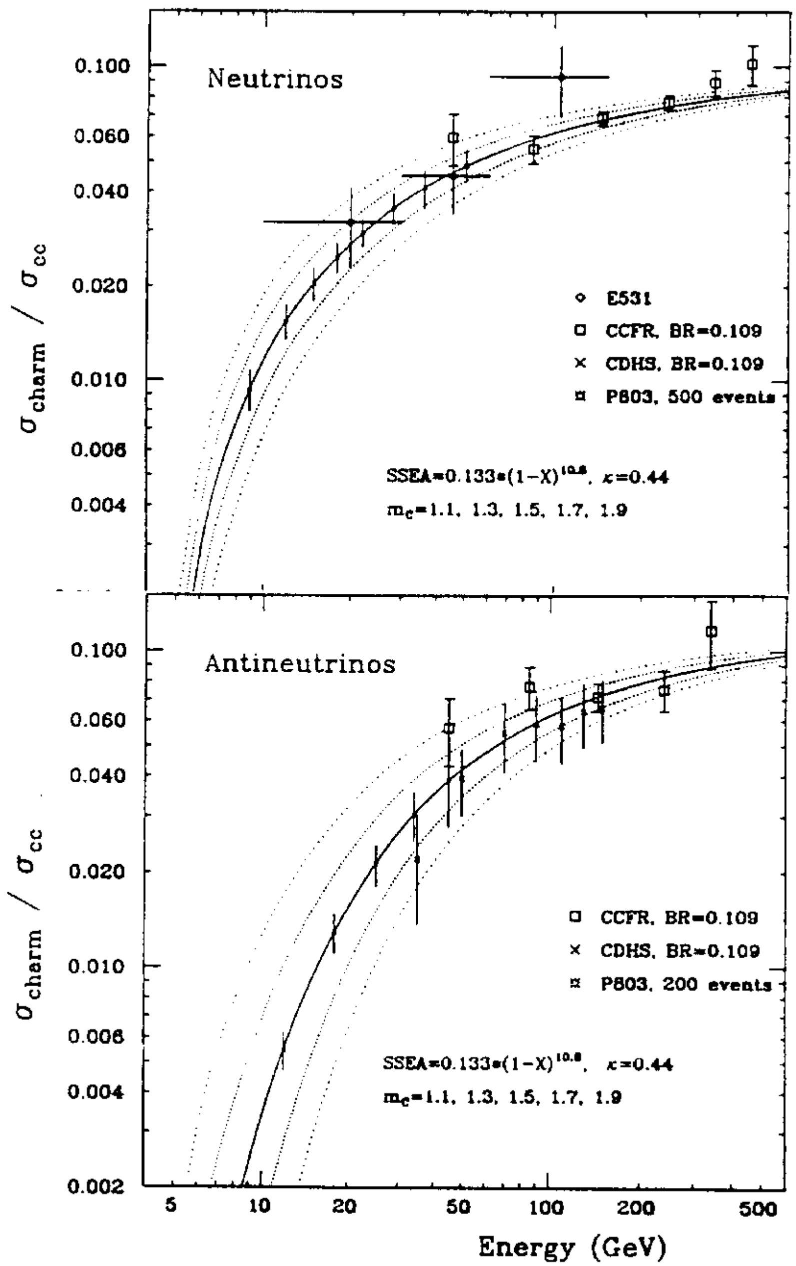


Figure 8: Simulation of the Main Injector emulsion experiment showing its expected sensitivity to the electroweak parameters

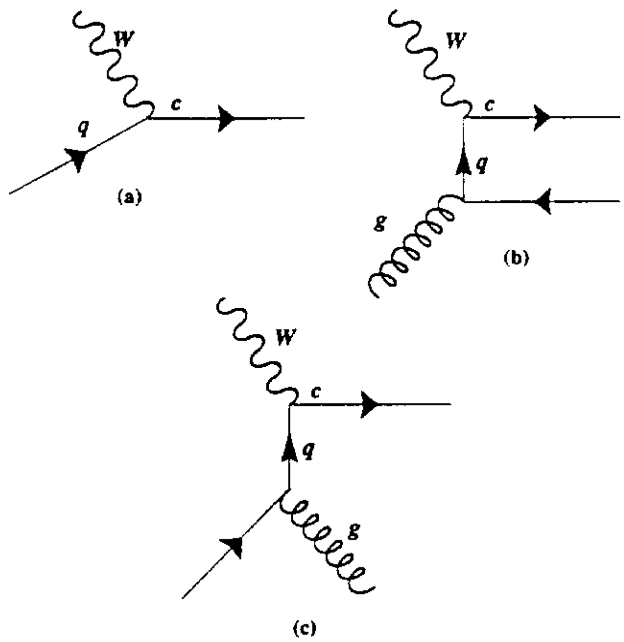


Figure 9: LO and NLO diagrams contributing to charm production by neutrinos

2.4.3 Determination of $\sin^2\vartheta_W$: $R' = \sigma(NC_{\bar{\nu}})/\sigma(NC_\nu)$

One way in which the unpleasant features of the charged current denominator in the standard R can be avoided is to eliminate the normalization altogether. This has been suggested in Fermilab Proposal P788[31]. According to the scheme outlined there, in order to normalize the neutral current cross section, and therefore continue to minimize through cancellation the parton distribution uncertainties, the ratio of antineutrino to neutrino neutral current cross sections would be determined. There is still considerable sensitivity remaining for $\sin^2\vartheta_W$ and the premium is then on knowing the precise number of neutrinos and antineutrinos. This would be accomplished through the implementation of a unique neutrino beam which would be produced in the slow-spill extracted Tevatron cycle from tagged K_L^0 mesons. By linking up the sign of the tagged muon with the observed neutral current event, the $\nu/\bar{\nu}$ character of the responsible beam neutrino can be determined. A drawback to such a system is that the occupation level of the proton buckets must be kept as close to one as possible, which limits the amount of instantaneous rate which the experiment could tolerate with this technique. That, in turn, might limit the statistical precision available for other physics studies such as precision structure function tests, which may be required.

Therefore, in order to collect significant samples the target/calorimeter envisioned for this measurement would be a large iron calorimeter of a size three times larger than that of the old CDHS detector, or 3500t. With this size detector, the data sets should be about 300k charged current events in a couple of fixed target running periods. The technique for distinguishing neutral from charged currents would be the traditional statistical subtraction based on event length. It was estimated that the correction at the Tevatron using this method might be as high as 15% with an uncertainty which cannot be properly assigned without considerable study. Discussion of the discrepancy between the quoted CDHS charged current $\rightarrow$ neutral current correction $(22 \pm 0.35\%)$ and the CCFR correction $(22 \pm 1.65\%)$ resulted in controversy. It should be noted that the CDHS measurement relied on a normalization for the short CC subtraction by carefully modeling the long events in a region that is much less plagued with theoretical uncertainty,namely the extremely high y region. It was left as an exercise for the participants to try to reconcile the extreme differences in these uncertainties and many felt that an analysis scheme that did not rely on such details was preferable and probably necessary in order to reach the precision required. While still relying on a statistical subtraction, it was noted that the R' method is likely to be less sensitive in this regard than the traditional measure, R. There will be no substitute for detailed simulation and an analysis of the present E744/E770 data in attaining a reasonable resolution to this issue.

In order to reach the desired precision on $\sin^2\vartheta_W$, the parton uncertainties become a serious problem, and in particular, the antiquark distributions must be known very well. The present determination of $\overline{Q}Q$ would lead to an unacceptably large error on $\sin^2\vartheta_W$ of $\pm 6\%$. Hence, this must be reduced in the proposed experiment or from some external source. The plan would be to attempt to determine this quantity by again utilizing the features of the tagger to carefully measure charged current events. Eventually, the total error is anticipated to be at the 2% level on $\sin^2\vartheta_W$.

2.4.4 *Determination of* $\sin^2\vartheta_W$*: Normalization using inverse muon decay.*

A second experiment was considered during the workshop which surfaced within the context of both the discussion of the Weinberg angle and QCD tests[32]. The goal of this experiment would be to maximize the statistical power in a neutrino experiment by utilizing a more conventional neutrino beam (such as a sign-selected Quadrupole Triplet beam or a more open-geometry dichromatic beam) with a greatly enhanced target calorimeter along the theme of the present CCFR detector. Here the plan would be to utilize the full capability of the Main Injector upgrade and to collect a reconstructed sample of the size of 15M νCC and 3M $\overline{\nu}CC$ events. The particular neutral current measurements would also eliminate the DIS charged current normalization, replacing it with the theoretically straightforward inverse muon decay process,

$$\nu_\mu + e \rightarrow \mu^- + \nu_e. \tag{15}$$

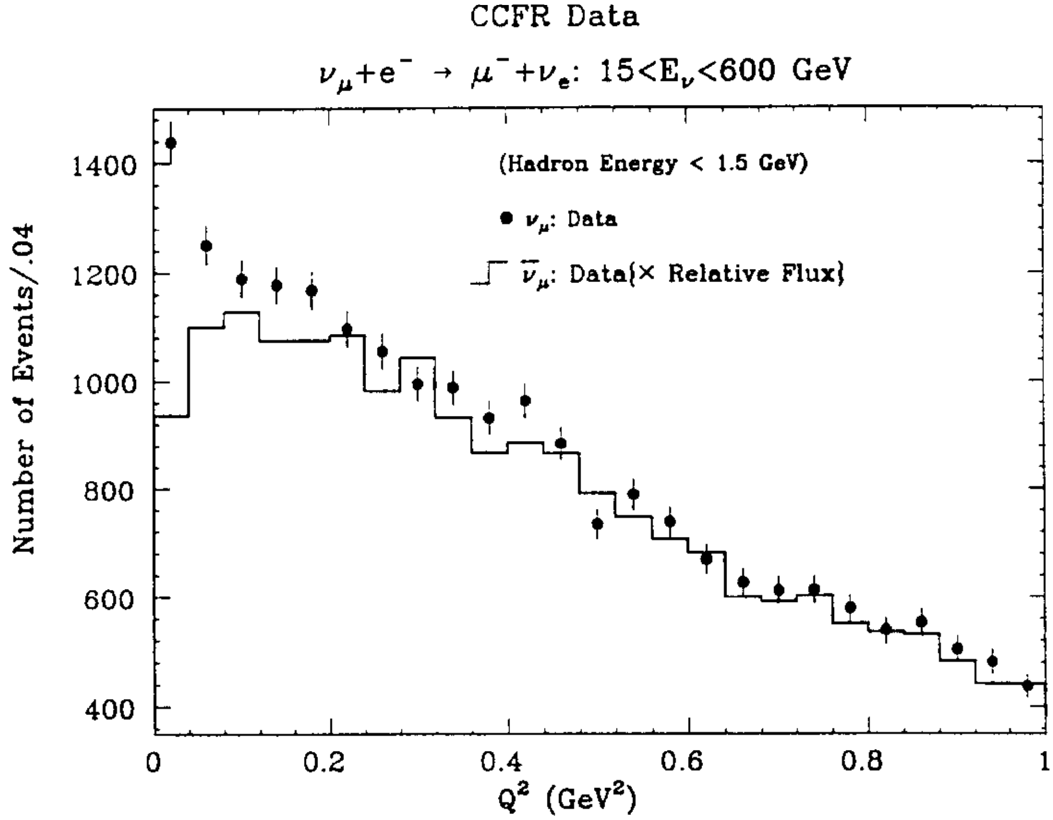


Figure 10: E744 signal for inverse muon decay

In addition, other techniques such as the y extrapolation scheme will be used. All of these schemes rely on high statistics. This reaction has been studied by the CCFR group[37)] and Figure 10 shows the signal for this process which, with enough statistics, could be measured for different energy ranges to establish the neutrino flux. Once that is done, there is a variety of measurements that can be made which would lead to an eventual extraction of $\sin^2\vartheta_W$. These include the traditional $R = NC/CC$ and $\overline{R} = \overline{NC}/\overline{CC}$ measurements, the desirable, but difficult Paschos-Wolfenstein[38)] test,

$$R^- = \frac{\sigma(\nu NC) - \sigma(\bar{\nu}NC)}{\sigma(\nu CC) - \sigma(\bar{\nu}CC)}, \tag{16}$$

as well as R'. Each of these techniques is very different in their individual sensitivities to the experimental and theoretical systematics and may also have different sensitivities to higher order effects such as heavy fermions.

