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Neutrino Physics

Deborah A. Harris

Fermi National Accelerator Laboratory
Batavia, Illinois - USA

The field of neutrino physics has expanded greatly in recent years with the discovery that neutrinos change flavor and therefore have mass. Although there are many neutrino physics results since the last DIS workshop, these proceedings will concentrate on recent neutrino physics results that either add to or depend on our understanding of Deep Inelastic Scattering. They will also describe the short and longer term future of neutrino DIS experiments.

1 Introduction

The focus of the world-wide neutrino physics program in recent years has been on oscillations, which pushes the energy of desired neutrino beams lower and lower, since the oscillation phenomena are a function of the inverse of the neutrino energy. As these energies decrease, one might naively think that Deep Inelastic Scattering processes play a smaller and smaller role in extracting oscillation physics. However, as these oscillation experiments become more and more precise, and as they search for rare processes the importance of understanding deep inelastic scattering and the transition region between DIS and resonance interactions rises.

Diagrams for the neutral and charged current Deep Ineastic Scattering processes can be seen in Figure 1. Clearly, in the case of the charged current interaction, if the muon energy and direction with respect to the incoming neutrino direction can be measured (E_μ and θ, respectively), and if the total hadron energy (E_{had}) can be measured, then the kinematic variables for the scattering process can be reconstructed, as follows:

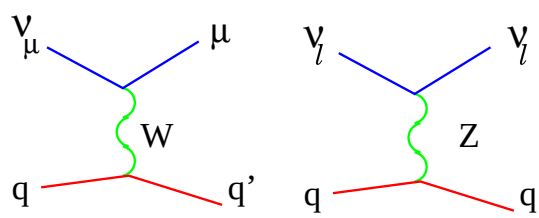

Figure 1: Feynman diagrams for the charged (left) and neutral (right) current Deep Inelastic Scattering Interactions

$$
\begin{aligned}
E_\nu &= E_\mu + E_{had} \\
Q^2 &= 4E_\nu E_\mu \sin^2\frac{\theta}{2} \\
x &= \frac{Q^2}{2ME_{had}} \\
y &= \frac{E_{had}}{E_\nu} \\
Q^2 &= M^2 + 2ME_{had} - Q^2
\end{aligned}
$$

Experiment	ν_μ Energy (GeV)	Proton Energy (GeV)	Wrong sign Contamination (%)
NuTeV	120	800	0.03, 0.4 (ν, $\bar{\nu}$)
CHORUS, NOMAD	27	450	6
DONUT	100	800	33
MINOS	3-15	120	few to 20
OPERA	15-25	400	few

Table 1: Table of the salient features of current and previous beamlines for neutrino experiments discussed in this document [6].

where M is the mass of the nucleon. If the charge of the outgoing muon can be measured, that will determine if the incoming lepton was a neutrino or an antineutrino.

2 Neutrino Detectors

As the world-wide neutrino physics program is evolving, so too are the detector requirements. While short-baseline experiments CHORUS and NOMAD have tried to develop more and more fine-grained detectors to probe the neutrino interaction vertex, long-baseline experiments MINOS and NOvA have tried to develop more and more economical ways to build high mass detectors.

The CHORUS detector consists of bulk emulsion films followed by electromagnetic and hadronic calorimetry, and their recent results in fact come from neutrino interactions that occurred in the 112 tons of fine grained electromagnetic calorimeter consisting of lead and scintillator [2]. The NOMAD detector consists of drift chambers surrounded by electromagnetic calorimetry [3].

The NuTeV detector consisted of steel, liquid scintillator, and drift chambers, followed by a magnetic toroid spectrometer and was the most coarse-grained detector of the experiments at a longitudinal segmentation of 10cm of steel [4]. The MINOS detector is made up of 2.54cm thick plates of steel interspersed with 1cm thick planes of solid scintillator [5].

As future neutrino oscillation experiments will need to minimize segmentation in order to minimize the costs per kiloton of active detector, they will need to rely more heavily on measurements made by fine-grained detectors to constrain models of neutrino interactions. Furthermore, as more and more statistical precision is achieved, more precise models will also be needed to correctly describe nuclear effects and rare processes that may provide backgrounds to searches for small oscillation signals.

