Part I

Physics Motivation and Goals
1 Neutrino Scattering and Long-Baseline Oscillation Experiments

The field of oscillation physics is about to make an enormous leap forward in statistical precision: first with MINOS in the coming year, and later in T2K and the proposed NO\(\nu\)A experiment. Unfortunately, our relatively poor understanding of neutrino interaction physics in the relevant energy range of these experiments gives rise to systematic uncertainties that could be as large as, or even larger than, their corresponding statistical uncertainties. We have studied the origin of some of these systematic effects, and how MINER\(\nu\)A’s measurements can reduce them to well below the statistical level.

1.1 Introduction

Over the past five years the field of neutrino oscillation has moved from seeing decades-old anomalies in cosmic ray [1] and solar [2] neutrino data to powerful cross checks of these anomalies (SNO data [3] and angular distributions in atmospheric neutrino data [4]), and most recently to terrestrial confirmation of the oscillation hypothesis (Kamland [5] and K2K [6]). The next steps in this field are to move to precision measurement of the mass splittings and mixing angles already observed, and search for other non-zero off-diagonal elements in the neutrino mixing matrix.

New, extremely-intense beams being built or planned will greatly increase the statistical reach and ultimate measurement precision for oscillation parameters. With these tremendous improvements in statistical accuracy, however, come new concerns about systematic uncertainties that until now have been a secondary concern. In particular, uncertainties in neutrino cross-sections and nuclear effects lead to systematic uncertainty in the extraction of mixing parameters. Although near detectors are a critical part of precision long-baseline oscillation measurements, they are often ill-suited to make the needed cross-section measurements because they tend to be similar to the coarse and massive far detectors. A near detector can at best constrain the convolution of the near flux, cross-section and detection efficiency. Uncertainties on all of these quantities must be incorporated into the analysis. The cross-section uncertainties we consider are only a subset of the whole, but when flux and efficiency are also taken into account, near-detector performance must be worse than we estimate here.

This chapter is divided into two sections. The first addresses uncertainties relevant for \(\nu_\mu\) disappearance experiments, whose aim is to precisely measure the mass splitting \(\Delta m^2_{23}\), and the mixing angle which has already been determined to be large, \(\theta_{23}\). To achieve these goals the experiments must measure oscillation probabilities as a function of neutrino energy. Two important concerns here are uncertainties in charged-current inelastic processes, and the scale of nuclear effects. Both inelastic channels and the nuclear environment alter the relationship between the true and measured neutrino energies. The second section discusses searches for \(\nu_e\) appearance, which if observed at accelerator energies would indicate a non-zero value of \(\theta_{13}\) or more exotic new physics. Because the size of the signal is unknown, the final sample may be dominated by signal (charged-current) cross-sections, and/or background (neutral- and charged-current) processes. In both cases, the experiments of the past are inadequate to precisely predict the far detector event samples.

1.2 \(\nu_\mu\) Disappearance

Precision measurement of the mass splitting between two neutrino eigenstates requires analysis of the oscillation probability as a function of neutrino energy \(E_\nu\) divided by baseline \(L\). The muon neutrino disappearance probability (in the standard 3-generation oscillation parameterization [7]) is
\[ P(\nu_\mu \rightarrow \nu_\mu) = 1 - \cos^4 \theta_{13} \sin^2 2\theta_{23} \sin^2 \left( \frac{1.27\Delta m^2_{23} (eV^2)L(km)}{E_\nu(GeV)} \right) - \ldots \]  

where the additional terms are \( O(\sin^2 2\theta_{13}) \) or smaller. Currently \( \Delta m^2_{23} \) is known to within a factor of two and \( \cos^4 \theta_{13} \sin^2 2\theta_{23} \) must be larger than 0.9, at 90\% confidence level [8]. Since \( \sin^2 2\theta_{13} \) has been constrained below 0.1 by the CHOOZ reactor experiment[9], this means \( \sin^2 2\theta_{23} \) itself is very close to 1. The fact that \( \theta_{23} \) is close to 45\° has been cited as a hint of the underlying symmetry that generates neutrino mass and mixing. Precise measurement of this angle is important because the level at which the mixing deviates from maximal may again give hints about the mechanisms responsible for the breaking that symmetry [10].

More precise measurements of \( \Delta m^2_{23} \) are required to extract mixing angles from eventual \( \nu_e \) appearance experiments. The challenge of \( \Delta m^2_{23} \) lies in measuring the true neutrino energy in both near and far detectors. Even if the two detectors have an identical design, any uncertainty in the “neutrino energy scale” of the \( \nu_\mu \) charged-current signal translates directly into an uncertainty in the extracted value of \( \Delta m^2_{23} \).

There are two different ways of measuring neutrino energies: kinematic or calorimetric reconstruction. We discuss both techniques here, and then explain how uncertainties in neutrino interactions lead to energy scale uncertainties and ultimately \( \Delta m^2_{23} \) uncertainties.

The first experiment to provide a precision measurement of \( \Delta m^2_{23} \) will be MINOS [11], which will start taking data early in 2005. MINOS will use both far and near detectors, which are magnetized steel-scintillator calorimeters with 2.54 cm longitudinal segmentation. The transverse segmentation of the 1 cm thick scintillator planes is 4 cm. MINOS will use Fermilab’s NuMI beam, with a baseline of 735 km, which can provide a variety of broad-band neutrino spectra. In its lowest-energy configuration, where MINOS expects to do most of its running, the peak neutrino energy in the \( \nu_\mu \) interaction spectrum is about 3.5 GeV.

T2K will use Super-Kamiokande, a water Cherenkov detector, and focus on single-ring muon-like events, for which the neutrino energy is reconstructed kinematically under the hypothesis of two-body scattering. T2K will use a narrow band off-axis neutrino beam from J-PARC in Tokai, whose peak flux is close to 700 MeV, and which originates some 295 km away [13]. The design of the near detectors has not been finalized, but should include a fine-grained tracker and a water Cherenkov detector.

The proposed NO\( \nu \)A experiment will use a calorimetric detector to improve measurement of \( \Delta m^2_{23} \). Because NO\( \nu \)A is optimized for \( \nu_e \) appearance rather than \( \nu_\mu \) disappearance, it will use near and far calorimeters made of scintillator planes interspersed with particle board or other scintillator planes. The longitudinal segmentation should be about 1/3 to 1/6 of a radiation length, and the transverse segmentation of the scintillator will be about 4 cm[12]. NO\( \nu \)A will also use the NuMI beam, but will place its detectors 12–14 mrad off the beam axis, to receive a narrow-band neutrino spectrum. NO\( \nu \)A with a baseline of 810 km, will run with a peak neutrino energy of about 2 GeV.

1.2.1 Kinematic neutrino energy reconstruction

Kinematic reconstruction assumes that a given event was produced by a particular process (for example, quasi-elastic scattering) and determines the neutrino energy based on a sufficiently constraining subset of the final-state particles under that hypothesis.

This technique is well-suited to water Cherenkov detectors, which perform best for single-ring topologies. In Super-Kamiokande detector, for example, the \( \nu_\mu \) charged-current signal consists of
single-ring, muon-like events, which are primarily quasi-elastic interactions. The energy of the incoming neutrino in that case can be determined using only the outgoing muon momentum ($p_\mu$) and direction ($\theta_\mu$):

$$E_\nu = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos \theta_\mu}$$

Since the absolute energy scale for muons can be fixed to within 2–3% by a variety of calibration techniques [107], and the reconstruction algorithms measure ring directions extremely well, it seems plausible that the neutrino energy scale could be determined with comparable precision. However, not all events producing a single muon-like ring are quasi-elastic interactions. Resonant excitation, and even deep-inelastic scattering, where pions are absorbed in the oxygen nucleus or emerge below Cherenkov threshold can lead to the same topology. Such events will have a reconstructed energy well below the true neutrino energy, because the recoiling hadronic mass is larger than assumed. The effect of this inelastic background could be corrected, if the energy-dependent ratio of quasi-elastic and resonant cross-sections were perfectly known, but since it is not, an uncertainty in the effective neutrino energy scale of the detector results.

Because the $\nu_\mu$ disappearance probability is nearly 100% for T2K, the relative abundance of quasi-elastic and inelastic events will be very different at Super-K than for the unoscillated beam sampled by a near detector.

Precision measurement of the differential cross-sections for single- and multi-pion production, as a function of neutrino energy, will reduce uncertainties in the subtraction of inelastic background, improving T2K’s neutrino energy resolution, and ultimately the precision of its oscillation measurements. Since the event samples are so different between near and far detectors, and because water Cherenkov technology cannot entirely eliminate the inelastic background, additional measurements with fine-grained detectors are required. Ideally, these measurements would include not only exclusive inelastic reactions, but also quasi-elastic scattering, with a well-modeled efficiency relative to the inelastic channels. Because the reconstructed energy for inelastic background is lower than the true neutrino energy (the background “feeds down”), it is essential to measure these cross-sections both at and above the T2K beam energy. Chapters 2 and 4 discuss MINER$\nu$A’s measurements of quasi-elastic and resonant cross-sections.

### 1.2.2 Calorimetric neutrino energy reconstruction

At neutrino energies above 1 GeV, calorimetric energy reconstruction is more efficient than kinematic reconstruction. In a low-threshold calorimetric device, the reconstructed or visible neutrino energy is simply the sum of all observed secondary particles’ energies. For a $\nu_\mu$ charged-current interaction, the muon energy can be determined by measuring its momentum by either range or curvature (if the calorimeter is magnetized), and the remaining activity can be summed to estimate the hadron energy. Scintillating calorimeters have a lower charged-pion detection threshold than Cherenkov detectors, so more of the total kinetic energy is visible for multi-pion interactions, which dominate the cross-section above a few GeV. As a result, neutrino energy reconstruction is less susceptible to bias from inelastic reactions than Cherenkov detectors.

For MINOS, the absolute energy scale for muons is fixed by knowledge of the steek plate thickness and muon energy loss processes. The thickness of each plate has been measured to better than 0.1% and they vary with an RMS of 0.4% [108]. In a muon test beam at CERN a 2% absolute scale calibration
was achieved [109]. The hadronic and electromagnetic energy scales have been calibrated with test beams on a prototype detector at CERN, and have been measured relative to the muon scale within better than 5% [110, 111]. It is still necessary to translate from the raw response to pions and muons to the energy of interacting neutrinos, however.

At neutrino energies of a few GeV and below, three effects become significant in translation between visible and and neutrino energies. Uncertainties in these effects must be understood and included in any precise measurement of $\Delta m^2_{23}$. One effect, independent of the target nucleus, is the rest masses of the secondary charged pions. Since MINOS lacks the granularity to measure the multiplicity of final state particles, a hadron-energy dependent multiplicity distribution must be assumed. The second and third effects are due to secondary particle scattering or complete absorption in the nucleus. All three effects reduce the visible hadronic energy, which in turn lowers the reconstructed neutrino energy. Importance of these effects grows larger as the parent neutrino energy decreases,[76] due to strong enhancement of the pion–nucleon cross-section near the $\Delta(1232)$ resonance [113].

To quantify the magnitude of nuclear effects on measurement of $\Delta m^2_{23}$ in a MINOS-like detector, a simple detector simulation was combined with the NEUGEN event generator [114] and NuMI fluxes at 735 km [115]. In this simulation the visible energy is simply defined as the sum of kinetic energies for all charged final-state particles, plus the total energy for the neutral pions, and photons, which are assumed to deposit all their energy as electromagnetic showers.

Figure 1 shows the variation of the ratio of visible to total neutrino energy for changes in nuclear absorption and scattering separately. In the plot on the left the target is assumed to be steel, and the parameter controlling pion absorption is set to zero or doubled. In the plot on the right all pion absorption is turned off, and the differences that remain are due to rescattering effects in steel, carbon, and lead. These rescattering effects have not been measured with neutrinos on high Z nuclei, so the rescattering variation can be considered as an error on extrapolation from the low-Z measurements that do exist. Because the $\nu_\mu$ disappearance probability should be large, the far and near detector energy spectra will be very different, and these effects will only partially cancel in a ratio between near and far detectors. The extent to which they do not cancel represents a systematic error on $\Delta m^2_{23}$.

If these pion absorption Z extrapolation effects are treated as the total systematic uncertainty due to nuclear effects, we can compare it to the expected MINOS statistical error. In this more complete analysis, the detector acceptance must also be taken into account. One cut which could reduce the error due to nuclear effects significantly would be to require a minimum muon energy. The less visible energy attributable to hadrons, the smaller the relative effect of nuclear uncertainties on the total neutrino energy measurement. Requiring the muon to take up most of the energy in an event lowers efficiency, of course, and reduces the statistical power of the far-detector data sample. Here a minimum muon energy of 0.5 GeV was required, in an attempt to approximate the acceptance of a real analysis.

If the uncertainties from nuclear effects correspond to the differences in Figure 1, then for a 0.5 GeV muon momentum cut they induce a $\Delta m^2_{23}$ error only slightly smaller than the statistical error expected by MINOS with $7.6 \times 10^{20}$ protons on target (POT) (see Figure 2).

As described in Chapter 8, MINERνA will measure neutrino interactions on steel, carbon, and lead and collect about 750K events on each target over the four year run. This represents an enormous improvement in both the statistics and the range of target nuclei over previous experiments, and would improve our level of understanding of nuclear effects dramatically. With sufficient data on several different nuclei, the error on Z extrapolation would be reduced since the nuclear models would be better constrained. The remaining uncertainties on the detector energy scale are likely due to uncertainties in pion rescattering in steel. Systematic uncertainty in $\Delta m^2_{23}$ with this new data in hand would be small.
Figure 1: Ratio of visible (reconstructed) to true neutrino energy for several different models of nuclear effects. The left plot shows the ratio for steel (solid) with the nominal pion absorption, as well as the same ratio for the pion absorption turned off or doubled from what is expected. The right plot shows the differences the ratio for three different target nuclei, where pion absorption is turned off to isolate the effects of pion rescattering.

cmpared to the statistical error, as is shown in Figure 2.