In order to distinguish the NC from CC samples, the reliance on the traditional iron calorimeter statistical subtraction would be abandoned in favor of an event-by-event selection utilizing faster flash ADC readouts of E770-like drift chambers. Preliminary indications suggest that corrections for CC → NC confusion would be at the 1-2% level and that a few percent determination is then feasible for $\sin^2\vartheta_W$.

Because of the likely wide-band character of the beam for this proposal there will be a contaminant flux of ν_e from the three-body kaon decays. In all detectors the DIS reactions of these neutrinos will all appear to be ν_μ neutral current events and so a subtraction must be made. There remains a considerable study that is required in order to understand the significance of this background. However, with the extremely large samples envisioned for this experiment (made possible by the proposed accelerator upgrades), considerable detail about the beam can be obtained and the actual K/π ratio determined as a function of radius. With this information and a careful beam simulation, it is hoped that this problem can be minimized.

3 HADRONIC STRUCTURE

3.1 Introduction

To a large extent over the last 10 years hadron physics has evolved into quark parton physics. We are dominated by the quark parton model and its more rigorous successor, the theory of Quantum Chromodynamics. Over the last decade QCD has established itself as the likely theory of strong interactions. On the other hand, while we use its precepts on a day to day basis (non-believers are treated as heretics), we are often dissatisfied by the lack of quantitative testing of the theory beyond its most primitive predictions. These predictions are often very close to those of the naive quark parton model. This situation is all the more unsatisfactory since we base a number of the projections to higher energies, for instance at the SSC, on the evolution of QCD processes over several orders of magnitude in cross-section and scale. Until very recently and even now the most sophisticated tests of the QCD and most of the measurements of parton distributions have come from fixed target experiments with some help from electron-positron colliders.

The QCD Phenomenology Subgroup was directed towards reviewing the status of the development of analysis machinery necessary to make more rigorous the tests of perturbative QCD and to make experimentalists more aware of just what are the fruitful directions toward which they might focus their attention. In this we shall consider the current status of the phenomenology of parton distributions from the point of view of understanding the distributions for ultimate use in other domains, for instance collider physics. We shall also consider the current level to which the experiments test the theory. Finally we consider whether the situation can be significantly improved by a "next generation" of experiments in several well defined classes.

3.2 Quantum Chromodynamic Phenomenology

3.2.1 General Comments

The study of hard scattering processes has two basic goals:

– to see if one can obtain a complete quantitative description of all such processes, for example, deep inelastic scattering, lepton production, direct γ production and hadronic jet production,

– to use the QCD parton formalism to determine the various types of parton distributions.

The latter will be discussed in more detail in the next section. However, it is necessary to make some remarks about the status of our theoretical understanding.

Up to the present time much of the phenomenological work has been based on calculations in the leading logarithm(LL) approximation. For quantitative tests calculations which include next-to-leading-logarithm (NLL) are imperative. Such calculational machinery now exists and makes predictions for a variety of single inclusive cross-sections including heavy quark[39)], jet[40)], γ[41)] and $\gamma\gamma$[42)] production in hadron-hadron collisions and photoproduction[43)]. In addition programs now exist which allow the calculation of various correlated observables in direct γ production and photoproduction to $\mathcal{O}(\alpha\alpha_S{}^2)$. Examples include $\gamma + jet$ final states in hadron hadron collisions and dijet cross-sections in photoproduction[44)].

In order to test the underlying QCD dynamics it became apparent that we need experiments with a wider range of rapidity and p_t than are currently available. For example, few direct γ experiments have yielded data for $y{\neq}0$ and only one extends beyond $y{\sim}1.5$. Accurate y distributions are needed, not only to test QCD dynamics but also for the parton distribution determinations.

Joint distributions, for example $\frac{d\sigma}{dp_T dy_1 dy_2}$ in direct γ production, are required both for testing QCD sub-process descriptions as well as for parton determinations. Cross-sections for $\gamma + jets$ and di-jets can be used to extract sub-process averaged angular distributions. The technology has been developed to calculate at least some of these to NLL accuracy.

At fixed target energies it may be useful to consider observables which depend on jet directions and not necessarily on jet energies. This would reduce the sensitivity to jet clustering algorithms, which are very tricky at fixed target energies, and also to the treatment of very soft particles.

NLL calculations in general show less dependence on the renormalization(μ) and factorization (M) scales than do the LL calculations. However the residual dependence can be very significant. There appear now to be several alternatives for the pragmatic practitioner:

Fastest Apparent Convergence[45)]:
Minimal Sensitivity[46)]: $\frac{\partial\sigma}{\partial\mu^2} = \frac{\partial\sigma}{\partial M^2} = 0$
Brodsky-Lepage[47)]: choose scales to absorb fermion loop contributions
Fixed Scale: $\mu^2 = M^2 = np_t{}^2, \frac{1}{4} < n < 4$

Although the whole subject was discussed in several fora at this Workshop, it clearly has the ring of a religious subject and is therefore unlikely to have a definitive resolution short of eliminating all groups except one. One possibility which was considered is to treat the possible variations as an estimate of the residual theoretical uncertainties in the way that one takes the difference between two measurements as an estimation of the errors on those measurements. That is, treat the problem as a systematic uncertainty. This can then be probed from different directions, perhaps taking advantage of the possibility that some observables may have less scale dependence than others, at least for some range of kinematic variables. For example, the di-jet cross-section in photoproduction appears to be much less sensitive than the single jet cross-section. Other examples should be identified and studied. Unfortunately there is little guarantee that such criteria indicate anything profound about the "all-order" calculation of the process, but will hopefully lead to a less confusing situation.

3.2.2 Determination of the Parton Distributions

The discussions in this section are given in the context that there is a more than 10 year history of determination of parton distributions going back to the early analyses of Buras and Gaemers[48)] and developing through, for example, Gluck, Hoffmann and Reya[49)], Duke and Owens[50)], EHLQ[51)], MRS[52)], and more recently Diemoz et al[53)]. At the Snowmass workshop in 1988 a group containing both experimentalists and theoreticians considered the limitations in both data and analyses. It was clear[54)] that the global fitting of structure function data requires rather more care than just the inclusion of quoted statistical uncertainties. A whole range of experimental and theoretical uncertainties need to be explored and taken into account in the analysis. As a followup to this study, Morfin and Tung[5)] are on the verge of publishing new sets of parton distributions in which they include systematic errors and handle some of the inconsistencies in the data in a consistent manner. They have also included a range of possible small-x behavior allowed by the current data, but provide distinct extrapolations to the physics processes explored in colliders from the Tevatron to the SSC. At the moment they have included all major lepton scattering structure function data together with the high statistics Drell-Yan experiments, E288 and E605. The plan is to systematically include all viable QCD hard processes in a global analysis on a continuing basis. Recently, an analysis including deep inelastic data from BCDMS[55)] and prompt photon data on fixed targets[56)57)] has been published[58)]. It was found that all the considered data could be described with a unique set of parameters and that the gluon distribution in the nucleon was well constrained. A further analysis involving the prompt photon data using a π[59)] beam as well as the constraints on the π valence distributions arising from dimuon data[61)] lead to the determination of the gluon distribution in the pion[62)]. The Durham group is also involved in a joint analysis of deep inelastic, prompt photon and dimuon data to determine the proton structure function[63)].

Precision electroweak studies necessarily rely on accurate determinations of parton distributions. The theory makes no predictions at this stage for the actual distributions, merely their interaction and evolution. The NLL calculations of cross-sections requires parton distributions determined to the same order and defined in the same scheme. Knowledge of the gluon distribution, in particular, must be improved in order to accurately describe the dominant processes at collider energies. Further knowledge of all parton distributions at very low x_{Bj}, of the order 10^{-3}, is important in order to overlap with collider experiments in that region. Even then, the ability to overlap with HERA is almost nil; a subject which will likely cause some future consideration at DESY as little can probably be done about it at Fermilab. Determinations of the electroweak parameters and tests of the theory were discussed in the previous section. In both the collider and fixed target regimes the limitations are given by the knowledge of the flavor dependence of the distributions of the ocean quarks.

There is no universally accepted best way of determining individual distributions since they enter different processes in different linear combinations with different weights. In addition the experiments are sensitive to different Q^2 and x_{Bj} ranges, where Q^2 is the relevant hard scattering scale. This necessitates some form of global approach, using as many varieties of data as possible. On the other hand blind fitting of all data is also probably not the relevant thing to do since the data are of varying quality. At the present time, calculations exist within the NLL formalism for deep inelastic lepton nucleon scattering, lepton pair production and direct γ production .

High precision measurements of $F_2{}^p - F_2{}^n$ in muon experiments and xF_3 in ν experiments can accurately determine $\Lambda_{\overline{MS}}$. Discussions of proposed and discussed experiments[1)],citebazizi1 suggested that a precision measurement is possible with errors in the region of $10 - 30$MeV. Such measurements are desirable since these non-singlet observables do not depend on the gluon distribution. To date the non-singlet data have always been inferior to that on observables such as F_2 with a singlet component due to experimental limitations and statistics.

Use of F_2 alone, even with the high statistics data available from BCDMS[55)], leaves a well-known correlation between the value of $\Lambda_{\overline{MS}}$ and the gluon distribution. The gluon enters only through the evolution equations, a larger(smaller) value of $\Lambda_{\overline{MS}}$ corresponds to a harder(softer) gluon. The effect is primarily to limit the sensitivity to the gluon rather than to limit the determination of $\Lambda_{\overline{MS}}$. On the other hand, this is not, by any means, the only correlation between Λ and the parameters of the parton distributions and other implicit input to the fits such as the ranges of kinematic variables, theoretical functional forms for the parton distributions, etc. in the fits.

In single photon production the correlation is quite different since $\Lambda_{\overline{MS}}$ affects the absolute cross-section through α_S. The gluon distribution also affects the absolute cross-section, but in this case a hard gluon increases the calculated cross-section thus forcing a decrease of $\Lambda_{\overline{MS}}$. The correlation between the two objects is opposite in the two processes. Furthermore, the calculated cross-section receives direct contribution from the gluon through the QCD Compton diagram, not just through the evolution. Therefore, the combination of data from the two processes is more powerful than either type of data by itself. Of course it is also necessary to attempt to assure oneself that the data are correctly described by perturbative QCD since there is always the worry that strong higher twist effects[65] may be present especially at low p_T. A recent analysis of $\pi p \to \gamma X$ data by the WA70 experiment[59] did not find any evidence for higher twist effects[66]. Apparently no anomalies were observed in the x_F distributions nor any excess of isolated particles opposite the single photon. However, higher twist effects may nevertheless be present, and their effects may be responsible for the hard gluon distributions and large values of α_s extracted from fixed target data.[60] To properly pin down the role of high twist contributions experimentally, it is necessary to separate the p_T and x_T dependences of the cross section by doing the same experiment at two relatively widely spaced values of $\sqrt{s}$.

The sea distributions are strongly constrained by lepton pair production data in hadronic collisions. The dependence on both $\Lambda_{\overline{MS}}$ and the gluon distribution enter through the evolution equations as in deep inelastic scattering. However, the dependence via the sea gives another constraint on both $\Lambda_{\overline{MS}}$ and the gluon.

By jointly considering all three types of data, strong constraints on the valence quark, sea quark and gluon distributions are obtained, thereby justifying the concept of global fits. Note that jet photoproduction data, when it becomes available, will yield additional constraints when incorporated into these fits.