3 Neutrino Beams

Table 3 shows a compilation of recent and currently running neutrino expeirments and the salient features of each neutrino beamline: the average neutrinoenergy, the proton energy, and the antineutrino (neutrino) contamination during the neutrino (antineutrino) running. Because the primary motivation for each of these experiments are vastly different, they had different focusing systems, which result in very different wrong-sign contamination. For a broad survey of these neutrino beamlines and others see reference [6].

NuTeV was designed to measure the neutral to charged current cross section ratios for both neutrinos and antineutrinos separately, and as a result its beamline had to produce very pure beams of neutrinos or antineutrinos, compared to the other experiments.

DONUT, on the other hand, was designed to see evidence of nu_τ interactions, and therefore was essentially a beam dump experiment since the ν_τ's come from D_s decays which occur long before the D_s mesons could have a chance to be focused. To minimize backgrounds from non-D_s decays, there were no focusing elements in their beamline. In this case the number of neutrinos and antineutrinos are almost equal, so the antineutrino contamination is maximal.

The other experiments have horn system focusing and have a few per cent antineutrino contamination, at the peak (focused) but then the contamination gets significantly worse at higher energies.

4 Neutrino Results since DIS 06

4.1 Neutrino Oscillation Results

The primary physics goal of MINOS is to measure the muon neutrino survival rate as a function of neutrino energy, at a distance of 735km from the source of neutrinos. This measurement is already providing the world's most accurate measurement of the atmospheric mass squared difference between the neutrino mass eigenstates. Because of the high neutrino energies of the beam (the peak neutrino energy for the majority of MINOS data-taking is 3.5GeV), combined with the low energy threshold of the MINOS detector, MINOS can also look for sterile neutrinos by comparing the neutral current interactions between the near and far detector. Finally, the high statistics that the MINOS experiment has means that even with substantial backgrounds (primarily from neutral current deep inelastic scattering events), if they are well enough understood MINOS can also reach a new sensitivity in searching for $\nu_\mu \to \nu_e$.

At the time of the DIS08 workshop, the MINOS experiment had released ν_μ disappearance results based on 2.5×10^{20} protons on target. The neutrino energy distribution for the identified ν_μ charged current events with and without oscillations is shown in Figure 2. The best fit of the energy distribution gives a mass squared difference of $|\delta m^2_{32}| = 2.38 \pm 0.20(stat + syst)x10^{-3}eV^2$. The primary systematic uncertainties are listed in table 4.1. One can see from this table that understanding the neutral current background (which feeds into the charged current signal at low reconstructed neutrino energy, primarily from high y events where a pion has punched through the steel) is the dominant uncertainty in the mixing angle measurement, and the absolute hadronic energy scale, which itself is dominated by un-

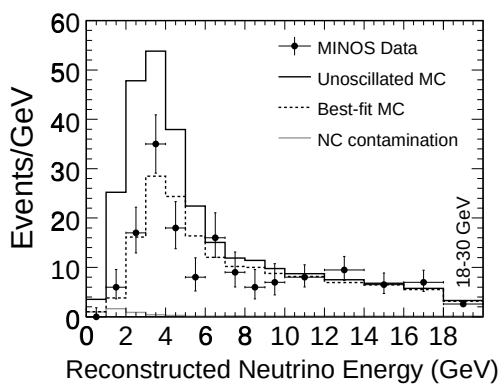

Figure 2: Reconstructed neutrino energy distribution for the data and monte carlo assuming oscillations at the best fit value and also assuming no oscillations [7]

Table 2: List of the largest systematic errors on the MINOS oscillation parameters from muon neutrino disappearance

Uncertainty	Shift in Δm^2	Shift in $\sin^2 2\theta_{23}$
Near / Far normalization $\pm 4\%$	.065	< 0.005
Absolute Hadronic Energy Scale $\pm 10\%$	0.075	< 0.005
Neutral Current Contamination $\pm 50\%$	0.010	0.008
All other systematic uncertainties	0.041	< 0.005
Total systematic (summed in quadrature)	0.11	0.008
Statistical error (data)	0.17	0.080

derstanding nuclear effects in neutrino scat-
tering, is the dominant systematic uncertainty in the mass squared splitting measurement.