1.3 $\nu_e$ Appearance

1.3.1 Signal and backgrounds

The goal of the next generation of neutrino oscillation experiments is to determine whether the last unmeasured neutrino mixing matrix element, (called $|U_{e3}|$ or $\sin \theta_{13}$) is non-zero. If $\theta_{13}$ is in fact non-zero future experiments could measure the neutrino mass hierarchy search for CP violation in the lepton sector. T2K and NO$\nu$A will probe this matrix element by measuring the $\nu_\mu \rightarrow \nu_e$ oscillation probability at a “frequency” corresponding to $\Delta m^2_{23}$. The oscillation probability for $\nu_\mu \rightarrow \nu_e$ in vacuum can be expressed [7]

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \left( \frac{1.27 \Delta m^2_{23} (eV^2)L(km)}{E_{\nu}(GeV)} \right) + ...$$

where the additional terms not shown are due to small effects from the solar mass splitting, $\Delta m^2_{12}$.

Identifying $\nu_e$ appearance in a $\nu_\mu$ beam is quite challenging for several reasons. From the CHOOZ reactor neutrino limit on $\sin^2 2\theta_{13}$ [9] the appearance probability must be less than about 5% at 90% confidence level. Also, the beams contain an intrinsic $\nu_e$ contamination as large as a few per cent. Finally, neutral-current and high-$\gamma$ charged-current $\nu_\mu$ interactions can produce energetic $\pi^0$, leading to electromagnetic showers that may resemble a $\nu_e$ charged-current event.

T2K and NO$\nu$A will reduce some of these backgrounds significantly below the level in current long baseline experiments by using detectors optimized for electron appearance, and by placing those
Figure 2: Fractional size of the statistical 90% confidence level region at $\sin^2 2\theta_{23} = 1$ for MINOS. Also shown are possible systematic uncertainties due to uncertainties in nuclear effects: the dot-dashed line are those effects described in the text, and the dotted line assumes uncertainties after dedicated nuclear effect measurements where pion rescattering and absorption are measured on the target nucleus (steel). Detector acceptance is modelled by requiring muons above 0.5 GeV. Also shown are the statistical errors for two different integrated proton intensities.

detectors off the beam axis. In two-body decay of the charged pion, the neutrino energy spectrum at small angles from the beam axis are narrower than the on-axis spectrum. Also, at these small angles the peak energy itself is reduced. The narrowest neutrino energy spectrum occurs when the far detector is placed at an angle corresponding to 90° in the pion center of mass. In this configuration, the $\nu_e$ flux comes from the three-body muon decays, so the intrinsic $\nu_e$ flux at lower energies does not increase at higher angles like the $\nu_\mu$ flux does. Also, the neutral-current background is always a steeply falling function of visible energy because the outgoing neutrino always takes some fraction of the incoming neutrino’s energy.

With this “off-axis” strategy, T2K and NOνA still expect some background after all analysis cuts, even in the absence of $\nu_\mu \rightarrow \nu_e$ oscillation. Measurement of the $\nu_\mu \rightarrow \nu_e$ probability requires accurate knowledge of this remaining background, and the cross-section and detection efficiencies for the $\nu_e$ signal.

1.3.2 Cross-section uncertainties with a near detector

Both T2K and NOνA will use near-detector measurements to predict the expected backgrounds at the far detector. In T2K, an on-axis near detector 280 m from the proton target will measure the spectrum and transverse beam profile, and at least one other off-axis detector will be focused on cross-section measurements. There are also plans to build a water Cherenkov detector 2 km from the proton target, but even then near- and far-detector efficiencies may not be identical. For NOνA, the near detector will be very similar in design to the far detector, and can be placed in a wide range of angles with respect to the beam. By making the near detector similar, NOνA hopes to minimize uncertainties in the detector response and efficiency. However, because the near detector will be as coarse as the far, it is
not optimized for cross-section measurements.

To see how any uncertainties (cross-section, detector acceptance, or flux) will arise in the far detector prediction based on the near detector data, it is useful to think about how the event samples are likely to change between near and far. At a near detector, the flux of muon neutrinos will have a very strong peak at a particular energy, while at the far detector that peak will (by design) have oscillated to mostly $\nu_\tau$. At these energies, $\nu_\tau$ cannot produce charged-current interactions, only neutral-current. Neutral-current samples are likely to be similar from near to far, provided the near detector is at a similar off-axis angle. Electron neutrino events at the peak are primarily from muon decays in the beam, which occur on average substantially farther downstream than the pion decays. Therefore, the extrapolation from the near to far detector tends to be different for all three event samples. If the relative population of the background sample among different categories cannot be predicted accurately (due to cross-section, detector or flux uncertainties), the far detector extrapolation will be wrong.

The MINOS and NO$\nu$A near detectors will both provide important constraints on neutrinos coming from NuMI. However, neither will be able to measure the charged- and neutral-current near detector backgrounds precisely. A finer-grained detector with improved timing resolution will be extremely useful to distinguish these two contributions which change so dramatically between near and far detectors.

A quantitative case study of how cross-section uncertainties may not completely cancel between near and far detectors, was performed using the simulation for an early design [116] of NO$\nu$A. Although NO$\nu$A’s final design will be different, the fundamental arguments remain unchanged: the mixture of contributing cross-sections at the far detector cannot, even in principle, be identical to the mixture at the near detector.

<table>
<thead>
<tr>
<th>Process</th>
<th>Statistics</th>
<th>Composition after all cuts in far detector</th>
<th>QE</th>
<th>RES</th>
<th>COH</th>
<th>DIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal $\nu_\mu$</td>
<td>175 ($\sin^2 2\theta_{13} = 0.1$)</td>
<td>55% 35% n/I 10%</td>
<td>20%</td>
<td>40%</td>
<td>100%</td>
<td>20%</td>
</tr>
<tr>
<td>NC</td>
<td>15.4</td>
<td>0 50% 20% 30%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\nu_\mu CC$</td>
<td>3.6</td>
<td>0 65% n/I 35%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam $\nu_\mu$</td>
<td>19.1</td>
<td>50% 40% n/I 10%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Rate of signal and background processes in a 50 kton NO$\nu$A far detector, assuming $\Delta m_{23}^2 = 2.5 \times 10^{-3}$ eV$^2$. Also listed are the present cross-section uncertainties for those processes. Charged-current coherent production was not included since it is should be unimportant compared to other charged-current processes.

The signal and background samples for the nominal 5 year run are listed in Table 1 along with the fractional contribution of each process to events of a given type passing all cuts, and the relative cross-section uncertainties [117]. Without a near detector, the total error on the background prediction from cross-section uncertainties, in the absence of $\nu_\mu$ oscillation, is 16%, which is equal to the statistical error. For oscillation at the level indicated in the table, the statistical error on the probability would be 8%, while the errors from cross-section uncertainties alone are 31%.

Figure 3 shows the projected error on $\sin^2 2\theta_{13}$ as a function of $\sin^2 2\theta_{13}$ itself, for present cross-section uncertainties. Should NO$\nu$A find a large signal, even in its first phase the measurement will be
Figure 3: Statistical error, present cross-section systematic error, and post-MINERνA cross-section systematic error in NOνA measurement of $\sin^2 2\theta_{13}$, as a function of $\sin^2 2\theta_{13}$.

systematics limited with existing knowledge of relevant cross-sections. Chapters 2, 4, and 6 explain how different channels will be isolated, and give the size of the expected samples. MINERνA should be able to reduce cross-section uncertainties for NOνA to about 5% for all charged- and neutral-current deep-inelastic scattering processes, 10% for neutral-current resonant processes, and 20% for neutral-current coherent $\pi^0$ processes. If these uncertainties were achieved, then systematic errors due to cross-section uncertainties would be well below the statistical errors, as shown in Figure 3.

1.4 Conclusions

It is clear from even these preliminary studies that MINERνA will play an important and potentially decisive role in helping current and future precision oscillation experiments reach their ultimate sensitivity. To get the most precise values of $\Delta m^2_{23}$ (which is eventually necessary to extract mixing angles and the CP-violating phase) our field must better understand and quantify the processes that occur between interaction of an incoming neutrino and measurement of the outgoing particles in a detector. Although the issues are different depending on whether the detector is a water Cherenkov or calorimetric devices, in both cases more information is needed. Extracting mixing parameters like $\theta_{13}$ and ultimately the neutrino mass hierarchy and CP-violation requires much better understanding of resonant cross-sections. Even setting limits on these parameters will require better measurements of neutral-current processes. The cost of curing our present ignorance pales in comparison to the possibility that an entire generation of oscillation experiments might miss out on an exciting discovery or end in a morass of inconclusive, ambiguous, contradictory or even wrong results because we have failed to invest the effort needed to understand the most basic interactions of the particle whose exotic behavior they were built to study. Precision measurement of exclusive cross-sections and nuclear effects will finally put a field making tremendous strides in luminosity and statistical power on a sound systematic foundation.
2 Quasi-Elastic Scattering

2.1 Introduction

Quasi-elastic scattering dominates the total $\nu$–N interaction rate in the threshold regime $E_{\nu} \leq 2$ GeV. Precision measurement of the cross-section for this reaction, including its energy dependence and variation with target nuclei, is essential to current and future neutrino-oscillation experiments.

2.2 Nucleon Form-factors in Quasi-elastic Scattering

MINER$\nu$A’s large quasi-elastic samples will probe the $Q^2$ response of the weak nucleon current with unprecedented accuracy. The underlying V-A structure of this current includes vector and axial-vector form-factors. The essential formalism is given in reference [14].

\[
\langle p(p_2)|J^+_A|n(p_1)\rangle = \overline{\pi}(p_2) \left[ \gamma_\lambda F^V_\lambda(q^2) + \frac{i\sigma_\lambda q^n \xi F^A_\lambda(q^2)}{2M} + \gamma_\lambda \gamma_5 F_A(q^2) \right] u(p_1),
\]

where $q = k_\nu - k_\mu$, $\xi = (\mu_p - 1) - \mu_n$, and $M = (m_p + m_n)/2$. Here, $\mu_p$ and $\mu_n$ are the proton and neutron magnetic moments. The pseudoscalar form-factor is not shown since it is small for $\nu_\mu$.

The vector part of this matrix element can be expressed using $G^p_E(q^2)$, $G^n_E(q^2)$, $G^p_M(q^2)$, and $G^n_M(q^2)$. It has been generally assumed that the $q^2$ dependence of these form-factors can be described by the dipole approximation:

\[
G_D(q^2) = \frac{1}{\left(1 - \frac{q^2}{M_D^2}\right)^2}, \quad M_D^2 = 0.71 \text{ (GeV/c)}^2, \quad F_A(q^2) = \frac{g_A}{\left(1 - \frac{q^2}{M_A^2}\right)^2}
\]

then $G^p_E = G_D(q^2)$, $G^n_E = 0$, $G^p_M = \mu_p G_D(q^2)$, $G^n_M = \mu_n G_D(q^2)$. As discussed below, the dipole parameterization is far from perfect. MINER$\nu$A will be able to measure deviations of $F_A$ from this form. In general, the axial form-factor $F_A(q^2)$ can only be extracted from quasi-elastic neutrino scattering.\(^1\)

2.2.1 Vector form-factors

Electron scattering experiments at SLAC and Jefferson Lab (JLab) have measured the proton and neutron electromagnetic (vector) form-factors with high precision. The vector form-factors can be determined from electron scattering cross-sections using the standard Rosenbluth separation technique[15], which is sensitive to (two-photon) radiative corrections, or from polarization measurements using the newer polarization transfer technique[16]. Polarization measurements do not directly measure form-factors, but rather the ratio $G_E/G_M$. Recently, discrepancies in electron scattering measurements of some vector form-factors have appeared; study of quasi-elastic reactions in MINER$\nu$A may help reveal the origin these discrepancies. Figure 4 shows the BBA-2003 (Bodek, Budd, Arrington 2003) fits to $G^p_E/G_D$. There appears to be a difference between the two methods of measuring this ratio. The newer polarization transfer technique yields a much lower value at high $Q^2$ and indicates a difference between the electric charge and magnetization distributions. The polarization transfer technique is believed to be

\(^1\)At low $Q^2$, below 0.1 (GeV/c)^2, its behavior can also be inferred from pion electroproduction data.
more reliable and less sensitive to radiative effects from two-photon corrections. In addition, Figure 4 shows that dipole amplitudes provide only a first-order description of form-factor behavior at high $Q^2$.

In general, these deviations are different for each of the form-factors and are shown in [17]. If the electric charge and magnetization distributions of the proton are indeed different, accurate measurement of the axial form-factor’s high-$Q^2$ shape in MINERνA can provide important new input to help resolve differences in electron scattering data.

To obtain the correct neutrino cross-sections [17], the input form-factors must be correct. The $Q^2$ distribution measured in neutrino scattering is sensitive to both the vector and axial form-factors. However, using an incorrect axial form-factor to match the the $Q^2$ distribution in neutrino scattering (to compensate for old dipole vector form-factors) results in a 6–8% error in the calculated neutrino cross-section. Therefore, updated vector form-factors and better-measured axial form-factors are required. MINERνA will measure the $Q^2$ dependence of $F_A$ in neutrino scattering and compare the calculated cross-section with the measured cross-section.