Flavor differentiation among the ocean quarks is still poor. High precision measurements of dimuon yields can constrain the charm sea in muon experiments and the strange sea in neutrino experiments[67]. Measurements over the full y range are needed for the latter. Flavor differentiation is especially enhanced through precision fits to the y distributions in neutrino charged current scattering[68]. High statistics data on $\bar{\nu}$ DIS and dimuon production will contribute substantially to advancements in this area. As mentioned above a NLL formalism for treating heavy quark production is in process[30] and should be implemented in such an analysis.

Theoretical uncertainties will remain, even in NLL calculations, especially for direct photon production These were referred to in the introduction to this subsection and are related to scale uncertainties which will however propagate to the determination of the parton distributions. The only possibility is to use different prescriptions and compare them in order to estimate the uncertainties. Often the choice of scale most strongly affects the normalization rather than the shape. Therefore it is conceivable that fits can be made in which the relative normalizations of the different data types is left arbitrary and only the shape information is used. It remains to be seen what power is left in the data if this is done for all of the data sets.

3.2.3 Extensions to the QCD Analysis Program

There is a calculation[69] for deep inelastic scattering and lepton pair production, in which the dominant $O(\alpha_S{}^2)$ terms are included. This formalism should be used to estimate the effects of the newly calculated contributions.

The bulk of the available hadron-hadron data for jet, single photon or dilepton production are for $y \sim 0$. It is necessary to obtain the y distributions with good statistical accuracy at different p_t values. The point is that the jet or single photon cross-sections involve the integral

$$\int_{x_a min}^{1} G_i(x_a) G_j(x_b) \sigma_{ij} dx_a, \tag{17}$$

with $x_{amin} = \frac{x_t e^y}{2 - x_t e^{-y}}$ and $x_b = \frac{x_a x_t e^{-y}}{2x_a - x_t e^y}$. Such x_{min} effects are useful at collider energies as they permit discrimination between different gluon distributions by using the rapidity distributions of direct photons at $p_T \simeq 10$GeV (see the Report on Collider Phenomenology at this Workshop).

Increasing the y value samples smaller values of x_b, but one still has a convolution with $< x_a > \sim < x_b > \sim x_T coshy$. Photon+jet or dijet data observables such as $\frac{d\sigma}{dp_T dy_1 dy_2}$ determine x_a and x_b via,

$$x_{a,b} = \frac{x_t}{2}[e^{\pm y_\gamma} + e^{\pm y_{jet}}]. \tag{18}$$

Independent control of y_γ and y_{jet} therefore allows a broader range of $x_{a,b}$ to be probed.

3.2.4 Single Photon Issues

At low values of x_T the bremsstrahlung contribution is significant. A leading logarithm estimate at $x_T = 0.05$, $\sqrt{s} = 1.8$TeV yields the result that the bremsstrahlung contribution is $\frac{2}{3}$ of the direct graphs. More work is needed to understand this component and match the theoretical predictions to the collider data which include only a part of the bremsstrahlung contribution because of photon isolation cuts. For fixed target data this component is relatively small, of the order of 30% at low p_T. The fixed target direct photon experiments typically constrain the gluon distribution at larger x values than the collider experiments. This large x information is vital for two reasons

– the momentum sum rule constrains the overall normalization of the gluon distribution. Thus, differently shaped distributions cross over in the low x region, typically between $x \sim 0.05$ and $x \sim 0.1$. It is necessary to get to large x in order to be sensitive to the power of $(1 - x)$.

– In the large x region the effects of scaling violations are larger; it would be nice to see these effects in the data.

The collider experiments yield complementary information by probing the low x region and, modulo the caveats about the bremsstrahlung contribution, such information is necessary to help constrain the low x behavior of the parton distributions. A wide coverage in rapidity is helpful as explained above. Knowledge of this low x region is crucial for extrapolation to SSC energies. Current analyses often use a $Q^2 > 5 - 10\text{GeV}^2$ cut to reduce the effects of charm thresholds and target mass corrections which effectively eliminates the low x data. This is clearly the region in which HERA has a chance to contribute. However, if at all possible, it is desirable to have an overlap with the low energy data so that the lever arm in $\ln Q^2$ is maximized. At present the extent to which this can be achieved is problematic.

3.2.5 *Higher Twist Effects*

As mentioned above, deep inelastic analyses are often made with the lower Q^2 data cut away in the hope that this removes target mass corrections (TMC) and higher twist effects which are theoretically intractable at the present time. There is evidence in the data, when combining muon scattering data from CERN with electron scattering data from SLAC, that a signal of a non-vanishing twist-4 term is observed at high x_{Bj}[67]. However, the opposite trend, if any trend is observed at all, is seen in neutrino scattering. [70]. Hence, the situation for higher twist is perhaps confused both experimentally and theoretically (perfect agreement between experiment and theory?). More attention may be required in this area should experiments such as the Main Injector neutrino oscillation experiment be run with the subsidiary goal of studying "regular" charged and neutral current physics.

It is therefore prudent to worry about whether similar effects can be present in the hadron scattering data. When considering hadron scattering, indeed there are specific kinematic regions at large x_T and low to moderate p_T, say $4 - 8\text{GeV}$, where the effects of the "intrinsic k_T" of the target partons can be expected to be important. This issue is especially important if nuclear targets are used since these may introduce further sources of p_T broadening. Measurements of $hh \to \gamma\gamma + x$[71], for which a NLL calculation exists[71] can be of assistance. The goal would be to disentangle the "higher twist, intrinsic k_T" contributions, the nuclear effects and the calculable dynamic QCD effects.

3.2.6 *Conclusions*

The number of next-to-leading logarithm calculations has increased dramatically in recent years, thereby making possible "global" fits to data on electron, muon, and neutrino deep inelastic scattering; dilepton production; direct photon production; and jet photoproduction. A formalism also exists for calculating correlated observables in photoproduction and direct photon processes. The potential exists for decisive, accurate determinations of parton distributions as well as tests of the underlying dynamics. In the near term there are a number of contributions which could be made in a vigorous fixed target program:

– increased precision measurements in order to resolve the BCDMS/EMC discrepancies and to improve the determinations of Λ_{QCD} from both singlet and non-singlet measurements and to improve the knowledge of the composition of the ocean.

– increased rapidity coverage of high statistics direct photon, dilepton and jet cross-section measurements.

– accurate correlation observables in hadron-hadron and photon-hadron interactions.

– overlap between lepton scattering data with present accelerators and that expected from HERA.

3.3 Experimental Possibilities

3.3.1 Lepton beams.

Deep inelastic scattering of electrons provided the seminal experimental information which, while predicted by Bjorken[72)], stimulated development of the Quark Parton Model and the emergence of QCD. The first evidence for the scale breaking associated with the latter came from a muon beam experiment at Fermilab in the 1970*s*. Since that date a series of large, relatively well supported lepton scattering experiments, both muon and neutrino, at CERN and at Fermilab have made major contributions to our knowledge of the systematics of the quarks, the gluons, the roles of their quantum numbers and the coupling parameters of the theory. Even the series of experiments at SLAC has offset the relatively low energy by judicious choice of kinematics and the high flux of electrons. Currently there are muon experiments running at CERN and Fermilab but no neutrino experiments. We examine below the question whether a further generation of lepton scattering experiments can make a major step forward. The context of the question is set by the discussion of phenomenology above and the expectations for HERA, the electron-proton collider at DESY, Hamburg[74)]. It should be emphasized that we imposed rather restrictive limitations on the breadth of study possible in the time available. To a large extent the possible experimentation which emphasizes the hadronic final state and which has also contributed good insight into the field of hadronic physics, was neglected.

A Muon Experiment[64)]

The current state-of-the-art structure function experiments have measured the scale parameter, Λ, of the strong interaction with an error of about 100MeV. The value of Λ_{QCD} is in the region $100 - 200$MeV. When expressed in terms of the coupling constant, $\alpha_S(100\text{GeV}^2) = 0.1585 \pm 0.0025 \pm 0.009$, as quoted by Feltesse[73)] for the recent hydrogen and carbon measurements of BCDMS. This puts the level of experimentation in better perspective. In fact these determinations come from data sets with statistical errors of the order of 1% over a wide region of Q^2 and x_{Bj} and with systematic errors of various sorts which are estimated at the $2 - 7\%$ level.

The agreement or disagreement between the data sets also provides an independent measure of the errors. The disagreements are in the region $10 - 15\%$ in the worst cases. The extent to which they test and agree with QCD was discussed above.

The working group considered the situation and attempted to evaluate the physics that could be done with a high luminosity muon scattering experiment using the upgraded Tevatron muon beam. It also considered the apparatus that would be required.

As noted in the above short summary of the data, the experiments can be interpreted as determining α_S. On the other hand they as yet make little statement, certainly none explicitly, about the evolution of the coupling constant. Indeed comparing the world knowledge from different processes a systematic trend is not evident. The group therefore considered that a primary goal of an experiment with high luminosity should be to observe the evolution of α_S exploiting the available moderate to high x_{Bj} reach.

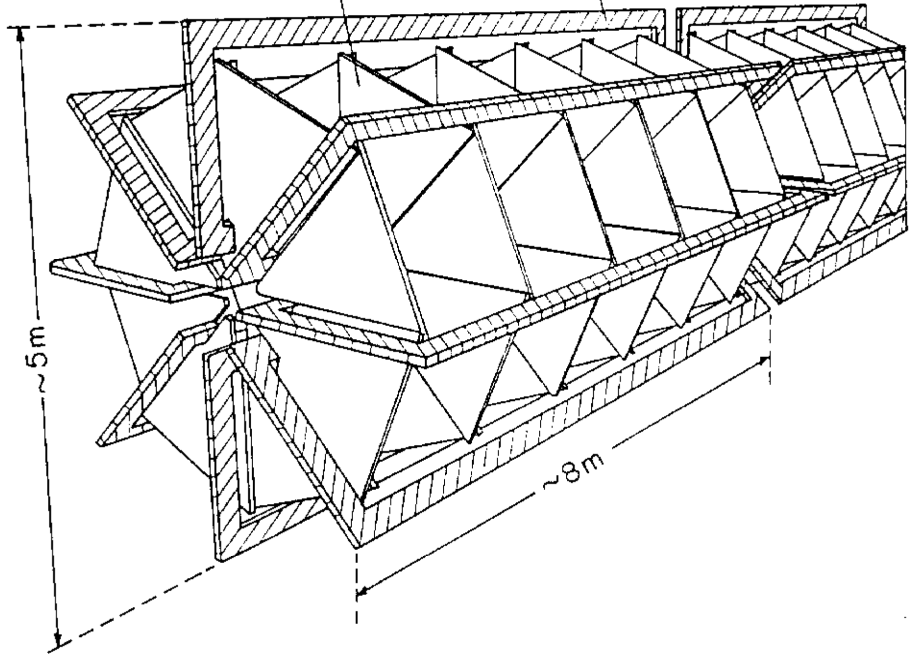
The evolution of the coupling constant, its running, can in fact be observed and disentangled from possible higher twist effects. Λ_{QCD} can be measured at the level of 10MeV. This represents nearly an order of magnitude improvement in the knowledge of this parameter. In terms of α_S this is a 1% measurement. It should perhaps be emphasized that these are experimental statements. If the theory is such that in fact there are complicating issues at this level then they would be observed and the theorists could think again. The QCD predictions for R at fairly low x_{Bj} and high Q^2 can be tested. Λ_{QCD} can also be measured using the non-singlet $F_2{}^p - F_2{}^n$.

A second and important function of the experiment would be to furnish even better parton distributions for use in all parton model applications.