While not optimized to search for ν_e appearance, MINOS does represent the first chance to perform a high statistics search for this channel at a long baseline. The backgrounds for MINOS (and indeed for all future $nu\mu \rightarrow \nu_e$ searches fall into three categories: neutral current events, high y charged current events where the primary muon is lost, and intrinsic ν_e contamination. The first two backgrounds can fake a signal when a neutral pion in a DIS-generated shower is energetic enough to be considered as a primary electron in a ν_e charged current event, and that pion is mis-identified as an electron. So while the total hadronic energy distribution of neutral current events is reasonably well-known in the DIS region, the neutral pion energy distribution is the critical quantity that needs to be measured. For the MINOS experiment, the first two backgrounds are larger than the third background, and the sum of the background contributions can be constrained by the near detector.

The problem with a near detector in an appearance search, however, is that if the near detector is identical to the far detector, then it is not enough to simply measure all the events in a near detector that would pass all the selection critera: in order to extrapolate from the near to far detector the experiment must know what the fractions of the three components are. The background from ν_μ charged current interactions in the near detector will be proportionally much smaller in the far detector for MINOS because a large fraction of the ν_μ's will have oscillated to ν_τ's, which at these energies are below threshold for a ν_τ charged current interaction.

In order to understand what fraction of events in the MINOS near detector are from each of these components, MINOS has done two very different studies. The first is to turn off the focusing of the parent pions that make the neutrino beam: in this case the relative fractions of the three backgrounds will change dramatically, since there are no longer as many high y ν_μ charged current events that would have the correct reconstructed neutrino energy. The second study is to look at the hadronic activity of ν_μ charged current interactoins where the muon signal has been removed, and compare the electromagnetic component of that activity between the data and the monte carlo. The conclusion from both of these studies is that the original modeling of the hadronic shower disagrees with what is seen in the near detector, and in order to tune the simulation to agree one must decrease the electromagnetic component of that activity [8].

4.2 Charm Production Results

Neutrino Deep Inelastic Scattering provides a unique window on charm production and measurements of the strange sea because of the simple fact that charmed mesons when produced will decay to muons 10% of the time, and will do so well before they interact in the detector, unlike produced pions and kaons. So in a ν_μ or $\overline{\nu}_\mu$ beam, the signature for charm production is two oppositely charged muons, as shown in Figure 3. Neutrino (anti-neutrino) Charm production can occur from scattering off a strange (anti-strange) quark or off a down (anti-down) quark (where the latter process is Cabibbo-suppressed).

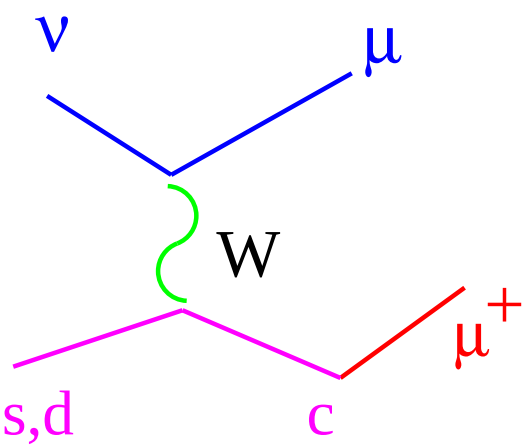

Figure 3: Feynman Diagram for Charm Production in Neutrino scattering.

4.2.1 CHORUS

The CHORUS experiment, designed to look for $\nu_\mu \to \nu_\tau$ oscillations by using emulsion, recently published high statisics results on charm production by looking for two-muon events that originated in their 112-ton lead scintillator calorimeter. This sample is the second largest sample of two-muon events from a neutrino experiment, and can be used to constrain the integral over x of the strange sea relative to the non-strange sea (parameterized as κ), the charm quark mass (m_c), the Petersen fragmentation parameter ϵ_P, and the branching fraction of charmed mesons to muons B_μ. The primary muon, or the one coming from the neutrino interaction vertex, is identified as the one having the largest transverse momentum with respect to the beam direction. With that classification the CHORUS experiment found 8910 two-muon neutrino events and 430 two-muon anti-neutrino events. The cross section results can be found in [9], and Figure 4 shows the excellent data-monte carlo agreement after fitting for the physics parameters.