2.2.2 Axial form-factor

Neutrino scattering provides the only practical route to precision measurement of the axial form-factor above $Q^2 = 0$, and the functional form of $F_A(Q^2)$. The fall-off of the form-factor strength with increasing $Q^2$ is traditionally parameterized (approximately) using an effective axial-vector mass $M_A$. Uncertainty in the value of $M_A$ contributes directly to uncertainty in the total quasi-elastic cross-section. Earlier neutrino measurements, mostly bubble-chamber experiments on deuterium, extracted $M_A$ using the best vector form-factors, other parameters, and models available at the time. Changing these input assumptions changes the extracted value of $M_A$. Hence, precision extractions of $M_A$ and $F_A$ require using the best possible vector form-factors and coupling constants. The value of $M_A$ is $\approx 1.00$ GeV/c$^2$, to an accuracy of perhaps 5%. This value agrees with the theoretically-corrected value from pion electroproduction[18], $1.014 \pm 0.016$ GeV/c$^2$. 

![Figure 4: The (BBA-2003) fits to $G_E^p/G_D$, using cross-section data only (solid), and with both the cross-section and polarization transfer data (dashed). The diamonds are the from Rosenbluth extractions and the crosses are the Hall A polarization transfer data.](image-url)
The fractional contributions of $F_A$, $G^p_M$, $G^n_M$, $G^p_E$, and $G^n_E$ to the $Q^2$ distribution for quasi-elastic neutrino and anti-neutrino scattering cross-sections in energy range of the NuMI beam are shown in Figure 5. The contributions are determined by comparing the BBA-2003 cross-sections with and without each of the form-factors included. MINERνA will be the first systematic study of $F_A$, which accounts for roughly half of the quasi-elastic cross-section, over the entire range of $Q^2$ shown in the figure.

Figure 5: Fractional contributions of $G^p_M$, $G^n_M$, $G^p_E$, $G^n_E$, and $F_A$ to the $Q^2$ distributions for quasi-elastic neutrino samples in the energy range of the NuMI beam. Because of interference terms, the sum of the fractions does not necessarily add up to 100%.

2.2.3 Physics of vector and axial form-factors

In deep-inelastic charged-current scattering from quarks, the vector and axial couplings are equal ($V$-$A$). Similarly, in electron scattering from quarks (vector current), there is a well-defined ratio between electric and magnetic scattering from point-like Dirac quarks. At low momentum transfers, all of these relations break down. For example, in quasielastic and resonant production at very low momentum transfers, the charge and anomalous magnetic moments of the neutron and proton mean the ratio of electric and magnetic scattering for the vector current is not the same as for free quarks. Similarly, from neutron decay, we know that $g_a(Q^2 = 0) = 1.267$ instead of 1.0, so vector and axial scattering differ at $Q^2 = 0$.

There are efforts in progress by lattice gauge programs to calculate the anomalous vector and axial magnetic moments of the proton and neutron, and the $Q^2$ dependence of all the form-factors in the low- and high-$Q^2$ regions. The normalization of the magnetic form-factors at $Q^2=0$ are constrained to equal the charge and anomalous (vector and axial) magnetic moment. The slope at low $Q^2$ is related to the mean square charge radius of the proton and neutron. The dipole form assumes that the charge and magnetization distributions of the various types of quarks and antiquarks have an exponential form. For $Q^2$ above $0.5$–$1.0$ (GeV/c)$^2$ this non-relativistic picture breaks down. The ratio $G_E/\mu G_M \approx 1.0$ (at low $Q^2$) implies that the charge and magnetization distribution of the proton are the same, but at higher
the ratio becomes much smaller, and more sophisticated models are required (e.g. lattice gauge theories). Therefore, measurement of the axial form-factor over a wide range of \( Q^2 \) is of great interest. In this section, we show MINERνA’s sensitivity to three different models of the axial form-factor:

- **Model 1**: A simple dipole approximation currently used for the magnetic form-factor of the proton, with different axial and vector radii. This is the current standard assumption.
- **Model 2**: A model in which the ratios \( G_M^p/G_D \) and \( G_E^p/G_D \) are equal, and decrease with \( Q^2 \).
- **Model 3**: A model based on duality, which requires the axial and vector parts of \( W_{1\text{elastic}} \) to be equal above \( Q^2 = 0.5 \, (\text{GeV}/c)^2 \), and therefore increase with \( Q^2 \), as described briefly in the next section.

### 2.2.4 Quark/hadron and local duality

In modern language, the concept of quark-hadron duality can be related to the momentum sum rule in QCD, and various other moments of the structure functions. It has been shown by Bodek and Yang that with inclusion of target mass corrections, NNLO QCD describes deep-inelastic scattering and the average resonant cross-section down to \( Q^2 = 0.5 \, (\text{GeV}/c)^2 \). The concept of local duality implies that the integral of the QCD predictions (including target mass) in the threshold region up to pion threshold, should be equal to the integral of the elastic peak. Since for QCD, the vector and axial contributions to \( W_1 \) and \( W_2 \) are equal, local duality predicts that vector and axial part of the quasi-elastic form-factors should become equal around \( Q^2 = 0.5 \, (\text{GeV}/c)^2 \). This means that the dipole approximation must break down for both vector and axial form-factors.

The vector and axial components of \( W_{1\text{elastic}} \) become equal at \( Q^2 \sim 0.5 \, (\text{GeV}/c)^2 \) for both BBA and dipole form-factors. The requirement that this vector/axial ratio remains equal to 1.0 for higher \( Q^2 \) yields a definite prediction that the axial form-factor is 1.4 times larger than the dipole prediction at higher \( Q^2 \).

### 2.2.5 Axial form-factor measurement in MINERνA

Figure 6 shows a typical quasi-elastic event, as simulated in MINERνA.

In \( \nu n \rightarrow \mu^- p \), the outgoing proton carries kinetic energy of approximately \( Q^2/2M_N \). So for low \( Q^2 \), the challenge is identifying events with a very soft recoil proton; for high \( Q^2 \), this proton is high energy and may interact in the detector, making particle identification more challenging. The main strategies of the current analysis are:

- At low \( Q^2 \), accept quasi-elastic candidates with a single (muon) track, and discriminate from background by requiring low activity in the remainder of the detector
- At higher \( Q^2 \), reconstruct both the proton and the muon, and require kinematic consistency with

\[
x = 1 \quad \text{and} \quad p_T^{\text{tot}} = 0
\]

Simple cuts based on these ideas yield reasonable efficiency and good purity, even at high \( Q^2 \).

This analysis uses the NEUGEN generator and the hit-level MINERνA detector simulation and tracking package to model signal selection and background processes.

Initial event identification requires one or two tracks in the active target. One of these tracks must be long range (400 g/cm\(^2\)) as expected for a muon. If a second track forms a vertex with this track,
Figure 6: A simulated charged-current quasi-elastic interaction in MINERνA. The proton (upper) and muon (lower) tracks are well resolved. In this display, hit size is proportional to energy loss within a strip. The increased energy loss of the proton as it slows and stops is clear. For clarity the outer detector is not drawn.

it is assumed to be the proton. No other tracks may be associated with this vertex. The muon track momentum is reconstructed with a fractional uncertainty of 10–20%.

For low $Q^2$, the proton track (if found) is effectively required to lose energy by $dE/dx$ alone, since only limited detector activity not associated with the primary tracks is allowed by the selection criteria. We attempt to recover some of the resulting efficiency loss by allowing hits on tracks near the proton track to be associated with it. Figure 7 shows the fraction of hits not associated with the lepton or proton in the quasi-elastic events and in expected background processes. For higher-$Q^2$ events a similar procedure could be applied, but it is not particularly effective nor efficient.

The energy of the proton for the high-$Q^2$ sample (where the proton almost always interacts) is reconstructed calorimetrically with an expected fractional energy resolution of $35%/\sqrt{E_{proton}}$.

Although muons are identified by requiring a single long track, no attempt was made (in this initial analysis) to improve particle identification by requiring a $dE/dx$ consistent with the muon or proton tracks. This requirement should be particularly effective for protons of $O(1)$ GeV momentum, and such a requirement can be imposed to optimize the analysis in the future. In addition, it may be possible to improve the efficiency by allowing a shorter muons, with a $dE/dx$ requirement, without sacrificing purity.

If a quasi-elastic interaction is assumed, one can reconstruct the event kinematics from only the

---

$^2$See Section 11.4.5.
Figure 7: Left: The fraction of hits associated with the muon and the proton tracks in quasi-elastic candidates, for events with one or two vertex tracks, and measured $Q^2$ between 0.1 and 1 (GeV/c)$^2$. Right: Significance of the difference between $Q^2$ from the quasi-elastic hypothesis and $Q^2$ from the final state energy, for quasi-elastic candidates with measured $Q^2$ above 1 GeV$^2$.

momentum and direction of the final state $\mu$. Neglecting the binding energy of the final-state proton,

$$E_{\nu}^{QE} = \frac{M_N E_\mu - m_\mu^2}{M_N - E_\mu + p_\mu \cos \theta_\mu}.$$ 

If a proton track is identified and its angle and energy are also measured, one can additionally require consistency with the quasi-elastic hypothesis. Two constraints are possible, one on the $x$ of the reconstructed interaction and one on the total $p_T$ of the observed final state.

If the interaction is truly quasi-elastic, then $x = 1$, and therefore $Q^2 = 2M_N\nu$ where $\nu = E_{\text{had}} - M_N$, and $E_{\text{had}}$ is the energy of the hadronic final state. In this analysis, we test this by comparing $Q^2$ reconstructed from the lepton kinematics under the quasi-elastic hypothesis to $2M_N\nu$ and forming $(Q^2 - 2M_N\nu)/\sigma$ where the dominant part of the calculated error $\sigma$ for this term comes from the smearing of hadronic final-state energy. Figure 7 shows the significance of this $Q^2$ difference for two track quasi-elastic candidates with observed $1 < Q^2 < 3$ (GeV/c)$^2$, for quasi-elastic, resonant and deep-inelastic events. This cut can be applied without identifying a proton track if the visible energy, less the muon energy, is assumed to be $\nu$.

The $Q^2$ significance ($x$) cut does not use information on the proton direction, and so we impose a second kinematic cut on the total transverse momentum $p_T$ relative to the incoming neutrino direction. This selection requires that a proton track is identified, and we cut on the significance of the difference from $p_T = 0$: $p_T^{\text{tot}} < 2\sigma_{p_T}$ if $Q^2 < 3$ (GeV/c)$^2$, and $p_T^{\text{tot}} < 3\sigma_{p_T}$ for higher $Q^2$.

### 2.2.6 Results

Table 2 shows the efficiency and purity of the quasi-elastic sample for different $Q^2$ bins after each cut. Using these efficiencies and purities, we have determined uncertainties on $F_A$ including efficiency and
Figure 8: The quasi-elastic neutrino cross-section along with data from various experiments. Representative calculations are shown using BBA-2003 form-factors with $M_A = 1.00 \text{ GeV/c}^2$. The solid curve uses no nuclear correction, while the dashed curve [19] uses a Fermi gas model for carbon with 25 MeV binding energy and 220 MeV/c Fermi momentum. The dotted curve is the prediction for carbon including both Fermi gas Pauli blocking and the effect of nuclear binding on the nucleon form-factors [20](bounded form-factors). The predicted MINERvA points, with errors, are shown. The data shown in the bottom plot are from FNAL 1983 [21], ANL 1977 [22], BNL 1981 [23], ANL 1973 [24], SKAT 1990 [25], GGM 1979 [26], LSND 2002 [27], Serpukov 1985 [28], and GGM 1977 [29]. The data have large errors and are only marginally consistent throughout the $E_\nu$ range.
\[ \frac{(Q^2 - 2M\nu/c^2)}{\text{err}_p} \]

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<th>(\nu)</th>
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<td>0.344 0.554</td>
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<td>0.467 0.420</td>
<td>0.311 0.700</td>
</tr>
</tbody>
</table>

Table 2: Efficiency and purity in \(Q^2\) bins for quasi-elastic candidates

Figure 9: Left: Estimation of \(F_A\) (left) and \(F_A/\text{dipole}\) (right) from a four year MINER\(\nu\)A run, in the quasielastic analysis described in the text, where (left) assumes a pure dipole form-factor with \(M_A = 1.014\) GeV/c\(^2\). Also shown is \(F_A\) extracted from deuterium bubble chamber experiments using the \(d\sigma/dq^2\) from the papers of FNAL 1983 [21] BNL 1981 [23], and ANL 1982 [30]. Also shown is the expectations from Model 2 (dashed line) and Model 3 (dotted line) for the axial form-factor. Figure 9 shows the expected values and errors of \(F_A\) in bins of \(Q^2\) for the MINER\(\nu\)A active carbon target, after a four-year exposure in the NuMI beam. The method to extract \(F_A\) from \(d\sigma/dq^2\) is given in [32]. Clearly the high-\(Q^2\) regime, which is inaccessible to K2K, MiniBooNE and T2K, will be well-resolved in MINER\(\nu\)A. Figure 9 shows these results as a ratio of \(F_A/\text{F}_A(\text{Dipole})\), demonstrating MINER\(\nu\)A’s ability to distinguish between different models of \(F_A\). We show the three different models (described earlier) for \(F_A\) as a function of \(Q^2\). Model 2 is a factor of 5 lower at high \(Q^2\), as indicated.
by $G_E/G_M$ data, while model 3 (based on duality) is a factor of 1.4 higher. MINER$\nu$A will be able to measure the axial nucleon form-factor with precision comparable to vector form-factor measurements at JLab. Note that resolution effects are not included in this extraction of $F_A$, but the typical $Q^2$ resolution for quasi-elastic events at high $Q^2$ is $\sim 0.2 \ (GeV/c)^2$ which is smaller than the bin size.