The FNAL beam is well suited to the experiment under consideration. The final restriction on beam intensities comes from systematic problems in the detectors. The FNAL beam has three advantages over the CERN beam. It can deliver higher energy beams (up to 600GeV versus 300GeV); it can deliver 2.5 times as many muons per unit time at a given beam energy when the instantaneous flux is limited by the detector; the machine RF is 53MHz making the bucket structure easier to utilize (compared to the 100MHz at CERN after the upgrade). It is clear that Fermilab is the best place to do a high precision, high luminosity muon experiment.

Two basic detector configurations were considered, see (Figure 11): an air core toroid experiment similar in geometry to the BCDMS experiment, the other a double dipole based on the current E665 configuration. The former has a target of approximately 25m length, the second one of about 10m, so that both will have very high luminosity. The prime consideration then becomes the question of systematics. The main differences between the experiments are:

– for a given beam energy the range of Q^2 over which the acceptance of the air core toroid is flat is twice that for the double dipole.The dipole would have to utilize regions of reduced acceptance to achieve the same range with concomitant uncertainties in the determination of that acceptance.



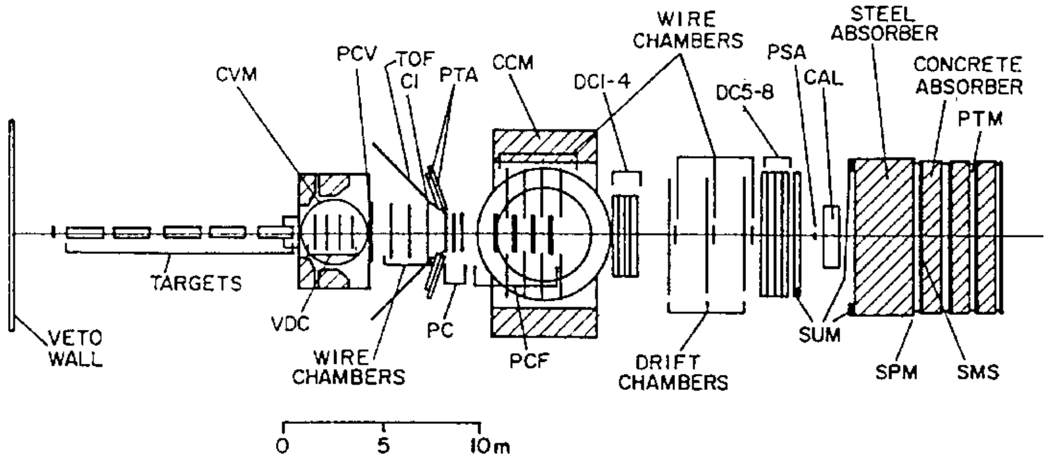


Figure 11: Layouts of the Air Core Toroid and the Double Dipole Experiments

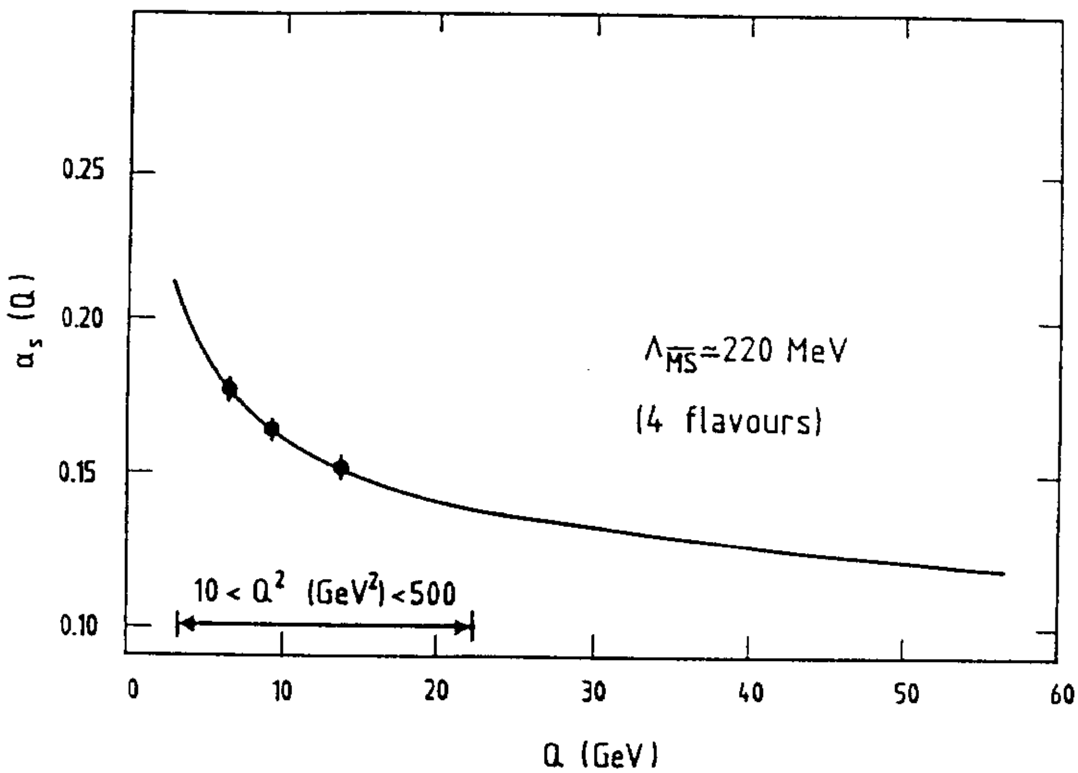


Figure 12: Projected Measurements of the Strong Interaction Coupling Constant

– the air core toroid has a field completely determined by the coil geometry and the current, there being no magnetic material involved. This means that the field calculations are reliable and furnish an important check of the field measurements. The level of accuracy in the fractional momentum needed is of the order of 10^{-4} for all possible trajectories.

– the recurrent nature of the apparatus and the relative behavior of the muon and hadrons makes the pattern recognition a relatively straightforward problem. The hadrons with sign opposite to the beam are swept out, those with the same sign, typically of lower momentum than the scattered muon are well separated from much of the muon trajectory.

– in the major part of the dipole acceptance there is no material, in that of the toroid there are the coils of the toroid. This limits the maximum acceptance to 60%. On the other hand this 60% is well defined and after some study, it is not considered a problem.

As far as triggering is concerned, both experiments would rely on selection of the scattered muon track. In the case of the double dipole experiment there is experience of what is needed from E665. For the toroid the possibilities were discussed and will be the subject of further study.

The physics possibilities are illustrated in Figure 12 which plots the anticipated α_S measurements as a function of Q^2 for the toroid experiment run at

Fermilab. This is to be compared with the current situation in which the existing data, from different processes do not convincingly exhibit a running α_S. The conclusions to be drawn are therefore that the physics measurements are very important and are eminently possible at Fermilab. While the new Main Injector would presumably ease the questions of proton economy, it is not a fundamental requirement for these experiments. The air core toroid would be clearly superior to the dipole; on the other hand the dipole apparatus largely exists and is therefore less expensive.

A Neutrino Experiment

In a previous section a high luminosity neutrino experiment[32)] was discussed in the context of its potential contribution to the determination of $sin^2\vartheta_W$. The potential of such an experiment to contribute to measurements of the strong coupling constant would also be rather impressive. The experiment discusses the use of 10^{19} protons to produce of the order of 15 million neutrino charged current events, but more importantly, 3 million anti-neutrino charged current events. The structure function xF_3 is absent in muon scattering but contributes in neutrino scattering; it is associated with the parity violating component of the weak current. This structure function is flavor non-singlet which means that its evolution as a function of Q^2 within QCD is entirely determined by terms involving the valence quark distributions. It contains no contribution from the gluon distribution. In charged lepton scattering the only non-singlet available is the difference of F_2 for proton and neutron which involves using a deuterium target and making a subtraction. The difference between neutrino and anti-neutrino measurements yields xF_3 (also involving a subtraction). Previous measurements[75)] with good systematic control have been severely limited by the statistics of the anti-neutrino samples.

Because of the statistical precision, the proposed experiment would attack several systematic issues which have caused problems to neutrino experiments in the following ways:

– there would be a yield of about 10000 inverse neutrino decay events which would permit the absolute normalization of the experiment at the 1% level since the cross-section is entirely determined by well known parameters and theory. This would be a manifest improvement over present techniques which are somewhat convoluted.

– the relative normalization of data sets would be achieved using effectively four independent methods.

– the limiting systematic caused by the uncertainty in muon momentum in an iron spectrometer with limited sampling could be very much improved by either increasing the sampling frequency (more chambers) or by removing the iron completely and using an air core toroid along the lines discussed in the section on muon experiments. For comparison the current E744/E771 experiment obtains an uncertainty in the scattered muon momentum at the level of 0.5 – 1.0%; the

BCDMS experiment, also with an iron spectrometer but with much more frequent sampling, quotes 0.15%. The expectation for the air core toroid is a further factor of 5 improvement, that is to say 0.03% (although the effects of energy loss uncertainties in the target have not yet been estimated). Careful calibration of this muon system will be a prerequisite for measurements of this type.

With this array of improvements it seems plausible that a measurement of Λ_{QCD} using xF_3 can be obtained of a quality sufficient to give an error of 10MeV, to be compared with the currently competitive 100MeV. Retaining an iron core spectrometer would degrade the error to something of the order of $20 - 50$MeV. In addition to this primary QCD measurement, improved determinations would be obtained of the ratio of $R = \frac{\sigma_L}{\sigma_T}$, the structure function F_2, the sea quark distributions through the hundreds of thousands of dimuon events, perhaps the differences between $F_{2,3}^{\nu}$ and $F_{2,3}^{\bar{\nu}}$ and the gluon distribution. Some of these quantities will only be explored with further, new generation neutrino experimentation.

3.3.2 Hadron Beam Experiments

Direct Photon

The lepton scattering experiments discussed above involve the interaction of the electroweak current with the partons. The gluon therefore does not participate at the lowest order and even with the current level of experimentation the sensitivity to the gluon distribution is limited. An alternative line of attack is to attempt to identify a process which is well understood from the theoretical point of view and in which, in some sense, the gluon contributes at leading order. Although not the only possibility, one which has received much recent attention both experimentally and theoretically, is that of direct photon production by a hadron beam on a hadron target. An experimental advantage is that the photon is its own parton jet, so information is obtained by the measurement of the final state photon kinematics without having to sum over an ill defined jet of final hadrons.

The phenomenological situation and the sensitivity of the current measurements has been discussed above. In this section we discuss the experiments themselves, their limitations and expectations, the possible extension to include associated hadrons to better determine the parton kinematics, and finally the desirability of a further generation of fixed target measurements. The measurements discussed here have their counterparts in collider physics. In fact, some of the relevant measurements even at current fixed target energies were made at the CERN ISR. The physics clearly overlaps. However, it becomes clear that this is not a situation where one concludes that one approach is better than another. The two are complementary because they cover different ranges of x_{Bj} for the gluon. This is discussed in a recently presented rapporteur's talk[76]. The Single Photon Working Group[77] examined the systematic uncertainties of current direct photon experiments in detail. Current state of the art experiments achieve $20 - 30\%$ systematic

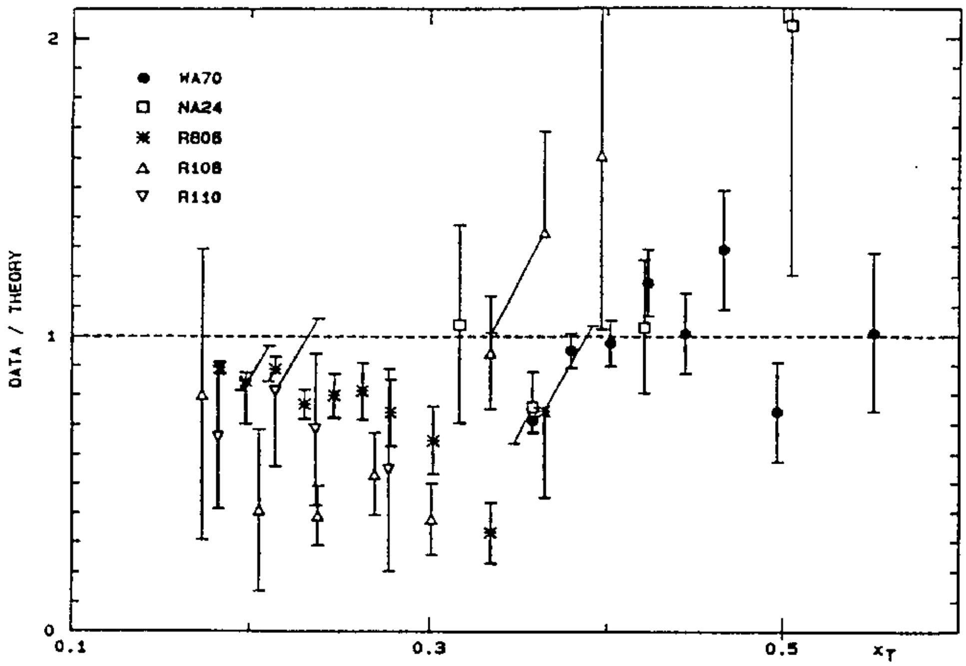


Figure 13: Comparison of Single Photon Data with Theory

errors, for example WA70 and UA6 at CERN[56],cite55b. E706[76] at Fermilab can be expected to achieve about 20% systematic uncertainty, especially with upgrades being implemented for the 1990 run. Figure 13 illustrates the current level of agreement where 20% discrepancies are clearly visible.