The leading order fit results are as follows:

$$\begin{aligned} m_c &= (1.26 \pm 0.16(stat) \pm 0.09(syst))GeV/c^2 \\ \kappa &= 0.33 \pm 0.05(stat) \pm 0.03(syst) \\ \epsilon_P &= 0.065 \pm 0.005(stat) \pm 0.009(syst) \\ B_\mu &= 0.096 \pm 0.004(stat) \pm 0.008(syst) \end{aligned}$$

These fits assume that the strange and anti-strange seas are identical, and the results are in agreement with but slightly more precise than other measurements.

4.2.2 NuTeV

The NuTeV experiment was designed to measure $\sin^2\theta_W$ by comparing the neutral to charged current ratio of the difference between neutrino and antineutrino cross sections. In order to make this measurement NuTeV had to cleanly identify neutral current events as

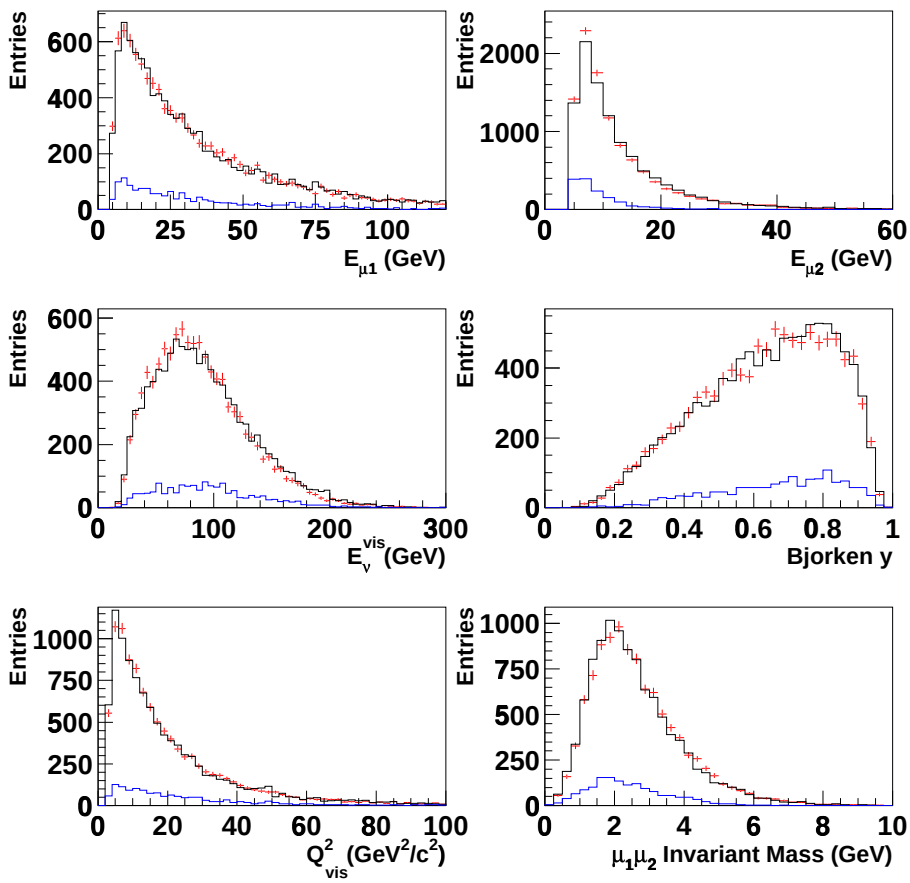

Figure 4: Kinematic variables measured in CHORUS two-muon events for both data and monte carlo. The blue lines represent the background from non-charm decays. Taken from referece [9]

being either from neutrino or antineutrino interactions. The only way to do this is to use extremely pure neutrino and anti-neutrino beam. The result, whose uncertainty was dominated by statistics, was more precise than all previous neutrino scattering measurements of $\sin^2\theta_w$, and was three sigma from the expectation that would come from electroweak observables at the Z pole [10].