Figure 9 shows the extraction of $F_A$ from Miller, Baker, and Kitagaki, using their plots of $d\sigma/dq^2$. For $Q^2 > 2 \ (GeV/c)^2$ there is essentially no measurement of $F_A$. Even the measurements of $F_A(Q^2)$ below 2 $(GeV/c)^2$ have significant errors, hence one cannot assume $F_A$ is a dipole for low $Q^2$. The maximum $Q^2$ values that can be achieved with incident neutrino energies of 0.5, 1.0, 1.5 and 2 GeV are 0.5, 1.2, 2.1 and 3.0 $(GeV/c)^2$, respectively. Since K2K, MiniBooNE, and T2K energies are in the 0.7–1.0 GeV range, these experiments probe the low $Q^2 < 1 \ (GeV/c)^2$ region where nuclear effects are large (see Figures 10). The low-$Q^2$ ($Q^2 < 1 \ (GeV/c)^2$) MiniBooNE and K2K experiments have begun to investigate the various nuclear effects in carbon and oxygen. However, higher $Q^2$ data are only accessible in experiments like MINER$\nu$A, which can span the 2–8 GeV neutrino energy range. MINER$\nu$A’s measurement of the axial form-factor at high $Q^2$ will be essential to a complete understanding of the vector and axial structure of the neutron and proton.

**Figure 10:** Pauli suppression in a Fermi gas model for carbon with binding energy $\epsilon = 25 \ MeV$ and Fermi momentum $k_f = 220 \ MeV/c$. A similar suppression is expected for quasi-elastic reactions in MINER$\nu$A.

### 2.3 Nuclear Effects in Quasi-elastic Scattering

#### 2.3.1 Fermi gas model

There are three important nuclear effects in quasi-elastic scattering from bound targets: Fermi motion, Pauli blocking, and corrections to the nucleon form-factors due to distortion of the nucleon’s size and its pion cloud in the nucleus. Figure 10 shows the nuclear suppression versus $E_\nu$ from a NUANCE[33] calculation using the Smith and Moniz[34] Fermi gas model for carbon. This nuclear model includes Pauli blocking and Fermi motion but not final state interactions. The Fermi gas model uses a
nuclear binding energy $\epsilon = 25$ MeV and Fermi momentum $k_f = 220$ MeV/c. Reference [34] shows how the effective $k_f$ and nuclear potential binding energy $\epsilon$ (within a Fermi-gas model) for various nuclei is determined from electron scattering data.

2.3.2 Bound nucleon form-factors

The predicted distortions of nucleon form-factors due to nuclear binding are can be as large as 10% at $Q^2 = 1$ (GeV/c)$^2$ to 15% at $Q^2 = 2$ (GeV/c)$^2$. With carbon, iron and lead targets, MINER$\nu$A can compare measured form-factors for a range of light to heavy nuclei. Figure 8 shows the cross-section suppression due to bound form-factors. As is described in [20], these effects can cause variations up to 10% in the differential cross-sections at MiniBooNE, K2K and T2K energies.

Requiring vector and axial contributions to $W_1$ be equal for $Q^2 > 0.5$ (GeV/c)$^2$ introduces further suppression at low $Q^2$. Changing the various assumptions in $d\sigma/dq^2$ as calculated with dipole form-factors introduces 5–10% effects on the $Q^2$ distributions these experiments will see.

2.3.3 Intra-nuclear rescattering

In neutrino experiments, detection of the recoil nucleon helps distinguish quasi-elastic scattering from inelastic reactions. Knowledge of the probability for outgoing protons to reinteract with the target remnant is therefore highly desirable. Similarly, quasi-elastic scattering with nucleons in the high-momentum tail of the nuclear spectral function needs to be understood. More sophisticated treatments than the simple Fermi gas model are required. Conversely, inelastic reactions may be misidentified as quasi-elastic if a final-state pion is absorbed in the nucleus. With its constrained kinematics, low-energy neutrino-oscillation experiments use the quasi-elastic channel to measure the (oscillated) neutrino energy spectrum at the far detector; uncertainty in estimation of non-quasi-elastic background due to proton intra-nuclear rescattering is currently an important source of systematic error in K2K.

The best way to study these effects is to analyze electron scattering on nuclear targets (including the hadronic final states) and test the effects of the experimental cuts on the final-state nucleons. MINER$\nu$A can address proton intra-nuclear rescattering by comparing nuclear binding effects in neutrino scattering on carbon to electron data in similar kinematic regions. Indeed, MINER$\nu$A members will be working with the CLAS collaboration to study hadronic final states in electron scattering on nuclear targets using existing JLab Hall B data. This analysis will allow theoretical models used in both electron and neutrino experiments to be tested. Other work in progress, with the Ghent[35] nuclear physics group, will develop the theoretical tools needed to extract the axial form-factor of the nucleon using MINER$\nu$A quasi-elastic data on carbon. The ultimate aim is to perform nearly identical analyses on both neutrino and electron scattering data in the same range of $Q^2$. 

20
3 Coherent Pion Production

MINERνA will be able to study both charged- and neutral-current coherent neutrino-nucleus scattering with unprecedented precision. This chapter summarizes several preliminary studies to estimate the efficiencies and backgrounds in neutral- and charged-current analyses for different nuclei. MINERνA’s high rates, range of nuclear targets, fine granularity, strong pattern recognition capabilities, and good electromagnetic calorimetry make it ideal for measurement of charged and neutral-current coherent processes.

3.1 Introduction

Coherent neutrino-nucleus reactions, in which the neutrino scatters coherently from an entire nucleus with small energy transfer, leave a relatively clean experimental signature and have been studied in both charged-current ($\nu_\mu + A \rightarrow \mu^- + \pi^+$) and neutral-current ($\nu_\mu + A \rightarrow \nu + \pi^0$) interactions of neutrinos and anti-neutrinos. Although the coherent interaction rates are typically an order of magnitude or more lower than other single-pion production mechanisms, the distinct kinematic characteristics of these events allow them to be cleanly identified. Because the outgoing pion generally follows the incoming neutrino direction, this reaction is an important background to searches for $\nu_\mu \rightarrow \nu_e$ oscillation, as these events can easily mimic the oscillation signature of a single energetic electron shower. Neutral-current coherent production will be discussed in more detail in Section 3.3.3; we first turn our attention to the charged-current channel where the kinematics can be fully measured and the underlying dynamics explored.

![CC Coherent Pion Production Cross Section](image)

Figure 11: Charged-current neutrino–carbon coherent cross-sections. Results have all been scaled to carbon assuming an $A^{1/3}$ dependence, and $\sigma(CC) = 2\sigma(NC)$ [36].
3.2 Theory

It is well known from electron scattering that at low $Q^2$ and high $\nu$, vector mesons are abundantly produced through diffractive mechanisms. These interactions are interpreted as fluctuations of the virtual photon intermediary into a virtual meson with the same quantum numbers, which by the uncertainty principle can travel a length

$$l \sim \frac{\nu}{Q^2 + m^2}$$

where $m$ is the mass of the meson in question. For the weak current, similar fluctuations can occur, into both vector- and axial-vector mesons. From the Adler relation and “partially-conserved axial current” (PCAC) hypothesis, it is known that the hadronic current at low $Q^2$ is proportional to the pion field. The hadronic properties of the weak current in these kinematic regions have been investigated through study of nuclear shadowing at low $x$ and coherent production of $\pi$, $\rho$, and $a_1$ mesons. Coherent scattering therefore allows investigation of the PCAC hypothesis and hadron dominance models of the weak current in detail [37].

A number of calculations of coherent scattering, involving substantially different procedures and assumptions, have been made over the past thirty years[38, 39, 40, 41]. These calculations factorize the problem in terms of the hadron-like component of the weak current and the scattering of this hadron with the nucleus. The calculations assume PCAC as a starting point but quickly diverge when it comes to the number of hadronic states required to describe the weak current and how the hadron–nucleus scattering should be treated. The Rein-Sehgal model, used by both NUANCE and NEUGEN, describes the weak current only in terms of the pion field; the $Q^2$ dependence of the cross-section is assumed to have a dipole form. Other calculations rely on meson-dominance models[40] which include the important contributions from the $\rho$ and $a_1$ mesons. Figure 11 shows the coherent charged-current cross-section as a function of energy, compared to the model of Rein and Sehgal as implemented in NEUGEN and the calculation in [41].

3.3 Experimental Studies of Coherent Production

MINER$\nu$A, with its high-intensity, wide-band beam, excellent pattern recognition capabilities, good electromagnetic calorimetry, and variety of nuclear targets, has the potential to greatly improve our experimental understanding of coherent neutrino scattering processes. The variety of nuclear targets - from carbon to lead - in MINER$\nu$A make possible a detailed measurement of the A-dependence of the coherent cross-section. An additional strength of the experiment is its strong pattern recognition capabilities for both the neutral-current and charged-current channels. Identified samples of charged-current coherent events can be used to study the differential cross-sections for coherent scattering. Comparison of the total rates for neutral- and charged-current production, and their pion energy and angular distributions will also provide useful tests of the various models. Several recent models predict CC/NC ratios differing by around 20% [38, 41].

Systematic comparison of charged- and neutral-current coherent production is currently a topic of considerable interest. In the low energy range there is very limited data on either process from bubble chamber experiments, and data from K2K and MiniBoone is only now exploring at least the neutral-current process at $\sim 1$ GeV in carbon and oxygen. While data on single $\pi^0$ production from these experiments are in reasonable agreement with predictions [42, 43], study of the charged-current process is limited by detector capabilities and because the $Q^2$ distribution for all inelastic events shows a strong...
<table>
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</table>

Table 3: Existing measurements of coherent pion production[37].

depletion at low $Q^2$ compared to Monte Carlo predictions [44, 45]. Numerous explanations for this low $Q^2$ anomaly have been suggested [17, 46]. Since coherent events occur at low $Q^2$, they have been under scrutiny as a possible contributor to the disagreement. Empirically it has been noted that the discrepancy could be largely resolved by eliminating charged-current coherent interactions from the Monte Carlo entirely. While this suggestion is a drastic one, it does point out the need for better understanding of charged-current coherent scattering in the several-GeV region. The remainder of this section summarizes simulated analyses carried out on coherent interactions in MINERνA.

### 3.3.1 Charged-current cross-section

The kinematics of coherent scattering are quite distinct compared to the more common deep-inelastic and resonant interactions. Because the coherence condition requires that the nucleus remain intact, low-energy transfers to the nuclear system, $|t|$, are needed. Events are generally defined as coherent by making cuts on the number of prongs emerging from the event vertex followed by an examination of the $t$ distribution, where $t$ is approximated by:

$$-|t| = -(q - p_\pi)^2 = \left(\sum_i(E_i - p_{\perp i})^2 - (\sum_i p_{\perp i}^2)\right)^2$$

With its excellent tracking capabilities, MINERνA’s inner detector can measure this kinematic variable well.

To quantify MINERνA’s ability to measure the charged-current coherent cross-section, a Monte Carlo study was carried out using the GEANT detector simulation described in Section 11.2. Analysis cuts were tuned on a sample of coherent interactions corresponding to a four-year run with the three-ton fiducial volume (24650 events). Events were generated according to the appropriate mix of low, medium, and high energy beams. This study used the Rein-Seghal [38] model of coherent production, as implemented in NEUGEN3. A low-energy beam sample containing all reaction channels was used for background determination. Based on published bubble chamber analyses, charged-current reactions should be the largest background contributor, in particular quasi-elastic and $\Delta$-production reactions where the baryon is mis-identified as a pion or not observed. To isolate a sample of coherent interactions, a series of cuts are placed on event topology and kinematics.
Topological cuts  An initial set of topological cuts are applied to isolate a sample of events which contain only a muon and charged pion. These cuts are based on the hit-level and truth information as provided by the GEANT simulation.

1. **2 Charged Tracks:** The event is required to have 2 visible charged tracks emerging from the event vertex. A track is assumed to be visible if it produces at least 8 hit strips in the fully active region of the detector which are due to this track alone.

2. **Track Identification:** The two tracks must be identified as a muon and pion. The muon track is taken to be the most energetic track in the event which does not undergo hadronic interactions. The pion track is identified by the presence of a hadronic interaction. The pion track is required not to have ionization characteristic of a stopping proton (which is assumed can be identified 95% of the time).

3. **$\pi^0$/neutron Energy:** Because MINERνA is nearly hermetic we also assume that neutral particles will produce visible activity which can be associated with the event and used to exclude it. Events with more than 500 MeV of neutral energy ($\pi^0$ or neutron) produced in the initial neutrino interaction are rejected.

4. **Track Separation:** To make good measurements of the two tracks, the interaction point of the pion must be more than 30 cm from the primary vertex, and at this interaction point, at least 4 must strips separate the two tracks in at least one view.

Kinematic cuts  Because coherent and background processes have very different kinematics, cuts on kinematic variables are effective in isolating the final sample. In this analysis, the true pion and muon 4-momenta were used as the reconstruction values. For the final event rates we reduce our overall signal sample by 0.65 to account for this short-cut. The difference between true and reconstructed variables obviously depends strongly on the pattern recognition and reconstruction capabilities of the detector, and this value is considered reasonable for reconstruction of the event kinematics for coherent events. Figure 17 shows the true and reconstructed angular distributions for neutral pions produced via the neutral-current reaction, in this case the difference between truth and reconstructed quantities is negligible.