We also see the feature mentioned above as a positive feature , the experiments at different energies have little overlap, this makes judgement and arbitration between them difficult. The Fermilab-E706 data with high statistics is expected to alleviate the situation. Figure 14 contains a preliminary single photon spectrum from their first data run in 1988 which was very short. The data span a range which translates to $0.25 < x_T < 0.5$. It is expected that the data from the next run, in 1990, will give meaningful data over the range $0.2 < x_T < 0.7$.

Significant reduction of systematic errors, down to the 10% level, appears very hard to achieve. The experiments are particularly sensitive to errors of calibration of the electromagnetic calorimeter detectors, in particular to the uniformity and stability of the energy response. The residual muon background at large p_T also presents problems along with the Monte Carlo calculation of neutral meson decay backgrounds. It might also be noted from the discussion of the phenomenology that there are competitive uncertainties in the theoretical treatment.

At this time, since the potential of the E706 spectrometer has not yet been fully exploited, it is premature to consider the construction of a new device. This is especially so since at this workshop there was no clear proposal for a better experiment than the current E706. On the other hand it is also true that it is

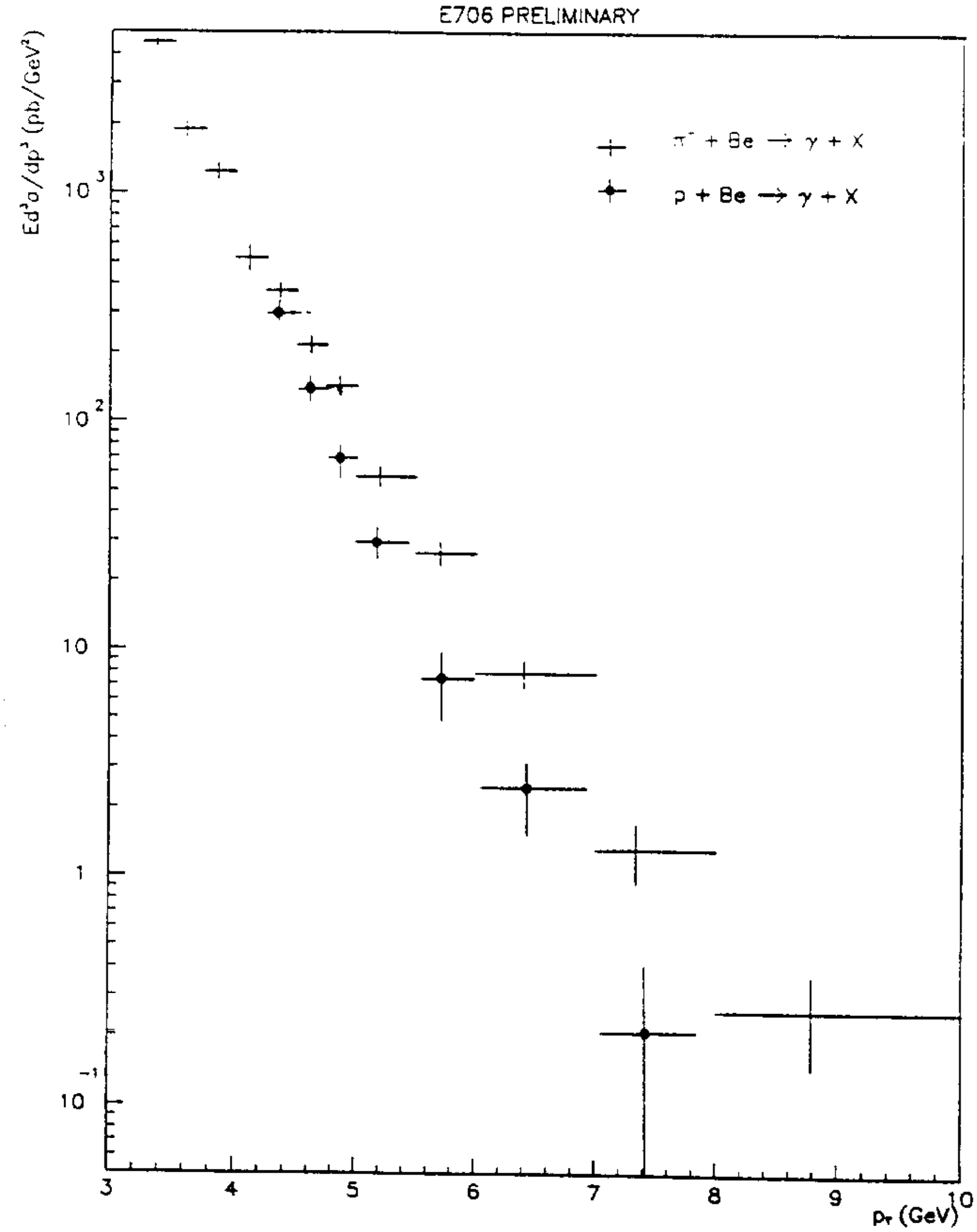


Figure 14: Preliminary Single Photon Production Cross-sections from E706

quite possible, indeed probable, that incremental improvements can be made in subsequent runs of E706, with upgrades as found necessary in the learning process.

Two such improvements are planned for the upcoming run:

- lowering of effective threshold for readout in the electromagnetic calorimeter, this would lead to an improved energy determination and improved detection of low energy photons, which would in turn lead to a smaller background from asymmetric π^0 decays;

- installation of a new silicon system and straw tube chambers (this is in progress) which should provide improved resolution and efficiency for charged tracks and hence better vertex and associated jet reconstruction.

The discussion of the phenomenology emphasized the need for more complex quantities than the p_T spectrum of single photons. Of particular interest would be an accurate measurement of the double differential inclusive photon cross section($\frac{d\sigma}{dp_T dy}$) which would extend the accessible parton x-range. The measurement of the photon+jet cross section($\frac{d\sigma}{dp_T dy_1 dy_2}$) would provide better control of the kinematics of the initial partons (allowing more stringent comparisons with theory). This is important because the NLL QCD calculation[44)] of photon+jet cross section has just become available.

Given the present uncertainties in absolute normalization for both experimental measurements and theoretical predictions, accurate determination of shapes of the distributions should be stressed in the hope that they are less sensitive to theoretical uncertainties.

One possible problem in looking to E706 as the arbiter between different experiments in different kinematic ranges is that the experiment has, so far, emphasized data from a beryllium target. The working group looked at the issue of running with liquid targets[79)]. The conclusion was that high statistics data with hydrogen and deuterium targets are essential to facilitate studies of nuclear target effects in prompt photon production and to provide direct comparison with other experiments (in particular, to help resolve the discrepancy between WA70 and ISR measurements). This might well be achieved with a third run of E706.

At low p_T there is always the possibility that the QCD diagrams are not the only contributors. It has been seen in deep inelastic scattering how higher twist effects can persist to fairly high Q^2. Measurements with at least two substantially different beam energies are recommended to help separate p_T and x_T and, in addition, to further constrain determinations of the gluon distribution.

Measurement of pairs of large p_T direct photons with good statistics on both hydrogen and nuclear targets is of interest not only as a test of perturbative QCD predictions, but also as a source of information on intrinsic parton k_T[71)], higher twist contributions and nuclear effects. These could manifest themselves for instance through a broadening of the photon pair p_T as function of atomic number.

Direct photon production offers a unique opportunity for testing QCD predictions of color coherence phenomena[80)], due to well-defined lines of color flow.

Large variations in the multiplicity of associated particles as a function of angle in the reaction plane are expected.

Other options for direct photon physics at Fermilab in the 1990's include:

- measurement of spin asymmetry in direct photon production with polarized proton beam and target. This may provide information about gluon polarization in nucleons, an issue considered in detail by the spin physics subgroup.

- measurement of very low $x = 0.01 - 0.0001$ behavior of gluon distribution in a forward measurement of direct photon production at the collider. The kinematics are a little unusual, $p_T{}^{\gamma}$, $p_T{}^{jet} = 10 - 20\text{GeV}$, E_{γ}, E_{jet} = a few hundred GeV, y_{γ}, $y_{jet} = 3 - 4$ both with the same sign of y. The experiment appears feasible with a detector providing γ, π^0 separation in this energy range. Detection of the recoil jet is important to select the desired parton kinematics. Charged track measurement is needed to permit the imposition of isolation requirements which could reduce the contribution of the bremsstrahlung graph. In this kinematic configuration this contribution is large but theoretically ill determined. Careful study of the reasonably expected range of the bremsstrahlung component and the resulting uncertainty in the determination of the gluon distribution is needed before final conclusions can be drawn. Jet-jet production with similar kinematics should be considered as another source of information, that is not affected by such complications. These issues are being addressed in detail by the collider direct photon subgroup; a further study of the desirability of a dedicated experiment should await their conclusions.

Dimuon Experiments

Continuum dilepton production may be considered in QCD as an extension of single photon measurements or as the partner of lepton scattering experiments. In the lepton scattering case the virtual photon is spacelike , in muon pair production it is timelike. Perturbative QCD is expected to be relevant at moderate to large values of the virtual photon mass even for very low values of the virtual photon p_T. In the high mass, low p_T region the quark-antiquark annihilation graph tends to dominate. Therefore the experimental results from this process are sensitive to different QCD diagrams than the direct single photon data. If data were available for dimuon production at high pair p_T, then the differences should disappear. It may be possible to check this with collider dilepton measurements.

Fixed target dimuon data has been used to help determine the parameters of the anti-quark content of the nucleon. Dilepton production by meson beams also provides information on the structure functions of pions[61)] and, to a lesser extent, kaons. Recently E772 has measured the dilepton A-dependence in an experiment sensitive to the low x_{Bj} ocean content of the nucleon. This will be discussed in the section below on Nuclear Effects.

Within the phenomenology group, a group of dilepton aficionados[81)] gathered with the aim of promoting the incorporation of the dimuon data in phenomenological structure function fits. So far this has only occurred on a sporadic basis although the data in principle are very sensitive[82]. The ad-hoc group came to the conclusion that the existing ensemble of data should be subjected to careful global comparisons with the various deep inelastic lepton scattering results. This might suggest kinematic regions in which better data are needed.

It was also noted that the apparent higher-twist angular[83] distribution effects seen by the Chicago-Princeton and NA10 groups[84] at high x_F in $\pi - p$ dimuon production experiments should be studied in p-p experiments. It was further observed that collider data on dilepton production for masses between the upsilon family and the Z will be important in studying the low x_{Bj} regime but that it will not connect very well with fixed target data unless low mass data (staying above the ψ resonances!) can be taken at the highest possible fixed target energies.