By measuring something that is related to the difference between neutrino quark and anti-neutrino anti-quark cross sections, NuTeV was able to reduce systematic errors coming from uncertainties in the sea quarks. This is particularly important for the strange sea because of charm production, where there is a mass suppression in the charged current process but not in the neutral current process. However, the complete cancellation of uncertainties in the strange sea quarks depends on the assumption that the momentum distribution of the strange sea is equal to that of the anti-strange sea. S^- is a parameter of this difference, and

is defined as follows:

$S^- = \int [xs(x) - x\overline{s}(x)]\, dx$

and if S^- were equal to 0.0068, then this would move the NuTeV measurement of $\sin^2\theta_W$ into agreement with the prediction coming from the Z-pole measurements.

By looking at two-muon events in pure neutrino and anti-neutrino beams, NuTeV was able to identify the primary muon by the beam tune, and not the muon with the largest transverse momentum relative to the neutrino beam direction. NuTeV perfomed a next to leading order fit to the data, using CTEQ6 parton distribution functions, and assuming that the net strangeness of the nucleon must be equal to zero. The strange sea difference is found to be consistent with zero limited to be below what would be needed to account for the $\sin^2\theta_W$ discrepancy [11]: $S^- = 0.00196 \pm 0.00046(stat) \pm 0.00045(syst) \pm 0.00128(external)$

where the external uncertainty is dominated by the uncertainty in the charm to muon branching ratio, which itself is only known to 15%. The asymmetry measured by NuTeV can be seen as a function of x in Figure 5. The inner error band in the figure is from the systematic uncertainty from the charm branching ratio alone, and the outer error band is the total statistical and systematic uncertaiinty [11].

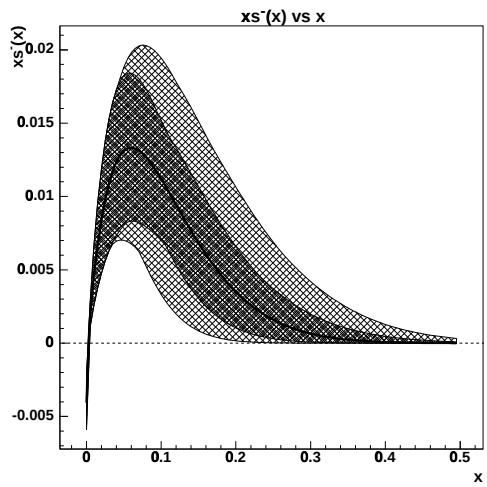

Figure 5: Strange sea asymmetry, $(s(x) - \overline{s}(x))$ as a function of x.

4.3 Total Cross Section Results

The NOMAD experiment was designed to see $\nu_\mu \to \nu_\tau$ oscillations by identifying τ interactions in a precise tracking detector neutrino target, surrounded by calorimetry. NOMAD has also measured the total charged current cross section for neutrinos using a very small fiducial region of their detector where the acceptance is well-understood. The flux was measured using events with very low hadronic activity in them, and then using the fact that at high energies those events are quasi-elastic events where the cross section is constant.

Because of the excellent tracking in the NOMAD detector and the high statistics, the experiment was able to determine the energy scale of the muon spectrometer by looking at the kaon mass peak. Then, the experiment could tie the hadronic energy scale to the muon energy scale by requiring the y distributions of the data and monte carlo to agree and allowing the hadronic energy scale to vary. The experiment found that a 5% hadron energy scale factor was needed to make the data and monte carlo agree. The resulting measurement is the most precise measurement so far below 40GeV, and was normalized to the world average neutrino cross section above 40GeV [12]. More importantly, the NOMAD measurement confirms the rise of the total cross section below 10GeV, something that was hinted at by previous experiments, as shown in Figure 6.