1. **$x_{Bj} < 0.2$:** Requiring Bjorken-$x$ (as reconstructed from the observed pion and muon 4-momenta) less than 0.2 eliminates much of the background from quasi-elastic reactions with $x_{Bj} \sim 1$.

2. **$t < 0.2$ (GeV/c)$^2$:** The most powerful variable for the identification of coherent events is the square of the 4-momentum transfer to the nucleus. Equation 5 relating $t$ to the observed particles in the event is used as the estimator of this quantity.

3. **$p_{\pi} > 600$ MeV:** Requiring $p_{\pi} > 600$ MeV effectively eliminates background from $\Delta$ excitation, which tends to produce lower energy pions.

The cumulative effect of these cuts on the signal and background samples is shown in Table 3.3.1, and the signal and background distributions for several of the important cut variables are shown in Figure 13. The relative normalizations of the two distributions in the initial plot is arbitrary; subsequent plots show the effect of the applied cuts.
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<td>x&lt;0.2</td>
<td>2223</td>
<td>100</td>
</tr>
<tr>
<td>t&lt;0.2</td>
<td>2223</td>
<td>19</td>
</tr>
<tr>
<td>p_x &lt; 600 MeV</td>
<td>1721</td>
<td>12</td>
</tr>
</tbody>
</table>

Table 4: Analysis cuts to isolate a sample of coherent interactions. The cuts are described in the text.

Figure 12: Topological and kinematic quantities for signal (solid) and background (dashed) processes. Top Left: Visible charged tracks. Top Right: Distance between the event vertex and the location of the pion interaction (in cm). Bottom Left: Bjorken-x as computed from the true pion and muon 4-momenta. Bottom Right: Square of the 4-momentum transfer to the nucleus (in GeV²) as calculated from the pion and muon 4-momenta.
Figure 13: Left: Coherent cross-sections measured by MINERνA compared with existing published results. MINERνA errors here are statistical only. Right: Measurement of the coherent cross-section as a function of atomic number in MINERνA. The shaded band indicates the range of previous measurements. Error bars indicate the size of the experimental errors in a single 1-GeV bin. The curve shows the prediction from the Rein-Seghal model. Crosses are the prediction of the Rein-Seghal model for scattering from carbon, iron, and lead, circles are the predictions of the Paschos-Kartavtsev model.

Applying this set of cuts to our signal sample we find that 7698 signal events pass all cuts, which gives an overall efficiency of 31%. Applying the factor 0.65 to account for the fact that we have not used fully reconstructed quantities for our kinematic cuts gives us a final event sample of 5004 events. Applying these cuts to the background sample we find that 12 events out of 20k pass all cuts. Normalized to the total event rate, this gives an expected background of 4400 events. We note that in this analysis other important variables for background rejection, related to associated activity around the vertex, were not used. Figure 13 shows the expected precision of the MINERνA measurement as a function of neutrino energy. Here we have only included the statistical error on the signal and assumed that the measured value is that predicted by Rein-Seghal. No attempt has not been made to quantify the systematic errors on this measurement other than that resulting from the background subtraction. Previous measurements of the coherent cross-section were statistics limited.

### 3.3.2 A-dependence of the coherent cross-section

Another task for MINERνA will be comparison of reaction rates for lead and carbon. The expected yield from lead will be \( \approx 1800 \) charged-current events, assuming the same efficiency. The A-dependence of the cross-section depends mainly on the model assumed for the hadron–nucleus interaction, and serves as a crucial test for that component of the predictions. No experiment to date has been able to perform this comparison. For reference, the predicted ratio of carbon to lead neutral-current cross-sections at 10 GeV in the Rein-Sehgal and Paschos models are 0.223 and 0.259, respectively [57]. Figure 13 shows the predicted A-dependence according to the model of Rein and Sehgal.
3.3.3 Neutral-current cross-section

Neutral-current $\pi^0$ production can occur through a number of mechanisms - resonant production, coherent production, and deep-inelastic scattering. Figure 14 shows a striking example of MINER$\nu$A's response to coherent $\pi^0$ production.

By requiring two well-separated electromagnetic clusters that shower in the scintillator target, and extend at least 6 scintillator planes, about 30% of the coherent $\pi^0$ events produced in the detector are retained. Furthermore, by requiring the ratio of the energy in the two clusters to that of the total event energy to be above 90%, and requiring any extra energy to be less than 100 MeV, reduces both the $\nu_e$ ($\nu_\mu$) charged-current contamination to a few (less than one) events. Figure 15 shows these two last variables, where the coherent $\pi^0$ peak is clearly visible in the plot on the right. The resulting sample in this simple analysis (1000 events per year in 3 tons of fiducial mass) is roughly half resonant $\pi^0$ production and half coherent $\pi^0$ events, which can be separated by studying the angular and energy distribution of the events, as well as the presence or absence of additional particles at the production vertex identified by the two photon showers.

Neutral pions from resonance excitation are neither as energetic nor as collinear as those produced coherently. Resonant $\pi^0$ are particularly susceptible to final-state nuclear interaction and rescattering, which will be studied in detail by MINER$\nu$A using charged-current reactions.

As a proof-of-concept, a sample of neutral-current single-$\pi^0$ events has been selected using simple cuts. For events with two well-separated electromagnetic clusters ($E_\pi \equiv E_1 + E_2$), each passing through at least six planes of the fully-active region, requiring $E_\pi/E_{\text{tot}} > 90\%$ and $E_{\text{tot}} - E_\pi < 100$ MeV efficiently isolates a neutral-current $\pi^0$ sample, as shown in Figure 16. After these cuts, the contamination of $\nu_e$ and $\nu_\mu$ charged-current interactions (combined) is less than 1%. The resulting sample contains about 2400 neutral-current $\pi^0$ events per 3 ton-yr, of which half are resonant and half
Figure 15: Variables that reject backgrounds to coherent $\pi^0$ measurements: (a) Other energy in the event for $\nu_\mu$ charged- and neutral-current events, and (b) Ratio of two photon energy to total event energy for $\nu_\mu$ charged-current sample (reduced by factor of 2), $\nu_e$ charged-current (increased by a factor of 10) and the neutral-current sample (normalized per ton per year, acceptance calculated for 3 tons fiducial volume)
Figure 16: Selection of neutral-current single-$\pi^0$ production. The variables plotted are the fraction of visible energy carried by the $\pi^0$ candidate ($E_{\pi}/E_{tot}$) and the residual energy $E_{tot} - E_{\pi}$. The left-hand plots show backgrounds from $\nu_\mu$ (top) and $\nu_e$ (bottom). The plot at top right shows the same distribution for true neutral-current $\pi^0$ production, and the lower right shows the subset from coherent scattering. In the neutral-current plots, notice the dramatic concentration of the coherent $\pi^0$ signal in a single bin, in the left-most corner of the graph. All samples shown are normalized to a 3 ton-yr exposure of MINER$\nu$A.
Figure 17: Angular distribution of neutral-current single-$\pi^0$ sample. The plot at left shows all events passing the cuts on $E_\pi/E_{\text{tot}}$ and $E_{\text{tot}}-E_\pi$ described in the text, broken down into coherent and resonant reactions. The coherent sample is strongly forward-peaked. The plot at right is a close-up of the forward region comparing the true and reconstructed $\pi^0$ angular distributions from the beam direction. The distributions are nearly identical, highlighting the MINER$\nu$A’s excellent angular resolution.

Coherent and resonant interactions can be cleanly separated by cutting on the $\pi^0$ angle to the beam direction, as shown in Figure 17, which also highlights MINER$\nu$A’s excellent $\pi^0$ angular resolution. The overall efficiency for selecting coherent neutral-current $\pi^0$ is about 40%.
4 Resonant Pion Production

4.1 Introduction

Simulations of resonant reactions rely on an early theoretical model by Rein & Sehgal [58] or results from electro-production experiments, since existing neutrino-induced resonant production data is inadequate. The theoretical and experimental pictures of the resonant and transition regions are far more obscure than quasi-elastic and deep-inelastic scattering. Since important backgrounds to present and proposed neutrino oscillation experiments originate from this poorly-understood regime, resonant pion production, careful study by MINER\(\nu\)A is vital.

Analysis of resonance production in MINER\(\nu\)A [59] will focus on several experimental channels, including inclusive scattering in the resonant region \((W < 2 \text{ GeV})\) and exclusive charged- and neutral-pion production. To date, efforts have focused on MINER\(\nu\)A’s performance for inclusive resonant production, particularly near the \(\Delta(1232)\) resonance. This preliminary analysis indicates that the resolution on \(W\) is about 100 MeV around the \(\Delta\), and the \(Q^2\) resolution is better than 20%. Despite this resolution smearing, and distortion introduced by Fermi motion of bound nucleons in carbon, the \(\Delta\) peak is still clearly visible in the reconstructed \(W\) distribution.

4.2 Analysis of Existing Data

Inclusive electron- and neutrino-nucleon scattering with \(W < 2 \text{ GeV}\) is dominated by resonance excitation. The large number of possible form-factors can be reduced through several assumptions. The prominent resonances are \(P_{33}(1232)\), \(S_{11}(1535)\), \(P_{11}(1440)\) and \(D_{13}(1520)\). The \(P_{33}(1232)\) has the largest contribution and must be understood. In electroproduction, the magnetic dipole term dominates, and emphasizes to one of the vector form-factors, \(C_V^3\), with a \(Q^2\) dependence steeper than the dipole parameterization. The contribution of \(C_A^5\) is determined by PCAC and also has a steeper \(Q^2\) dependence than the phenomenological dipole form. It is worth pursuing this program to see if these two form-factors are sufficient. Current wisdom is that form-factors steeper than the dipole reflect the larger size of the resonant states, due to the mesonic cloud surrounding them. A simplified model has been developed by Paschos, Sakuda and Yu[60], and describes existing data (within the large experimental uncertainties and inconsistencies mentioned below).

One inconsistency concerns the \(Q^2\) dependence. Two older experiments at ANL[61] and BNL[62] have noticed a difference between the data and theoretical predictions for \(Q^2 < 0.2 \text{ (GeV/c)}^2\). It appears that the same problem is apparent in newer experiments like K2K[64] in the same region of \(Q^2\). The BNL data can be fitted with the form-factors used in [60], except for \(Q^2 < 0.2 \text{ (GeV/c)}^2\) where the data falls faster than the theoretical curve (see Figure 18).

The muon mass, which influences the results in this region of \(Q^2\), was neglected in previous theoretical calculations.\(^3\) The effect of the muon mass can be seen from the Figure 18: it reduces the cross-section at small \(Q^2\), in agreement with the experimental trends. Summarizing these results: older measurements of \(d\sigma/dQ^2\) at ANL and BNL show a suppression at low \(Q^2\) which is not understood, and the \(Q^2\) dependence of the form-factors is steeper in the ANL data. Thus, new experiments are needed to resolve this discrepancy and better constrain theoretical models.

Better understanding of resonant production is also vital for quasi-elastic measurements. The pion

\(^{3}\)The muon mass has always been included in recent, experimentally-developed Monte Carlo programs like NEUGEN and NUANCE, however.
from a resonant excitation can be absorbed in the nucleus, resulting in an important experimental background to quasi-elastic scattering.

More issues remain to be investigated in resonant production. Near the $\Delta$, an isospin-1/2 amplitude is observed in electroproduction. As higher resonances cannot contribute much strength in this region, the amplitude must be a non-resonant background. The importance of this background grows with $Q^2$, to become the dominant term in deep-inelastic scattering.

Nuclear effects are significant in resonant reactions, via pion absorption and charge-exchange processes. A good “rule of thumb” is that in lepton-nucleus reactions on a light target such as $^{12}$C or $^{16}$O, pions with the same charge as the exchanged current are suppressed by $30 - 40\%$, and pions of different charge are slightly enhanced. For instance, in the neutrino charged-current reactions the $\pi^+$ yield is reduced. Half of this reduction is due to absorption and the remainder comes from change exchange of $\pi^+$ into $\pi^0$ and $\pi^-$. Since single-pion production is an important background to be subtracted in $\nu_e$ appearance and nucleon decay searches, uncertainties in final-state interactions will directly affect their ultimate sensitivity.

MINER$\nu$A can improve the situation with precision measurements of $d\sigma/dQ^2$, $d\sigma/dW$ and total cross-sections, to further constrain the form-factors and test final-state interaction models.

4.3 MINER$\nu$A Performance

Analysis of resonant production in MINER$\nu$A will focus on several experimental channels including inclusive scattering ($\nu, \mu^-$) for $W < 2$ GeV, neutral-pion production ($\nu, \mu^-\pi^0$) and charged-pion production ($\nu, \mu^-\pi^\pm$). Unlike inclusive charged-lepton scattering (i.e. $(e, e')$), measurements of neutrino inclusive scattering with wide-band neutrino beams cannot rely solely the outgoing lepton kinematics, since the incident neutrino’s exact energy is $a \text{ priori}$ unknown. This section focuses on performance for inclusive resonance production, particularly near the $\Delta(1232)$. A brief discussion of more sophisticated kinematic reconstruction possibilities is included at the end of this chapter. In an inclusive analysis, reconstructing the kinematics of an event ($Q^2$, $W$ and $y$) requires calculating the neutrino energy by estimating the hadronic energy and adding it to the much more precisely known $E_{\mu}$.