The implication of this is that more dimuon data would be very desirable if 1 TeV were available. However, at this Workshop, no group emerged that was willing to consider in detail a specific dilepton experiment at FNAL in the 1990s.

4 SPIN-DEPENDENT STRUCTURE FUNCTIONS

The recent EMC measurement[85] of the spin-dependent structure function $g_1^p(x, Q^2)$ has created renewed interest in measurements of this and similar quantities. The EMC collaboration has interpreted their result to indicate that, contrary to naive quark-parton model expectations, very little of the spin of the proton is carried by its constituent quarks. Several experiments have been proposed to check the EMC results and to make additional measurements which should help clarify the situation.

4.1 Phenomenology of Spin-Dependent Structure Function Measurements and Existing Data

The quantity actually measured in a DIS experiment is the asymmetry A

$$A = \frac{\sigma^{\uparrow\downarrow} - \sigma^{\uparrow\uparrow}}{\sigma^{\uparrow\downarrow} + \sigma^{\uparrow\uparrow}}, \tag{19}$$

where $\sigma^{\uparrow\downarrow}$ is the cross section when the spins of the beam lepton and target nucleon are antiparallel, and $\sigma^{\uparrow\uparrow}$ is the cross section when the spins are parallel. The polarizations of both beam and target are longitudinal, that is, along the beam direction. The references[85),86] give the details of the relationship between the measured asymmetry A, the virtual photon-nucleon asymmetries A_1 and A_2, and the spin dependent structure functions $g_1(x)$ and $g_2(x)$. A_2 is small in the kinematic range of the experiments being considered, so that $A \cong DA_1$ and $g_1(x) \cong [F_2A_1]/[2x(R+1)]$. Here D is the depolarization of the virtual photon and can be calculated from kinematic quantities. The quantities F_2, x, and R have the usual definitions. In the quark-parton model, $g_1(x)$ is related to the quark spin distributions in a simple way:

$$g_1(x) = \sum_i e_i^2[q_i^+(x) - q_i^-(x)], \tag{20}$$

where the summation is over all quark flavors, e_i is the quark charge, $q_i^+(x)$ is the parton distribution for quark i with momentum fraction x, having helicity along the direction of the proton's spin and $q_i^-(x)$ is the distribution function for quark i having helicity antiparallel to that of the proton. The integral of g_1 over all x is related to the net spin carried by the quarks :

$$\int_0^1 g_1(x)dx = [\frac{4}{9}\Delta u + \frac{1}{9}\Delta d + \frac{1}{9}\Delta s], \tag{21}$$

where $\Delta u = u(\uparrow) - u(\downarrow) + \bar{u}(\uparrow) - \bar{u}(\downarrow)$ is the net spin carried by up quarks, and similarly for Δd and Δs.

It is important to measure $g_1(x)$ well over the entire range of x, since it is the integral of g_1 that is related to two important sum rules. The EMC experimental result for this integral, for $< Q^2 >= 10.7\ GeV^2$, is $0.114 \pm 0.012 \pm 0.026$. Figure 15 shows the EMC data for g_1^p and its integral.

The Ellis-Jaffe sum rule[87)] (which is based on QCD current algebra and assumes an unpolarized strange quark sea) predicts for the integral of g_1 for the proton, $g_1^p(x)$, a value of 0.189 ± 0.005, a result which disagrees with the EMC result by about 2.5 standard deviations. The discrepancy may not be a disaster for QCD, since it could be explained, for example, by a substantial polarization of the strange sea or a substantial contribution to the integral from gluons.

Currently data exist for g_1^p only. The Bjorken sum rule[88)] uses fundamental arguments to relate the integrals of g_1^p and g_1 for the neutron, g_1^n, to the ratio of the axial and vector coupling constants G_A and G_V,

$$\int_0^1 [g_1^p(x) - g_1^n(x)]\, dx = \frac{1}{6} \mid \frac{G_A}{G_V} \mid \left(1 - \frac{\alpha_s}{\pi}\right). \tag{22}$$

Violation of the Bjorken sum rule would pose a serious problem for QCD. So clearly, in addition to checking the EMC result for g_1^p, a measurement of g_1^n is important.

Theoretical interpretations of the EMC result abound. One suggestion, based on perturbative QCD, is that the gluons carry a large fraction of the proton's spin[89)],citemarj6,citemarj7. Another suggestion based on the Skyrme model would have all of the spin of the proton carried by orbital angular momentum[92)]. Experiments discussed at this Workshop which would measure directly the spin distribution of the gluon should distinguish between these two very different possibilities. Still another suggestion [93)]attributes the EMC result to higher twist effects in the Q^2 range of the experiments (10 GeV^2 for EMC and lower for earlier experiments). However, one should keep in mind, (as emphasized by Ed Berger at this workshop)

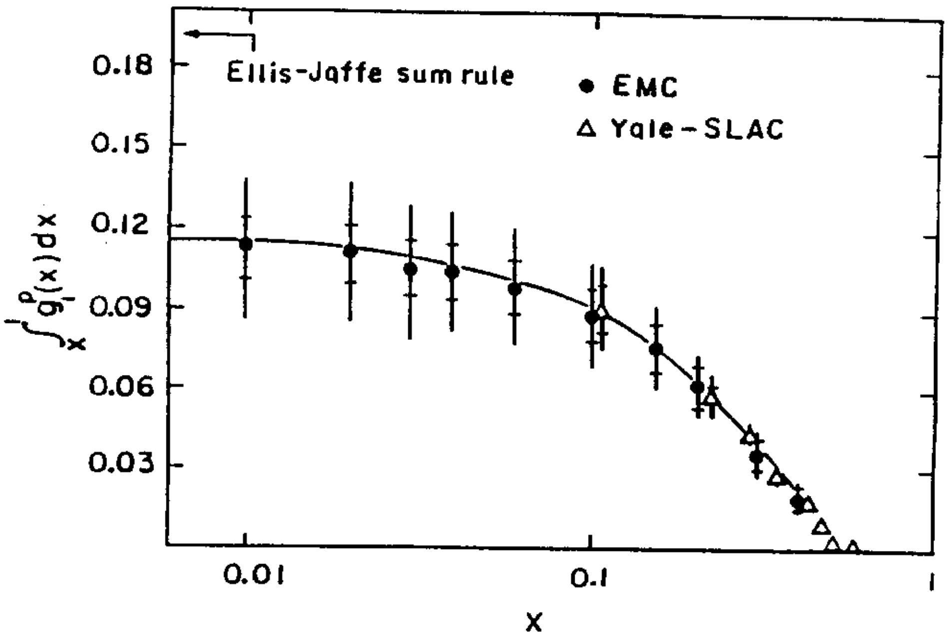


Figure 15: EMC and Yale-SLAC Polarized Structure Function Data

that the statistical significance of the EMC result is not overwhelming (slightly more than a two standard deviation effect). It has also been suggested that the systematic errors on the integral of g_1^p may be underestimated[94)]. Checking this result is important.

4.2 Experiments

Discussions of experiments to help clarify the situation were along two general lines. The first were remeasurements of g_1^p and a first measurement of g_1^n, to provide a test of the Bjorken sum rule. The second general class of experiments was a direct measurement of the spin-dependent structure function of the gluon through direct-photon production. A third type of experiment, mentioned briefly, was Drell-Yan production with a polarized beam and target[60)], which could measure directly the spin distribution of the sea quarks. Such an experiment might use existing apparatus but would require both polarized beam in the Tevatron and a polarized target.

Complaints about the lack of statistical precision in previous measurements point to the fact that all these experiments are difficult. Both a polarized beam and a polarized target are required. In most polarized targets, only a small fraction of the available nucleons are polarized, leading to a "dilution factor" of 0.1 to 0.3. All statistical error bars are divided by this factor. In addition, many polarized targets cannot reverse the polarization direction easily, resulting in larger systematic errors. Often the beam polarization cannot be reversed at all. Results from neutrons are usually obtained from polarized deuterons, and additional errors are introduced by extracting the neutron information from the proton-deuteron difference.

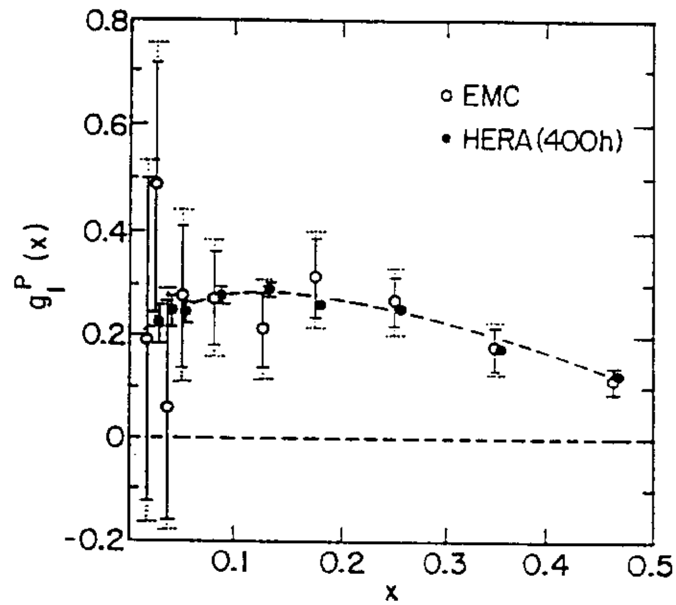


Figure 16: Expected Results for g_1^p from the HERMES experiment.

4.2.1 *Spin-dependent Quark Distributions through Deep-inelastic Lepton Scattering*

Three experiments in this category were discussed. The existence of an additional experiment (at SLAC) was noted but not discussed. The experiments discussed were HERMES at HERA, the SMC experiment at CERN, and an experiment in the muon line at Fermilab. Table 1 compares the important experimental features, kinematic ranges,and expected results for these three experiments.

The HERMES experiment[95)] intends to use a polarized internal gas jet target in the 35 GeV circulating electron beam at HERA. The target will use polarized hydrogen, deuterium, and He^3. The structure functions for the neutron will be measured from the hydrogen-deuterium difference and from He^3. (The polarization in He^3 is carried almost entirely by the single neutron). The expected luminosity is $3 - 10 \times 10^{32}\ cm^{-2} - sec^{-1}$.

Two advantages for this experiment are that the gas jet targets will have little or no dilution factors, in contrast to the standard targets used in conventional fixed-target experiments. Another advantage is that the target polarization can be reversed every 1-2 seconds. The targets can be polarized both longitudinally and transversely, allowing measurements of A_1 and A_2. The deuteron has two additional spin-dependent structure functions since it is a spin-1 object. The different target configurations will allow separation of g_1 and g_2 cleanly from these additional effects. However, the attainable Q^2 range is limited, with the maximum Q^2 expected to be about 20 GeV^2. Figure 16 shows the expected results for g_1^p, compared to the EMC data. If Hermes can do as well as advertised, their data will clearly be a great improvement, especially at low x.