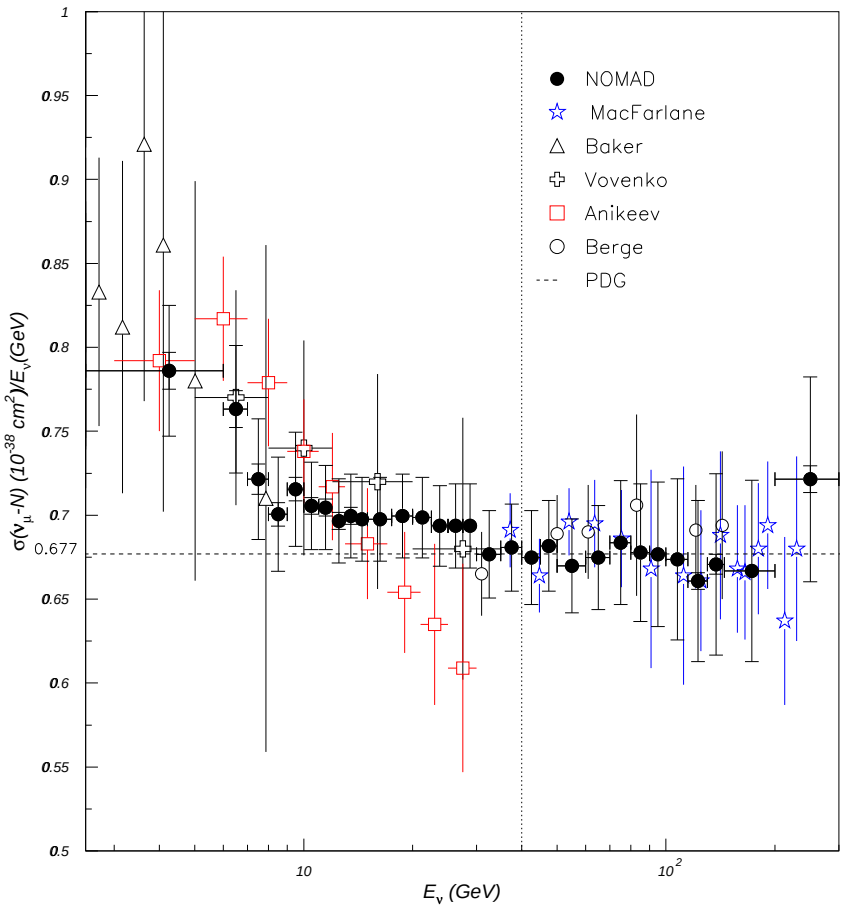

Figure 6: Total Cross Section results from NOMAD, compared with other experiments. Taken from referece [12]

5 Next Generation of Neutrino Experiments

The next generation of neutrino oscillation experiments will need to understand neutrino interactions better than ever before. The mass squared difference measurement will ultimately be limited by our understanding of nuclear effects and how they change the visible energy in a neutrino interaction, and the future experiments that are looking for $\nu_\mu \to \nu_e$ will need to make precise predictions not only of the backgrounds but also of the signals should they arise [13]. Ultimately, to measure the neutrino mass hierarchy and to look for CP violation in the neutrino sector, experiments will need to look for differences between neutrino and antineutrino oscillation probabilities, which are already themselves limited to being no larger than a few per cent.

5.1 MINERvA

The MINERvA experiment is designed to study neutrino-nucleus interactions in unprecedented detail using a fine-grained solid scintillator tracking detector surrounded by electromagnetic and hadronic calorimetry [14]. These measurements will be extremely useful to current and future neutrino oscillation experiments, but will also provide new information to the nuclear physics community that is eager to test its understanding of the nucleus that comes from charged current lepton scattering on nuclei with neutrinos.

The MINERvA detector will be placed in the NuMI beamline for high statistics in the few GeV neurino energy regime. Because the neutrino beam is so intense, the MINERvA experiment can get of order a million events in a 4 year run for each ton of target materials. The MINERvA experiment will have roughly 1 ton solid targets of lead, steel, 0.3 tons of carbon (graphite) and 3 tons of hydrocarbons (solid scintillator) as well as a 0.25 ton liquid helium target. An example of the kind of reach that MINERvA will have on the rare process of coherent scattering where an incoming neutrino scatters off the entire nucleus can be seen in Figure 7. The statistics for Deep Inelastic Scattering events will be far more impressive: roughly 4.3 DIS events are expected for a 4 year MINERvA run.