$E_h$ can be estimated by tracking and identifying every particle emerging from the scattering vertex,
or by summing up the $dE/dx$ energy deposited by all the reaction products (other than the muon). Tracking will be an important technique for analysis of resonance production, as primary vertex multiplicities will be low (typically $\mu + \pi + N$). However, calorimetric measurement of $E_h$ will be essential for inclusive resonance production, to minimize biases and because pions have a non-negligible probability of interaction or decay before stopping. For interacting and decaying particles, the energy not seen by active detector elements must be estimated.

As described in Section 11.4.6, MINER$\nu$A is an excellent hadronic calorimeter, with full hermeticity up to $E_h \sim 8$ GeV, and 90% containment up to $E_h \sim 15$ GeV, far above the region of interest for resonance channels. The $E_h$ resolution measured with simulated data can be described by

$$\frac{\Delta E_h}{E_h} = 4\% + \frac{18\%}{\sqrt{E_h} \text{(GeV)}}.$$ 

The kinematics of resonant events are reconstructed using $E_h$, and an assumed muon momentum resolution $dP/P = 9\%$. Figure 19 shows the good correlation of true $W$ and $Q^2$ with reconstructed quantities based on measured $E_h$. The $W$ and $Q^2$ resolutions obtained from the fit are shown in Figure 20. The $W$ resolution is about 100 MeV in the region of the $\Delta$, and the $Q^2$ resolution is slightly better than 0.2 $Q^2$. The effect of this smearing is shown in Figure 21 where the $\Delta(1232)$ peak is still visible in the $W$ spectrum from reconstructed kinematics. It is important to note that the $\Delta(1232)$ is already somewhat smeared by Fermi motion, as most scatterings take place on bound nucleons in carbon. Also note that a more mature analysis could correct for resolution smearing, yielding an even better measurement of the line-shape.

### 4.4 Conclusion

Thanks to its enormous samples and excellent resolution, MINER$\nu$A will perform the world’s best measurements of resonant pion production by neutrinos, a process of primary importance to future
oscillation and nucleon-decay experiments, and essential to better understanding the axial structure of the nucleon.

Analysis methods are being developed to exploit MINERνA’s tracking capability and refine the kinematic reconstruction of low-multiplicity resonant events. For instance, $E_\nu$, $W$ and $Q^2$ can also be estimated if only a single hadron’s momentum and direction are measured (in addition to the lepton). Reconstruction is also possible if the directions of both hadrons (but neither momentum) is measured. These kinematic fitting techniques will complement the calorimetric approach described above. A fully-developed analysis will leverage all available information, including measurement errors, for optimal performance, permitting a more accurate determination of $W$ in the neighborhood of the $\Delta$ and improving the analysis of resonant events.
Figure 21: (Top) True $W$ distribution for resonant events with $Q^2 < 1$ (GeV/c)$^2$. (Bottom) Reconstructed $W$ distribution for the same $Q^2$ range.
5 Strange and Charm Particle Production

High-statistics studies of exclusive strange-particle production by neutrinos will be possible for the first time in MINER$\nu$A. Sample sizes for several channels accessible to MINER$\nu$A in a four-year $\nu_\mu$ run are summarized in Table 5.3. Our results will impact other areas of particle physics, for example in estimation of atmospheric neutrino $\Delta S$ backgrounds to nucleon-decay searches. MINER$\nu$A’s physics program will also include searches for new processes, e.g. strangeness-changing neutral-current reactions and unusual baryon resonances such as the recently reported candidate pentaquark state in $K^+n$ and $K^{0}p$ systems. Extended running of the NuMI beam with $\bar{\nu}$ exposures will provide valuable data for many neutrino topics. Anti-neutrino exposure will facilitate study of $\Delta S=1$ single-hyperon production ($\Lambda, \Sigma, Y^*$), and would permit a novel measurement of CKM matrix elements. The major topics and their motivations are described below.

5.1 Backgrounds to Nucleon Decay

Current lifetime limits for nucleon decay ($\tau/\beta \geq 10^{33}$ years) have not diminished hopes for the eventual success of super-symmetric grand unification (SUSY GUTs). Indeed, there is strong motivation to proceed with more ambitious experimental searches. For the near future, improved searches will be carried out by Super–Kamiokande. Eventually these will be taken up by a next generation of underground detectors. Continued progress, either by improving limits to $10^{34}$ year lifetimes or discovering nucleon decay, hinges upon improved knowledge of certain neutrino interactions which, when initiated by atmospheric neutrinos, can imitate nucleon-decay signals. The most problematic of background reactions to SUSY GUT modes arise with neutral-current associated production of strangeness at threshold energies.

5.2 Measurement of $\sigma(\nu\Lambda K^+)$

We propose to measure the exclusive $\Delta S = 0$ neutral-current channel

$$\frac{d\sigma}{dE_\nu}(\nu_\mu p \rightarrow \nu_\mu K^+\Lambda),$$

from its threshold at $\approx 1$ GeV through its rise and plateau at $E_\nu$ between 10-15 GeV. For purposes of comparison and as a valuable check on systematics[65], we will simultaneously measure the the $\Delta S = 0$ companion charged-current reaction

$$\frac{d\sigma}{dE_\nu}(\nu_\mu n \rightarrow \mu^- K^+\Lambda).$$

5.3 Strangeness-changing Neutral Currents

Strangeness-changing neutral-current reactions have never been observed. Their occurrence at rates accessible in NuMI would imply new physics beyond the Standard Model. Existing limits on NC $\Delta S = 1$ processes are based upon searches for rare $K$ decays. Although there are experimental difficulties with unambiguous identification of such processes in neutrino reactions, there is nevertheless an opportunity for a search in the neutrino sector. A search for strangeness-changing neutral-current neutrino interactions can usefully clarify the extent to which new physics parameters may be missing from the analysis of weak radiative hyperon decays. It is plausible that neutrino reactions, in contrast to hyperon weak decays, may provide cleaner signals for a new weak current, since multi-loop quark-gluon diagrams which complicate hyperon decay analysis would be absent.
Table 5: Event samples for kinematically constrainable exclusive strangeness production reactions, in a four-year exposure of MINERνA’s three-ton inner fiducial volume.

5.4 Hyperon Beta-decay and Exotic Quark States

Hyperon beta-decay \( A \to B e^- \bar{\nu}_e \) provides a window onto weak hadronic current form-factors and their underlying structure. Recent high-statistics measurements of these form-factors using KTeV \( \Xi^0 \) hyperon beta-decays have been reported\[66\]; the results show that the level of SU(3) breaking is very small compared to expectations of modern theories\[67\]. These new results have been used to extract the CKM matrix elements \( V_{us} \)\[68\] \[69\]. Similar studies are possible anti-neutrino interactions that produce hyperons. The hyperon decays have the added feature of a self-analyzing power of the polarization vector. Thus the fundamental form-factors and CKM matrix elements will be accessible without the hindrance of double solutions due to the missing neutrino energy.

\( \Delta S = 1 \) production of pentaquark states like those recently announced\[70\], could be greatly extended here. In regard to these pentaquark states, with the production of hyperons and mesons together, a wealth of combinations can be thoroughly examined to search for the full spectrum of the pentaquark family\[71\] of particles as well as other exotic quark combinations such as di-baryons.

5.5 Charm Production

Charm production in MINERνA is suppressed by the relatively low energy of its beams, hence our reach will be limited. Nevertheless, the cross-section turn-on just above threshold is very sensitive to the bare charm mass and MINERνA can still make a valuable contribution. With the proposed beam running schedule for MINERνA we expect \( \sim 6500 \) charm events for a three-ton detector over the first five years, with an additional \( \sim 3200 \) from anti-neutrino beam running for \( x_F > 0 \).
6 Perturbative/Non-Perturbative Interface

6.1 Quark/Hadron Duality

Three decades after the establishment of QCD as the theory of the strong nuclear force, understanding how QCD works remains one of the great challenges in nuclear and particle physics. A major obstacle arises because the degrees of freedom observed in nature (hadrons and nuclei) are totally different from those appearing in the QCD Lagrangian (current quarks and gluons). The remarkable feature of QCD at large distances — quark confinement — prevents the individual quark and gluon constituents making up hadronic bound states from being examined in isolation. Making the transition from quark and gluon to hadron degrees of freedom is therefore essential to a description of nature based on first principles.

Experimentally, exploring this transition requires high-quality data in three kinematic regimes: in the scaling domain of large-$Q^2$ deep-inelastic scattering; in the hadronic region of resonances and quasi-elastic scattering; and, most importantly, in the moderate $Q^2$ region between the two, where the transition occurs. MINER$\nu$A can address this compelling topic with neutrinos for the first time. As Figure 22 demonstrates, MINER$\nu$A’s pioneering measurement will span all three regimes, and provide crucial data in the transition region.

![Figure 22: Available $x_{F3}$ data (open symbols) and the anticipated (resonant region) MINER$\nu$A data (colored distributions) in $x_{Bj}$ vs. $Q^2$. The curve indicates the commonly-accepted $W^2 = 4\text{ GeV}^2$ boundary between the resonant and deep-inelastic regimes. The color key to the right shows the corresponding, expected MINER$\nu$A statistics.](image)

Despite the apparent dichotomy between the partons and hadrons, in some cases the kinematic dependence of low-energy cross-sections (averaged over appropriate energy intervals) closely follows the scaling behavior at high energies, which is expressed in terms of quark and gluon degrees of freedom. This phenomenon, quark/hadron duality, reflects the relationship between confinement and asymptotic freedom, and the transition between perturbative and nonperturbative QCD regimes. Such duality is
quite general and arises in other physical processes, for instance $e^+e^-$ annihilation into hadrons, and semi-leptonic decays of heavy mesons.

In electron–nucleon scattering, quark/hadron duality links the physics of resonance production to the physics of scaling; it is the focus of renewed interest in understanding the structure of the nucleon [118, 119, 120, 121, 122]. Over 10 approved experiments at Jefferson Lab address this topic, and it is a major focus area of a planned energy upgrade there. Figure 23 illustrates duality in the $F_2$ structure function measured at Jefferson Lab citereport, for nucleons and nuclei. Data in the (hadronic) resonance region average to the perturbative scaling prediction, most dramatically in the nucleus where Fermi motion facilitates the required averaging and the partonic curve and hadronic data are indistinguishable.

![Figure 23: $F_2$ structure function per nucleon vs $\xi$ (the Nachtmann scaling variable, accounting for target mass effects) for hydrogen (top), deuterium, and iron (bottom). The data are all in the resonance region. The curves are based on a perturbative parameterization of GRV parton distribution functions at $Q^2 = 1.0 \text{ GeV}^2$, corrected for the EMC effect. Uncertainties shown are statistical only.](image)

Weak currents can provide complementary information (not accessible to electromagnetic probes) on the quark structure of hadrons, and allow important consistency checks on the validity of duality. While deep-inelastic neutrino structure functions are built on the same universal parton distribution functions as charged lepton scattering, the structure of resonant excitations by neutrino beams is sometimes strikingly different than those produced by virtual photons. On general grounds, duality should exist for weak structure functions [123], but its features may be quite unlike those observed in electron scattering.

Differences between electron and neutrino scattering can easily understood by considering specific resonance transitions. While a neutrino beam can convert a neutron into a proton, it cannot convert a proton into a neutron, (and vice versa for an anti-neutrino beam). Similarly, there are dramatic differences for inelastic production near the $\Delta$ resonance [124, 125] — because of charge conservation, only transitions to isospin-3/2 states from the proton are allowed.

Unfortunately, existing neutrino data are sparse in the resonance region [126], and thanks to the
small weak cross-section, often limited to heavy nuclei (since large target volumes are easier to handle and more affordable than light nuclei) [127]. As a result, no conclusive studies of duality in neutrino scattering have been possible.

The high-intensity NuMI beam at Fermilab makes possible a valuable complement to duality and resonance studies in electron scattering, and MINERνA will be an exceptional tool for such measurements. With its enormous data samples and fine-grained resolution specifically designed to accurately measure low-energy neutrino-nucleus interactions across the resonant and deep-inelastic regimes, MINERνA will be the premiere facility for exploring quark/hadron duality in neutrino scattering.

6.2 Structure Functions

Neutrino scattering plays a crucial role in extraction of fundamental parton distribution functions (PDFs). These PDFs describe parton constituents of protons and other hadrons, and (in the MS convention) are precisely defined in terms of operator matrix elements. The necessity of neutrino measurements is obvious, because only neutrinos can resolve the flavor of the nucleon’s constituents: $\nu$ interacts with $d$, $s$, $\overline{t}$ and $\overline{\tau}$ while the $\overline{\nu}$ interacts with $u$, $c$, $\overline{d}$ and $\overline{s}$. The weak current’s unique ability to “taste” only particular quark flavors significantly enhances the study of parton distribution functions. MINERνA’s high-statistics measurement of the nucleon’s partonic structure, using neutrinos, will complement ongoing studies with electromagnetic probes at other laboratories.

Large samples, and dedicated effort to minimizing beam-related systematics allow MINERνA to independently isolate all the structure functions $F_1^{\nu N}(x, Q^2)$, $F_1^{\overline{\nu} N}(x, Q^2)$, $F_2^{\nu N}(x, Q^2)$, $F_2^{\overline{\nu} N}(x, Q^2)$, $x F_3^{\nu N}(x, Q^2)$ and $x F_3^{\overline{\nu} N}(x, Q^2)$ for the first time. By taking differences and sums of these structure functions, specific parton distribution functions in a given $(x, Q^2)$ bin can in turn be determined. With the manageable systematic uncertainties expected, this experiment will dramatically improve the isolation of individual PDFs by measuring the full set of $\nu$ and $\overline{\nu}$ structure functions.