The HERMES experiment is not yet approved, but a feasibility study has

Table 1: Comparison of Spin-Dependent DIS Experiments

	HERMES	EMC	SMC	FNAL
X Range	0.02-0.8	0.01-0.7	0.01 - 0.7	0.005 - 0.7
Q^2 Range	1-20 GeV^2	1.5-70 GeV^2	1.5-70 GeV^2	3-130 GeV^2
Beam Energy	35 GeV	100-200	100 GeV	up to 500 GeV
Luminosity or Beam Intensity	3-10 $\times 10^{31}/cm^2$-sec	$2 \times 10^8 \mu$ /min	$2 \times 10^8 \mu$ /min	$2 \times 10^8 \mu$ /min
Beam Polarization	0.8	0.82 $\pm$ 0.06	0.80 $\pm$0.0 5	?
TARGETS:				
Materials	H, H^2, He^3	NH_3	Butenol and Deuterated butenol	NH_3, ND_3, (?)
Polarization	0.8		0.8	0.8
Dilution factor	1, 1, 0.3	0.176	0.135, 0.238	0.176, 0.300
Reversals	1-2 sec	once per week	few times per day	?
Expected errors:				
$\int g_1^n$	$\pm$ 0.9 $\pm$ 0.12 (H^2) $\pm$ 0.06 $\pm$ 0.09 (He^3)		$\pm$ 0.12 $\pm$ 0.06	
$\int g_1^p$	$\pm$ 0.02 $\pm$ 0.08 (H)	$\pm$ 0.12 $\pm$ 0.26	$\pm$ 0.06 $\pm$ 0.12	
Expected Data	1993	—	1991	?

been reviewed favorably. Polarized beam is expected to be stored in 1991, with first data expected in 1993.

In direct competition with HERMES is the SMC (Spin Muon Collaboration) experiment to be done at CERN[96]. This experiment proposes to use essentially the same apparatus as EMC (with some upgrades) and a 100 GeV muon beam to remeasure g_1^p to higher precision and measure g_1^n. The existing polarized target, again with some upgrades, to magnet, refrigerator and polarizing RF system will be used. A major improvement in the polarized target will be the ability to reverse the spin directions in less than 30 minutes, allowing frequent target reversals and reducing a major source of systematic error. In the EMC experiment, the target spins were reversed only once per week. In addition, the polarization of the muon beam will be measured and monitored during the run in two ways – from the energy spectrum of decay positrons and from elastic μe scattering[97]. For EMC, the beam polarization was calculated by Monte Carlo but not directly measured.

The SMC experiment has been approved, and CERN seems to be supporting this experiment strongly. The goal for first data is summer or fall of 1991.

The possibility of competing experiments at Fermilab was also reviewed[98]. A Fermilab experiment would use the existing E665 spectrometer with appropriate upgrades. Fermilab clearly wins from the energy standpoint, but that does not immediately translate into better precision on g_1^p and g_1^n. In fact, the measured asymmetry A decreases with energy as $1/E_\mu$. Fermilab could reach both higher Q^2(300 GeV^2 compared to 70 GeV^2) and lower x values (0.005 compared to 0.01). Fermilab and SMC would have nearly identical muon fluxes ($2 \times 10^8 \mu/min$). Fermilab does have the advantage of a duty factor which is twice that of CERN. Refer to Table I for a summary of the comparison between the experiments.

Fermilab has the disadvantage that it has no existing polarized target in the muon beam. One would either have to build a completely new target or obtain and modify an existing target. The cost of building a polarized target from scratch is about $\$1M$ per meter of target length. The time involved in constructing a new target is also significant, on the order of at least two to three years.

One area in which Fermilab may indeed have an advantage is in the detection and analysis of the hadron side of the event. Strickman *et al.*[99] and Close and Milner[100] have discussed the information to be gained from looking at the asymmetries in hadron production in DIS. For example, one might measure directly the spin distribution of the strange sea. E665 was designed to measure the hadronic side of the event very well, so perhaps they have an advantage. Possibilities along these lines are still being explored.

Unless hadron asymmetries turn out to be crucial, the conclusion of the workshop was that there was no strong advantage to repeating the SMC experiment at Fermilab, particularly in view of the cost of a new polarized target.

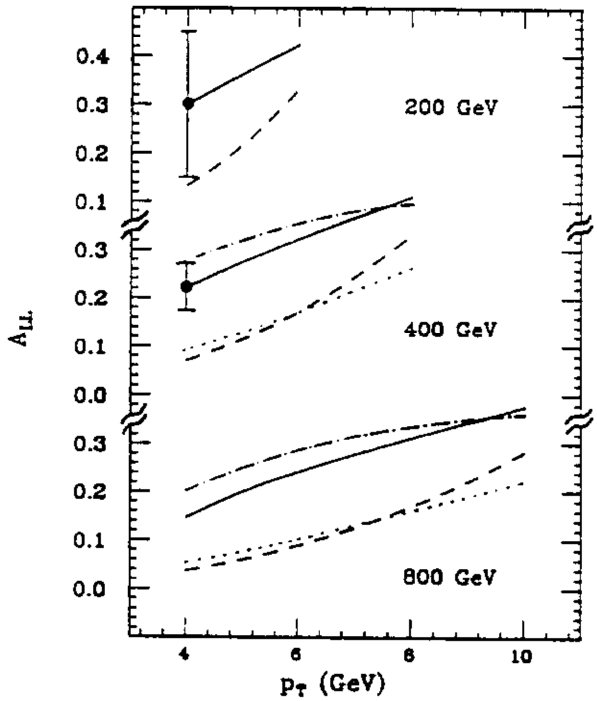


Figure 17: Expected Polarization Asymmetries in Direct Photon Production. The solid and dashed curves show the range of expected asymmetries for pd interactions, and the dot-dash and dotted curves are for pp interactions.

4.2.2 *Measuring the Gluon Spin Distribution with Direct Photons.*

If the spin of the nucleon is not carried by the constituent quarks, one obvious place to look for it is in the gluons. Direct photon production in a proton beam probes the gluon structure function directly, so this process would be a natural place to study the gluon spin distribution. Berger and Qiu[101)] have calculated the range of expected asymmetries in direct photon production for reasonable choices of the spin-dependent gluon distribution, shown in Figure 17.

Two direct photon experiments were discussed. One would require a substantial upgrade of the existing MP beamline[102)]. The other would require an extensive reconfiguring of the MW beamline to generate and transport polarized protons[103)]. These experiments are difficult, but there is currently no information at all about the spin distribution of the gluon. Even a measurement of the sign of the asymmetry would be important information.

The existing MP polarized proton beam at Fermilab currently can provide protons at 185 GeV/c with average polarization of 45%, and a flux of about 1×10^7 for 3×10^{12} primary protons on target. The actual flux of protons is higher, but only a fraction of them are polarized. This beamline produces polarized protons (and also antiprotons at a much lower intensity) from the parity violating decay of Λ^0's (or $\bar{\Lambda}^0$'s). Since the beam polarization is a function of the position in the beam spot, the MP beam line has an elaborate beam tagging system so that the polarization of each beam proton is known.

E704 will have its first extended run during the next fixed target cycle and will measure single-spin asymmetries for high p_t π^0's and high x_F π's (of all charges), K^0_S, Λ's, and Σ's. The experiment will also have a polarized target and measure $\Delta\sigma_L$ in pp interactions and A_{LL} for π^0 production. The existing apparatus is not optimized for single-photon detection, and at 200 GeV/c, the direct photon cross section is too small to make the experiment workable. The data point in Figure 17 at beam momentum of 200 GeV shows the expected error on the asymmetry at $p_t = 4$GeV/c. The proposed upgrade would increase the energy to 500 GeV and increase the flux a factor of three to four, up to $3 - 4 \times 10^7$ per spill.

To make a direct photon asymmetry measurement workable in even the upgraded MP beam line, one would need a polarized target with a substantially larger dilution factor than conventional NH_3 or other targets. A lithium deuteride (Li^6D) target in principle has a dilution factor of 0.5. Li^6 behaves as an alpha particle and a deuteron, and both the deuteron in the Li^6 and the deuteron chemically bound to the Li can be polarized. One such target has been used in an experiment in Switzerland, but many questions remain before this target material is well understood[104)].

An asymmetry measurement in direct photon production has other problems. Using the upgraded MP polarized beam, the maximum p_t at which one could get an asymmetry measurement is about 4 GeV/c. However, at that p_t and with a beam energy of 500 GeV, the ratio of direct photons to π^0s is about 0.1. For the proposed detector in MP, it is expected that about 40% of all observed single photons would actually be from π^0 decays. But the π^0s that fake direct photons may not have zero asymmetry. In fact, an earlier CERN experiment using a polarized target indicated that π^0 production at p_t up to about 2 GeV/c may have a large asymmetry. So to extract the true asymmetry for the direct photons one would have to know very well both the asymmetry of the background π^0's and what fraction of all observed single photons is background. It should be possible to measure accurately the π^0 asymmetry from the data, but knowing the fraction of fake direct photons may be more difficult.

Assuming the Li^6D target does work, and assuming a dilution factor of 0.5, one can calculate[102)] expected errors in the measured asymmetries for direct photon production in the MP line. Assuming $P_B = 0.45, P_T = 0.7$, and that the π^0 contamination in the direct photon signal is well understood, one arrives at the result (shown in Figure 17) that the error on the asymmetry at $p_t = 4$GeV/c is about $0.05 - 0.06$.

The E706 liquid argon calorimeter (LAC), in the MW beamline at Fermilab, has already had one successful run and has proven itself to be a excellent photon detector. The LAC has about twice the solid angle acceptance as the proposed upgrade of E704 and finer segmentation, so there are clear advantages in using it. There is also the advantage of using an existing and proven detector. So how to get a polarized beam to the LAC? The proposed scheme[105)] uses the parity-violating decay of Σ^+ to create a polarized proton beam. The estimated flux for the beam is 2×10^7 polarized protons per spill at 400 GeV, assuming 3×10^{12} primary protons on target, with an average polarization of 63%. Unlike MP, all of the beam is polarized, so one would not need a beam tagging scheme.

One disadvantage of the E706/MW option is that no polarized target exists for this experiment. As discussed above, a new target would entail additional expense in both time and money.

No detailed error estimates were presented for MW, and it remains to be seen what the uncertainties would be for MW relative to those of the MP. The larger solid angle coverage of the LAC would be partially offset by the lower beam energy. The MP beam is projected to have a factor of 1.5-2 more intensity, but the MW protons would have significantly higher average polarization. The "quality factors" for the beams, (polarization squared times intensity) are nearly the same.

Both of these experiments would benefit greatly from the increased intensity that would be available if polarized protons were accelerated in the Tevatron, a possibility which was discussed briefly.

4.3 Conclusions

Two general classes of experiments were discussed to improve existing knowledge of spin-dependent structure functions. Three DIS experiments were compared, HERMES, SMC, and FNAL. There seems to be no strong advantage to doing the experiment at Fermilab, particularly in view of the high cost of the required polarized target. One area in which Fermilab might have a definite advantage over other experiments is in studying the hadronic side of the event. This possibility was discussed, but no definite conclusions were reached.

The other class of experiments discussed was asymmetry measurements in direct-photon production to measure the spin-dependent structure function of the gluon. Fermilab seems to be the only lab at the moment that could consider doing these experiments, although they might be possible at UNK. Two options were considered — an upgrade of the MP beamline to 500 GeV, and a new beamline which could produce and transport polarized protons at 400 GeV to MW. In the upgraded MP line, one would expect to attain an error of about 0.05 on the asymmetry measurement at $p_t = 4$ GeV/c.

There are at least two caveats associated with this error estimate. For the Li^6D target, a dilution factor of 0.5 was assumed, but this target material is still in the early stages of development and many questions remained unanswered. It was also assumed that the π^0 contamination under the direct photon signal (which might have an asymmetry of its own) was well understood and could be corrected for without introducing significant error in the direct-photon asymmetry.

5 NUCLEAR

5.1 Phenomenology

Extensive experimental measurements of the differences between nucleon and nuclear cross sections have been made at fixed target energies [106]. Unfortunately, a clear and complete theoretical understanding of these measurements is lacking. The group addressing the need for further measurements with nuclear targets was confronted with this lack of understanding of a bewildering variety of different reactions. The relevance of these issues to a deep understanding of QCD is not in doubt; if only because a large fraction of the experimental data forming the underpinning of our knowledge of hadron interactions at fixed target energies has been taken on heavy nuclear targets. Beyond this experimental detail lies the even deeper problem of understanding the evolution of color states as they traverse nuclear matter.