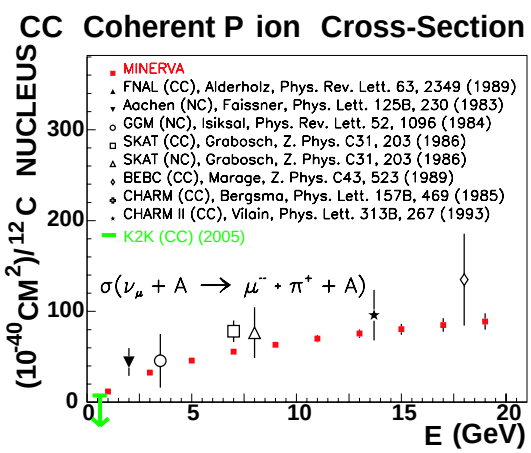

Figure 7: Example of MINERvA Cross Section results on coherent neutrino-nucleon scattering on scintillator.

The MINERvA experiment received full funding approval from the Department of Energy in November 2007 and is proceeding wtih detector construction. The experiment expects to begin taking neutrino data by the end of 2009.

Mode	Statistics	
	Neutrino	Anti-Neutrino
Charged Current DIS	600M	33M
Neutral Current DIS	190M	12M
Neutrino Electron Neutral Current Scattering	75k	7k
Neutrino electron Charged Current Scatering	700k	0k

Table 3: List of neutrino interaction channels and expected statistics for the proposed NuSonG run.

5.2 NuSONG

The NuSonG experiment is designed to measure $\sin^2\theta_W$ by looking at high energy neutrino interactions on electrons[15]. By comparing neutrino and antineutrino scattering off electrons (as shown in Figure 8), the hadronic uncertainties that affect neutrino-quark measurements such as NuTeV will be eliminated. The challenge with this measurement however is that to get ample statistics for such a rare process the detector must be both fine-grained to remove backgrounds, but extremely massive to get the statistics. The NuSonG experiment proposes to use the CHARMII detector design which includes a glass target with a quarter radioation length segmentation, proportional chambers and scintillator for tracking, plus a muon toroid for muon momentum measurements. The experiment will also need an extremely intense high energy neutrino beam that is very pure, such as the NuTeV beamline design.

The NuSonG experiment will collect huge samples of DIS events as well as neutrino-electron scattering events, and as such would represent a huge step forwards in high statistics neutrino DIS measurements to study structure functions. Table 5.2 lists the statistics that would be achieved in several different samples for the proposed run plan. The experiment is still in the proposal stage at the time of these proceedings.

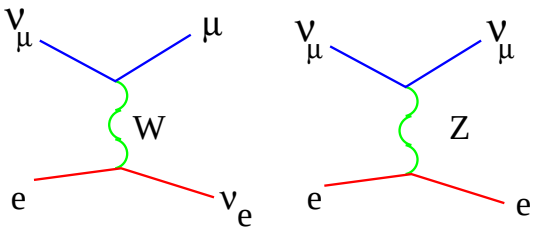

Figure 8: Feynman Diagrams for neutrino electron scattering, for both the neutral and charged current processes.

6 Conclusions

Although many neutrino experiments were taking data in the late nineties, there is still much to be learned from those data sets today. There was not time to discuss all of the results that have been released since the last DIS conference, but interested readers should see both the single[9] and associated[16] charm production results from CHORUS. NOMAD has results on both the total charged current cross section[12], and results on searches for the θ^+ resonance [17]. DONUT has produced a tau neutrino interaction cross section measurement with their 9 identified ν_τ Charged current events[18], and as discussed here, NuTeV has released new strange sea asymmetry results [11].

The MINOS experiment is still taking data and their near detector has recorded over 10 million deep inelastic scattering events. These events are being studied and cross section results will be forthcoming. The oscillation analyses on MINOS are finding that we have a lot to learn still about high y events, and that the better we understand Deep Inelastic Scattering, the better we can measure neutrino oscillations.

The future of neutrino DIS measurements is bright as well with the advent of the MINERvA experiment. By the next DIS conference our picture of neutrino interactions should be far more clear than it is today.

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