Extracting this full set of structure functions will rely on the $y$-variation of the structure function coefficients in the expression for the cross-section. In the helicity representation, for example:

$$\frac{d^2\sigma^\nu}{dx dQ^2} = \frac{G_F^2}{2\pi x} \left[ \frac{1}{2} \left( F_2^\nu(x, Q^2) + x F_3^\nu(x, Q^2) \right) + \frac{(1 - y)^2}{2} \left( F_2^\nu(x, Q^2) - x F_3^\nu(x, Q^2) \right) - 2y^2 F_L^\nu x, Q^2 \right].$$

By analyzing the data as a function of $(1 - y)^2$ in a given $(x, Q^2)$ bin, all six structure functions can be extracted.\(^4\)

6.2.1 Measurement of $xF_3$

Our studies indicate that systematic uncertainties in extraction of the $xF_3$ structure function are dominated by determination of the incident neutrino energy. For high-multiplicity, deep-inelastic scattering in MINERνA this energy will be measured indirectly, by summing the energy deposited by hadrons ($E_{\text{had}}$) and the outgoing muon:

$$E_\nu = E_{\text{had}} + E_\mu - M,$$

\(^4\)Note that for this type of parton distribution function study, anti-neutrino running will be essential.
where $M$ is the nucleon mass. Hence the neutrino energy resolution is dominated, in turn, by hadronic calorimetry.

In our Monte Carlo study of resonant scattering the hadronic energy resolution is approximately $20\%/\sqrt{E_{had}}$ with $E_{had}$ in GeV. This results in a 4–7% uncertainty for the four-momentum transfer, $Q^2$. A projected $xF_3$ structure function computed from CTEQ6M PDFs is shown in Figure 24 for three $Q^2$ values (1, 2, and 4 (GeV/c)$^2$) and a 7% $Q^2$ smearing.

![Figure 24: Variation in $xF_3$ due to uncertainty on the four-momentum transfer, $Q^2$, as described in the text.](image)

While the variations in Figure 24 are small, $xF_3$ itself is not directly observable. In practice, yields will be measured and used to extract differential cross-sections. The neutrino/anti-neutrino differential cross-section can be expressed as a linear combination of structure functions. The helicity representation of the differential cross-section can be used to extract $xF_3$ using the the $y$-dependence in a given $(x, Q^2)$ bin. MINER$\nu$A is clearly capable of precision measurement in the pivotal large-$x$ region.

Note the fully active region of MINER$\nu$A provides a wealth of information for each neutrino interaction. The fine segmentation provides excellent topological identification capability, and the optical system and read-out electronics are designed to provide accurate position, pulse height, and timing information for each strip to further enhance particle identification and reconstruction. Fully exploiting this abundance of information requires sophisticated pattern recognition and reconstruction software whose development is labor-intensive and becomes a high priority only after an experiment moves out of the design/construction phase. The reconstruction software developed for this proposal was intended for optimization of the detector design rather than high-level physics analyses. It is clear that more mature reconstruction algorithms allowing full reconstruction of many-particle final states will significantly improve the performance of this analysis.
6.2.2 High $x_B$ measurements

MINERνA’s precision measurements of parton distribution functions at high $x$ will complement a remarkable range of other experiments, from Jefferson Lab to LHC, as well as theoretical efforts to understand the dynamics of SU(6) spin/flavor symmetry breaking. The key obstacle to determining these PDFs has been accumulation of sufficient statistical power at high $x$, for light targets. As Figure 22 shows, MINERνA will probe precisely this low-$Q^2$, high-$x$ kinematic region, with a large data sample made possible by the unprecedented intensity of the NuMI beam.

Uncertainties in nucleon parton distribution functions at high $x$ arise from the flavor ratio $d(x)/u(x)$, as $x \to 1$ and the role of leading power corrections (higher twist) in extraction of high-$x$ quark behavior.

$d(x)/u(x)$ ratio at high $x$  Available leptoproduction data on hydrogen and deuterium have been unable to pin down the high $x$ behavior of $d(x)/u(x)$. Bodek and Yang’s analysis [132] indicates that $d(x)/u(x)$ approaches 0.2 as $x \to 1$. On the other hand, global QCD analyses, such as the CTEQ fits [133], do not indicate the need for this higher value.

There are several indications that current PDF parameterizations are not correct at high $x$. Comparing Drell-Yan pair production off hydrogen and deuterium (Fermilab E866 [137]) to the latest CTEQ global fits, CTEQ6 [138], suggests the valence distributions are overestimated at high $x$. Recent NuTeV results [139], on the other hand, imply that the valence distributions are underestimated at high $x$. As $x$ increases from 0.35, NuTeV’s measurements of $F_2(x)$ deviate in the positive direction from CCFR values currently used in global fits such as CTEQ and MRST (see Figure 25). NuTeV measurements at $x = 0.65$ are 20% higher than CCFR values for $\nu$ and almost 30% higher for $\bar{\nu}$, albeit with larger uncertainties. Since CCFR and NuTeV used the same detector, the difference is not attributable to nuclear effects.

![Figure 25: $F_2$ data compared to fits, from [139]. Shown is $(F_2 - F_{2 \text{model}})/F_{2 \text{model}}$](image)

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Efforts are underway to understand how the $d(x)/u(x)$ ratio affects this comparison. The flavor mixture in Drell-Yan scattering, measured in E866, approaches $4u(x) + d(x)$ as $x_{\text{beam}} \to 1$. This would suggest that $u(x)$ is overestimated and $d(x)/u(x)$ is underestimated as $x \to 1$. Full radiative corrections are only now being applied to the E866 results, however, and still-unresolved deuterium nuclear corrections have not been applied to either the E866 results or the deuterium data in the global fits. MINERνA’s large sample of high-$x$ events could be valuable in resolving this anomaly.

**Higher twist corrections**  PDF measurements at high $x$ are closely related to leading power corrections known as “higher twist effects”. $n^{\text{th}}$-order higher twist effects are proportional to $1/Q^{2n}$ and reflect the transverse momentum of quarks within the nucleon and increased probability of multiple-quark interactions with a larger scale (or equivalently, smaller $Q^2$) probe.

As with the $d/u$ ratio, different analyses of higher twist corrections leave unresolved questions that new data may help resolve. Recent work by Yang and Bodek [134] suggests that what has been measured as “higher-twist” in charged-lepton scattering can be explained by increasing the order (NNLO) of the perturbative expansion used in the analysis.

The only measurements of a higher-twist term with neutrinos are two low-statistics bubble chamber experiments: Gargamelle [135] with freon and BEBC [136] with NeH$_2$. Both analyses were complicated by nuclear corrections at high-$x$, but found a twist-4 contribution smaller in magnitude than for charged leptoproduction and, significantly, negative.

**SU(6) symmetry breaking**  Although a large body of structure function data exists over a wide range of $x$ and $Q^2$, the region $x > 0.6$ is not well sampled. MINERνA offers the first opportunity for precision measurement of this large $x$ regime with neutrinos. For $x \geq 0.4$, $q\bar{q}$ sea contributions become negligible, and the structure functions are dominated by valence quarks. Better knowledge of these valence quark distributions at large $x$ is vital for several reasons.

The simplest SU(6) quark model predicts a $d/u$ quark distribution ratio of $1/2$ for the proton, but after breaking this symmetry (as in nature), the ratio becomes much smaller. Various mechanisms have been suggested to explain why the $d(x)$ distribution is softer than $u(x)$. If the interaction between spectator quarks in a deep-inelastic collision is dominated by one-gluon exchange, for instance, the $d$-quark distribution will be suppressed, and the $d/u$ ratio will tend to zero in the limit $x \to 1$ [129]. This assumption is built into most global analyses of parton distribution functions, but has never been tested independently.

On the other hand, if the dominant mechanism in deep-inelastic scattering involves scattering from a quark with the same spin orientation as the nucleon, as predicted by perturbative QCD counting rules, $d/u$ tends to $\approx 1/5$ as $x \to 1$ [130]. Precision measurement of structure functions at large $x$ should give us new insights into the dynamics of spin/flavor symmetry breaking.

The ratio of neutron to proton structure functions at large $x$ will be a particularly interesting MINERνA measurement. Valence quark dynamics similar to charged lepton scattering are probed, but with different sensitivity to quark flavors. At the hadronic level, quark model studies reveal distinct patterns of resonance transitions to the lowest-lying positive and negative parity multiplets of SU(6) [124, 141, 142, 143]. Summing $N \to N^*$ matrix element contributions to the proton and neutron $F_1$ and $g_1$ structure functions in the SU(6) quark model yields the expected SU(6) quark-parton model results, providing explicit confirmation of duality. On the other hand, some models of spin-flavor symmetry breaking ($\lambda \neq \rho$) yield neutrino structure function ratios at the parton level which are in obvious conflict with
values from electroproduction. Neutrino data can therefore provide valuable checks on the appearance of duality and its consistency between electromagnetic and weak probes.

**LHC backgrounds** Quark distributions at large $x$ are essential to estimating backgrounds in searches for physics beyond the Standard Model at colliders on the energy frontier [131]. QCD evolution of parton distribution functions takes high-$x_B j$ PDFs at low $Q^2$ and evolves them down to moderate- and low-$x$ at higher $Q^2$. One of the larger contributions to background uncertainties at LHC will be the very poorly known high-$x$ PDFs at the lower-$Q^2$ values accessible to NuMI.

**Synergy with Jefferson Lab measurements** Global analyses and MINER$\nu$A’s own studies will both benefit from the significant kinematic overlap between Jefferson Lab and MINER$\nu$A data. High-precision structure function measurements at Jefferson Lab over the same $x$ and $Q^2$ ranges will provide valuable constraints on the vector coupling when extracting structure functions and PDFs from MINER$\nu$A data. In addition, Jefferson Lab data will help disentangle nuclear effects to obtain free-nucleon PDFs from bound targets.

Figure 26 shows the same $A$-dependence in low-$Q^2$ structure function data from Jefferson Lab (in the resonance regime) and high-$Q^2$ (deep-inelastic) data from CERN and SLAC [128]. This suggests that nuclear modulation of the structure functions, an easily parameterizable if not well understood effect, should be the same for MINER$\nu$A’s frontier kinematic range as in the well-measured deep-inelastic regime.

Other Jefferson Lab experiments will directly address issues of final state interactions and on-shell extrapolation, which are particularly important at large $x$. A major reason the $d(x)/u(x)$ ratio is not better known is the difficulty of accessing the structure of the neutron, due to the uncertainties in extracting information from neutrons bound in nuclei. To overcome this problem, the BONUS experiment at Jefferson Lab [140] has been approved to measure inclusive electron scattering on quasi-free neutrons using a novel recoil detector with low proton momentum threshold and high rate capability. These measurements will provide unambiguous neutron structure measurements, and reveal which of the available models best describe, for instance, on-shell extrapolation for bound neutrons. This information will be invaluable for extracting nucleon structure information with MINER$\nu$A, and facilitate our own unique ability to provide flavor decomposition information.

### 6.3 Testing Lattice QCD

Finally, MINER$\nu$A can measure the structure function moments calculable in lattice QCD. Predicted moments are currently available for $Q^2 = 4$ (GeV/c)$^2$, which is accessible to MINER$\nu$A. Comparing measured moments with calculations on the lattice over a range $Q^2 \approx 1 − 10$ (GeV/c)$^2$ would allow the size of higher twist corrections and quark-gluon correlations in the nucleon to be determined. An appreciable fraction of the strength of these moments falls in resonance region. While a broad reach in $x$ at fixed $Q^2$ is required to obtain the moments, precise resonance region data are imperative. Since the first moment is an integral over all $x$, energy resolution will have a smaller effect on this moment than on structure function measurements. Flavor decomposition for PDF moments and structure functions at large $x$ and low $Q^2$ offer MINER$\nu$A a clear and unique role in testing the results of lattice QCD.
Figure 26: Ratio of nuclear to deuterium cross-sections per nucleon, corrected for neutron excess, for Carbon (top), Iron (center) and Gold (bottom) versus $\xi$. The resonance data at low $W$ and $Q^2$ from Jefferson Lab (circles) are compared with the deep inelastic data at high $W$ and $Q^2$ from SLAC E139 (diamonds), SLAC E87 (crosses), and BCDMS (squares). The scale uncertainties for the SLAC (left) and JLab (right) data are shown in the figure.

### 6.4 Summary

MINER$\nu$A is uniquely poised to provide a wealth of information crucial to carrying our understanding of the nucleon beyond a perturbative description. MINER$\nu$A is the only experiment capable of investigating quark/hadron duality in neutrino scattering. Extraction of parton distribution functions at large $x$ is becoming an increasingly important and controversial topic, in which MINER$\nu$A’s contributions as the only precision neutrino experiment could be decisive. MINER$\nu$A can also investigate large-$x$ evolution, PDF ratios, and PDF moments - all part of a rich physics program at the perturbative/non-perturbative frontier.
7 Generalized Parton Distributions

One of the main goals of subatomic physics is to understand the structure of hadrons, and in particular the structure of the nucleon. The primary approach to this problem has been measurement of the nucleon form-factors, with (quasi-)elastic scattering (for $Q^2$ up to a few (GeV/c)$^2$), parton densities, through inclusive deep-inelastic scattering (DIS), and distribution amplitudes, through exclusive processes. However, the usual parton densities extracted from DIS are only sensitive to the longitudinal component of the parton distributions and do not give information on the transverse component, or other contributions to the nucleon angular momentum.