The nuclear group started by reviewing the status of nuclear phenomena in various fixed target reactions and the availability of data from heavy targets currently being analysed.

In the deep-inelastic scattering of leptons, new data from the NMC collaboration and data in hand by E665 should solidify the experimental situation in both the low-x shadowing and intermediate-x antishadowing regions. Equivalent data for neutrino scattering seems unlikely to exist at any point in the future! The nuclear dependence of Drell-Yan annihilation dimuons is forthcoming from E772.

The theoretical understanding of this data and the correct way to handle nuclear effects in structure function determinations is not clear. The regions affected, the low x and intermediate x range, are just those needed for extrapolations to collider energies and calculations of limits on new particle production at colliders.

A similar discrepancy exists for the nuclear dependence of heavy quark production. Existing data on open charm production and on vector meson production are not proportional simply to the number of nucleons present, as one would expect for hard collisions. Data forthcoming from E769 should help clarify the situation for open charm. Much existing data and preliminary data from E772 on vector meson production show a strong A-dependence[107]. More data on the production of heavy quarks in many different kinematical regions is surely needed.

Stan Brodsky and Mark Strikman both emphasized the importance of understanding heavy quark production A-dependence as a fundamental test of theoretical ideas on the intrinsic wave functions of hadrons and the propagation of hadronic states in strong colour fields. Some of the existing theoretical descriptions of quark excitation in nuclei predict an x_F dependence which is probably complicating existing data with it's limited coverage in x_F. The upcoming round of b-quark fixed target experiments will hopefully find B-mesons and measure the A-dependence of their production. If the A-dependence in the forward hemisphere is significantly less than unity the experiments will suffer a loss in rate - and the theorists will suffer a loss of face!

Many other reactions were mentioned. The interesting measurements on the nuclear dependence of elastic scattering at 90 degrees[108)] might be followed up by a measurement at higher energies and smaller angles. The A-dependence of direct photon production might be measured by E706 and should be related to the modifications of the gluon distribution in nuclei.

Changes in the fragmentation distributions of the hadrons produced in deep-inelastic scattering should also impact our understanding of formation zone and propagation length physics. Hopefully E665 will have good data on this soon. The A-dependence of high p_T hadrons and jets and also diffractive states is less clear both experimentally and theoretically. New data from E557, E605, E609, E672, and E711 should help define the outstanding questions, if not the answers[109)].

5.2 Experiments

Presentations by Stan Brodsky and Mark Strikman emphasized possible experiments that could be done with the higher energies and luminosities available in the upgraded fixed target program. They both emphasized that the nucleus can:

1.) act as a color filter
2.) modify the hadronization of jets
3.) separate different dynamical contributions to cross sections
4.) effect structure functions
5.) give access to different states
6.) probe soft QCD processes (diffraction, exclusive channels).

They also reiterated the view that better heavy quark and deep-inelastic A-dependence measurements were needed. The interplay between perturbative and non-perturbative QCD was seen by both as an area accessible to test by measurements with nuclei.

In particular, Brodsky pointed out a number of areas where anti-protons could be important probes. Measurements of deep inelastic lepton-nucleus scattering at SLAC and CERN show that nuclear structure functions are depressed below simple additivity at $x \leq 0.1$ and enhanced above additivity at $x \simeq 0.15$. The shadowing and anti-shadowing appear to be Q^2-independent; i.e., leading twist. It then follows from the QCD factorization theorem for inclusive reactions that the same non-additive nuclear features must appear at small values of $x_{q/A}$ in processes such as $\bar{p}A \to \ell^+\ell^- X$, $\bar{p}A \to \gamma\gamma X$, etc. Since the structure functions of anti-protons are well understood, high energy fixed-target $\bar{p}$-nucleus measurements at Fermilab can provide a definitive test of this fundamental QCD prediction[110)].

The production of the J/ψ in high energy anti-proton nuclear reactions at Fermilab is of interest for several reasons: (1): Measurements of J/ψ production by protons and pions in nuclei show an anomalous nuclear A-dependence and an x_f distribution at large longitudinal momentum beyond that predicted from the leading-order fusion subprocesses $gg \to c\bar{c}$ and $q\bar{q} \to c\bar{c}$.[111] (2): Formation zone arguments[112] predict that the time for forming the J/ψ in a high energy collision grows linearly with lab energy. The nuclear A-dependence of inclusive $\bar{p}A \to J/\psi X$ can be used to determine the cross section for the interactions of the $c\bar{c}$ as it traverses the nucleus. Low energy $\bar{p}$-nuclear reactions can determine J/ψ-nucleon cross section; at high energies, the physical J/ψ is formed outside the nucleus. (3): Measurements of the quasi-exclusive reactions $\bar{p}p \to J/\psi$ in a nucleus can be used to probe the proton's momentum distribution and the short-distance structure of the nucleus. The dependence of the cross section $\bar{p}A \to J/\psi(A-1)$ on the nuclear proton number Z also tests QCD "color transparency". Similar considerations are involved in the production of other $c\bar{c}$ and $b\bar{b}$ states by anti-protons in nuclei.

An essential feature of perturbative QCD analyses[113] of large momentum transfer exclusive reactions such as $\bar{p}p \to \bar{p}p$, $\pi\pi$, $K\bar{K}$, $\Lambda\bar{\Lambda}$, J/ψ, $\gamma\pi$, etc., is that the amplitude is dominated by wavefunction configurations in which the valence quarks of each hadron are at small relative impact parameter: $b_\perp \sim 1/Q$. Up to small power corrections,[114] this is even the case when multiple scattering (the "pinch" contribution) is the dominant subprocess. In QCD small color-singlet wavefunctions have diminished strong interactions; thus corrections due to initial and final state interactions can be neglected in large momentum transfer exclusive reactions. In particular, perturbative QCD predicts that the cross section for quasi-exclusive processes such as $\bar{p}A \to l^+l^-(A-1)$ or $\bar{p}A \to \bar{p}p(A-1)$ is not effected by nuclear attenuation at high pair mass and is linear in the number of protons in the target. This is the prediction of QCD "color transparency."[115] Some evidence for this novel effect has been reported at BNL in quasi-elastic large angle pp scattering in nuclei.[108]

6 GENERAL CONCLUSION

In this document we have described the work carried out in a period of order two weeks in rather pleasant surroundings in the mountains of Colorado. While some arrived well prepared, others among us arrived to learn and expand our thoughts. The conclusions which we will now attempt to draw are to be taken in the above context. In most cases subjects were considered by a mix of people, in general not by complete, full force collaborations fired up to propose and execute an experiment. Therefore these might be conclusions with a limited lifetime as there may be a better understanding that totally destroys what we see as a promising line of research. Or, there may be a comprehension that something we see as having difficulties or close to insurmountable problems may turn out to be perfectly feasible with more thought.

With these caveats we can consider the main threads of the work described above. We license ourselves to use the broad brush and ask what are the experiments and directions which emerge for the next generation at the Tevatron.

6.1 Neutrino Oscillations

With the Main Injector a ν_τ appearance oscillation experiment appears to be eminently feasible. It would require substantial new facilities and it will likely have competition from CERN but its goals and potential are clear. It could have important ancillary goals. This is an example of new physics made possible by the possible construction of the Main Injector.

6.2 Neutrino Electroweak Experiment

The major conclusion is that the physics case for a neutrino experimental determination of $\sin^2\vartheta_W$ was made and accepted IF the relative error in the measurement is at the level of 2%.

Of the two main proponents for new experimental thrusts which were discussed (an upgraded Tevatron with absolute flux determination using the inverse muon process and the tagged neutrino beamline) each advocated two different means of selecting neutral from charged current events: The former advocated an event-by-event pattern recognition and the latter advocated a conventional event-length statistical subtraction. Of these two discriminators, the discussions seemed to favor the former, especially in light of the discrepancy between two similar measurements at CERN and Fermilab. Either experimental direction would require the commitment of major resources, especially in terms of manpower.

For both of these proposals considerable work will be required in order to make an informed decision on this matter of the future of neutrino physics at Fermilab. This work must take the form of added analysis of the present Tevatron neutrino beam and test beam data as well as sophisticated simulations of the detector capabilities. This is especially true for the the pattern-recognition potential and ν_e contamination in the former proposal and the tagging inefficiencies for Λ decays and the $\frac{\overline{Q}}{Q}$ problem in the latter proposal.

6.3 QCD Structure Function Measurements with Lepton Beams

Both neutrino and muon scattering experiments were considered, the former as an adjunct to the $\sin^2\vartheta_W$ measurement. For both an accuracy of approximately $10-30$MeV seems possible using the non-singlet xF_3 structure function. The beam flux required for the neutrino experiment is such as to make the construction of the Main Injector a prerequisite.

Two different muon experiments were considered with the determination of α_S and Λ_{QCD} as the benchmark. Measurements of α_S over a sufficient range of

Q^2 to observe the evolution of the coupling constant would be possible in either. The better design for this particular measurement was found to be the large air core toroid which would be a large leap in technology for this type of measurement. The more modest extension of a currently operating dipole experiment perhaps offers similar if somewhat inferior potential. More studies are required here. In either case the Main Injector is not an absolute necessity but would ease somewhat the pressure on limited fixed-target proton economics.

In order to complete the program of helicity-separated parton distribution fits urged by the Snowmass Group[68)], an improved, high statistics neutrino experiment may be necessary. In order to observe the long-sought running of α_S, more muon and/or neutrino experimentation will likely be necessary. Finally, a completely satisfactory determination of Λ_{QCD} may only be possible with new generation, high statistics, systematically precise experiments of both muon and/or neutrino efforts. This latter conclusion clearly carries with it the recognition that there are serious hurdles (experimental and phenomenological) which would have to be overcome, such as understanding the A dependence in the case of the neutrino option.

Both lines of experimentation appear to offer qualitative improvements in the field. It is likely that there will be proposals for either a neutrino experiment or a muon experiment or even both.

It was amusing to note that there was even discussion between the muon and neutrino aficionados of the possibility of sharing the air core toroid since precision reconstruction and measurement of momentum is the key to each.

6.4 Single Photon Experiments

Compared to lepton scattering which is in its second decade at Fermilab, single photon experimentation is relatively new. The full potential of the current phase of experiments is just beginning to be realized. The contributions they can make to the phenomenology of QCD is potentially great and there are expectations of much work to do with variations of the present experiments. Contemplation of the next generation experiment can await the success of those on the floor.

6.5 Spin Dependent Structure Functions

As far as lepton scattering is concerned the muon beam at Fermilab offers good opportunities in this newly exciting region. However it turns out that there are not compelling arguments for the superiority of a Fermilab experiment over the ones currently in preparation at CERN and in the gas jet experiment at HERA.

The new possibility of measuring polarization effects in the gluon distribution through direct single photon asymmetries with a polarized beam on a polarized target was examined. Upgrades of the available beamlines would be both necessary and possible. The estimation of the error in the measurement is delicate and work is still in progress. The latter is especially aimed at some new polarized target materials. The experiment as discussed at this workshop is on the edge of feasibility. It would surprise no-one if the direction would mature and develop into a full proposal at some stage in the future. The motivation is high.

6.6 Nuclear Effects

Despite both experimental and theoretical interest in nuclear effects, no experiment emerged that would justify a dedicated effort in the 1990s at FNAL. The continued use of heavy targets is assured for luminosity and compactness and it is hoped, that where convenient, experiments will continue to record yields as a function of nuclear size. It is certainly possible that the analysis of the data from the last few fixed target runs may change this conclusion and point to a few sharp tests of the many ideas involved. That this has not happened yet may be only an indication of the wealth of data recorded (much not yet published) combined with the still confused theoretical understanding of nuclear phenomena.

6.7 Final Observation

Of the experiments which emerged as candidates for the next generation of Fixed Target experiments at Fermilab, several demand the Main Injector either as the direct source of protons for the experiments or as the provider of intensity to the Tevatron.

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