7.1 The Nucleon Spin Puzzle and GPDs

In the late 1980’s, results from polarized DIS showed that a relatively small fraction, about 20%, of the nucleon spin is carried by the valence quarks. The obvious candidates for the missing spin were the quark and gluon orbital momentum and gluon helicity. However, information on those quantities cannot be extracted from DIS.

In 1997, Ji [144, 145] showed that a new class of nucleon observables, which he called “off-forward parton distributions”, could be used to determine the spin structure of the nucleon. This work, along with developments by others, especially Radyuskin [146, 147] and Collins [148] showed that these distributions, now called generalized parton distributions (GPDs), had the potential to give a full three-dimensional picture of the nucleon structure. This exciting development has led to an immense amount of theoretical work in the last few years. Short reviews can be found in [149, 150] and a comprehensive review can be found in [151].

Ji showed that in leading twist there are four GPDs, which he called $H$, $\tilde{H}$, $E$, and $\tilde{E}$, for each quark flavor. $H$ and $\tilde{H}$ are nucleon helicity-conserving amplitudes and $E$ and $\tilde{E}$ are helicity-flipping amplitudes. The GPDs are functions of $x$, $\xi$ (a factor determining the “off-forwardness” of the reaction), and the total momentum-transfer squared, $t$. The GPDs can be accessed experimentally through reactions proceeding via the “handbag” diagram shown in Figure 27.

7.2 Deeply-virtual Compton Scattering

The most promising reaction to measure GPDs identified so far is deeply-virtual Compton scattering (DVCS). The DVCS reaction is shown in Figure 28a. An interesting feature of DVCS is that it can interfere with the Bethe-Heitler process, Figure 28b, which is completely calculable in terms of the nucleon elastic form-factors. This interference causes an asymmetry in the azimuthal distribution of the scattered proton allowing some quantities to be determined that would otherwise require a polarized target. However, DVCS involves a combination of the four GPD amplitudes, which cannot be separated using DVCS alone. Some complementary information can also be obtained from nucleon form-factor measurements and deep exclusive meson electroproduction.

Neutrino scattering provides a very similar reaction to DVCS. In this case, the virtual mediator is a $W^\pm$ with the production of an energetic photon, a $\mu^\pm$, with either a recoiling nucleon or nucleon resonance, as shown in Fig. 29. This “weak DVCS” reaction is very promising theoretically because it provides access to different GPDs than DVCS. It will help resolve the individual flavors, e.g. $d$ in neutrino scattering and $u$ in anti-neutrino scattering, and the interference of the $V$ and $A$ currents will give access to C-odd combinations of GPDs.
Figure 27: (a) Forward virtual Compton amplitude which describes the DIS cross-section via the optical theorem ($x_B = x$); (b) Handbag diagram occurring in the DVCS amplitude.

Figure 28: The DVCS process (a) along with the interfering Bethe-Heitler diagrams (b) and (c).

Figure 29: Reactions sensitive to GPDs in neutrino scattering.
7.3 Measurement of GPDs in MINER\(\nu A\)

Measurement of the GPDs requires measurement of exclusive processes. In addition, certain kinematic limits must be imposed to allow reliable calculations. In particular, the reaction should be above the resonance region \((W^2 > 4 \text{ GeV}^2)\), the momentum transfer should be small \((t < 0.2 \text{ (GeV/c)}^2)\), and \(Q^2\) should be large \((Q^2 > 2 \text{ (GeV/c)}^2)\), which implies a high-energy photon and low-energy nucleon in the final state. Although this does present certain experimental difficulties, it should be possible to detect these for charged currents in MINER\(\nu A\). A. Psaker, a student of A. Radyuskin, has made detailed calculations of the weak DVCS process for neutrinos in the 5-20 GeV range with the above kinematic constraints. He finds a cross-section of about \(10^{-41} \text{ cm}^2/\text{neutron}\) for CC reactions, with a relatively small energy dependence (the useful cross section increases slightly from 5 to 20 GeV). The cross section for protons (giving a \(\Delta^{++} \rightarrow p\pi^+\) in the final state would be about half the neutron cross section. This would yield a few thousand events for the full four-year run with a 3-4 kiloton active target.

Background studies have not yet been performed, but the most significant background should be events with a photon radiated by the out-going muon. It should be pointed out that these will be primarily for reactions on neutrons in carbon, not free nucleons. We are still studying this reaction to assess the effect of extracting GPDs from a bound nucleon.
8 Nuclear Effects in Neutrino Scattering

8.1 Introduction

Most neutrino experiments, including neutrino oscillation experiments, require massive nuclear targets/detectors to obtain useful reaction rates. Analysis of neutrino reactions with nuclear media requires understanding the nuclear environment’s effect on the process [72]. There are two general categories of such nuclear effects:

- The neutrino interaction probability on nuclei is modified relative to free nucleons. Nuclear effects of this type have been extensively studied using muon and electron beams, but have not been explored with neutrinos. Depending on the kinematic region, these nuclear effects can be quite different for neutrinos [73], and are important for neutrino energies typical of oscillation experiments.

- Hadrons produced in a nuclear target may undergo final-state interactions (FSI), including re-scattering and absorption. These effects may significantly alter the observed final-state configuration and measured energy [74, 75], and are sizable at neutrino energies typical of current and planned neutrino oscillation experiments [112].

The hadron shower observed in neutrino experiments is actually the convolution of these two effects. FSI effects are dependent on the specific final states that, even for free protons, differ for neutrino and charged-lepton reactions. The suppression or enhancement of particular final states by nuclear effects also differs for neutrino and charged lepton reactions. For these reasons, measurements of nuclear effects with charged leptons cannot be applied to neutrino-nucleus interactions without considerable care.

To study these questions in MINERνA, carbon, iron and lead targets will be installed upstream of the pure scintillator active detector. To measure the overall effect of the nucleus, the observed interaction rate, hadron spectrum and multiplicity will be measured for all three targets.

8.2 Modified Interaction Probabilities

Pronounced nuclear effects have been measured in charged-lepton scattering from a number of nuclear targets. The experimental situation is discussed in review papers [77, 78].

The mechanisms of nuclear scattering have also been studied theoretically. These mechanisms appear to be different for small and large Bjorken $x$ as viewed from the laboratory system. Bjorken $x$ is defined as $x = Q^2 / 2M\nu$, where $\nu$ and $q$ are energy and three-momentum transfer to the target and $Q^2 = q^2 - \nu^2$. The physical quantity discriminating between large and small $x$ regions is a characteristic scattering time, which is also known as Ioffe time (or length) $\tau_I = \nu / Q^2$ [79]. If $\tau_I$ is smaller than the average nuclear separation between nucleons, the process can be viewed as incoherent scattering off bound nucleons. This occurs for larger $x (> 0.2)$.

At small Bjorken $x$ the space-time picture is different. The underlying physical mechanism in the laboratory reference frame can be sketched as a two-stage process. In the first stage, the virtual photon $\gamma^*$ (or $W^*$ or $Z^*$ for neutrino interactions) fluctuates into a quark-antiquark (or hadronic) state. This hadronic state then interacts with the target. The uncertainty principle allows an estimate of the average lifetime of such a fluctuation as

$$\tau = 2\nu / (m^2 + Q^2),$$

(9)
where $m$ is the invariant mass of the hadrons into which the virtual boson converts. The same scale $\tau$ also determines the characteristic longitudinal distances involved in the process. At small $x$, $\tau$ exceeds the average distance between bound nucleons and coherent multiple interactions of this hadronic fluctuation in a nucleus are important. It is well known that the nuclear shadowing effect for structure functions results from coherent nuclear interactions by hadronic fluctuations of virtual intermediate bosons (for a recent review of nuclear shadowing see, e.g., [78]).

### 8.2.1 Nuclear effects in the incoherent regime at large $x$

If $x$ is large enough to neglect coherent nuclear shadowing, lepton scattering off a nucleus can be approximated as incoherent scattering from bound protons and neutrons. The most pronounced nuclear effects in this region are due to Fermi-motion, nuclear binding [80, 81, 82, 83, 84, 85, 86], and off-shell modification of nucleon structure functions [85, 86, 87, 88, 91].

A widely used approximation in description of nuclear structure functions is to neglect the final state interactions of resulting hadrons with the recoiling nucleus. In this approximation the nuclear structure functions can be written as the bound nucleon structure function averaged (convoluted) with the nuclear spectral function (for derivation and more details see [82, 85, 91]). Since bound nucleons are off-shell particles their quark distributions generally depend on nucleon virtuality $k^2$ as an additional variable. Off-shell effects in structure functions can be viewed as a way to describe in-medium modification of structure functions. This effect was discussed in terms of different approaches in the literature [84, 88, 85, 87, 90, 91].

![Figure 30: The ratio of iron to deuterium structure functions as measured by SLAC E-139 and CERN BCDMS collaborations in experiments with electron and muon beams (left panel). Also shown are the results of model calculation at fixed $Q^2 = 10 \text{ GeV}^2$ which account for binding, Fermi-motion and off-shell effects in nuclear deep-inelastic scattering [91]. The ratio of lead and carbon structure functions calculated at fixed $Q^2 = 10 \text{ GeV}^2$ within the same approach is presented in the right panel. Predictions of the convolution approach are compared to data on charged-lepton deep-inelastic scattering in Figure 30. Model calculations of nuclear structure functions use realistic nuclear spectral functions. Data seem to indicate that some off-shell modification of bound nucleon structure function is necessary [91]. The right panel of Figure 30 displays the ratio of lead and carbon structure functions calculated within the same approach. It appears nuclear effects at large $x$ are practically saturated.](image-url)
in carbon. Similar effects are predicted for neutrino structure functions $F_2$ and $xF_3$. MINERνA will provide valuable information on nuclear effects in this region.

8.2.2 Nuclear effects at small $x$

Nuclear shadowing effects have been discussed extensively in the literature. A recent paper [78] reviews both experimental data and theoretical models of nuclear shadowing for charged-lepton scattering. This effect is interpreted as the coherent interaction of a hadronic component of the virtual photons with the target nucleus. The structure functions at small $x$ can be represented as a superposition of contributions from different hadronic states.

In fixed-target experiments events with small Bjorken $x$ are correlated with low four-momentum transfer ($Q^2$). At low $Q^2$ the vector meson dominance model (VMD) appears to be a good tool to study nuclear corrections to structure functions [78, 92]. In VMD the structure functions are saturated by contributions from a few low-mass vector meson states. For the interactions driven by the electromagnetic current usually only the isovector $\rho$ and the isoscalar $\omega$ and $\phi$ mesons are important at low $Q^2 < 1$ GeV$^2$ [92]. The structure functions in this model have strong $Q^2$ dependence. In the generalized versions of VMD, higher-mass states including the continuum have also been considered, making the model applicable at higher $Q^2$ [78, 92].

The VMD approach has also been applied to weak interactions [93]. The vector current, in close analogy with the electromagnetic current, is assumed to be saturated by $\rho$ meson contribution at low $Q^2$. The axial-vector channel requires inclusion of contributions from the axial-vector meson $a_1$. There are still a number of interesting physics questions related to the analysis of the axial-vector channel for neutrino interactions.

It should be emphasized that neutrino scattering at low $Q^2$ is dominated by the axial current. Indeed, contributions to the structure functions (and cross-sections) from the vector current vanish as $Q^2 \to 0$ due to vector-current conservation. The axial current is not conserved and for this reason the longitudinal structure function $F_L$ does not vanish at low $Q^2$. It was observed long ago by Adler that neutrino cross-sections at low $Q^2$ are dominated by the contribution from the divergence of the axial current [94]. The latter, because of PCAC, is saturated by the pion contribution, so low $Q^2$ neutrino cross-sections and structure functions are determined by pion cross-sections. For the longitudinal structure function at low $Q^2$ the Adler relation is

$$2xF_L^{\text{PCAC}} = \frac{f_\pi^2}{\pi} \sigma_\pi(s, Q^2),$$

(10)

where $f_\pi = 0.93m_\pi$ is the pion decay constant ($m_\pi$ is the pion mass) and $\sigma_\pi(s, Q^2)$ the total pion cross-section at the center-of-mass energy $s = Q^2(1/x - 1) + M^2$ for an off-shell pion with mass $\sqrt{Q^2}$. Equation (10) determines the dominant contribution to $F_2$ and neutrino cross-sections at small $Q^2$ for nucleon and nuclear targets.

It is important to realize that Eq. (10) is not a consequence of the pion dominance of the axial current, i.e. fluctuation of the axial current to a pion which interacts with the target [97]. Indeed, the single-pion fluctuation of the axial current gives a vanishing contribution to the neutrino cross-section. Instead, the axial current in neutrino interactions can produce heavy states such as the $a_1$ meson and $\rho\pi$ pair, which interact with the target. The overall contribution of all such states is described by the PCAC relation. The detailed mechanism of this phenomenon is not fully understood and MINERνA can provide new insights on physics driven by the axial current in neutrino interactions.
The strength of nuclear shadowing is controlled by mesonic cross-sections \( \sigma_v \) for the vector current. In the axial-vector channel the relevant quantity is the pion cross-section. To quantitatively understand nuclear effects, the multiple scattering effect on the cross-section is calculated using Glauber–Gribov multiple scattering theory [95, 96, 92, 97]. If \( l_f \) is small compared with the nuclear radius, as is the case for heavy nuclei, then multiple scattering effects are important. It should be emphasized that the multiple scattering correction is negative because destructive interference of the forward scattering amplitudes on the upstream nucleons causes shadowing of virtual hadron interactions on the back-face nucleons.

The onset of coherent nuclear effects can be estimated by comparing the coherence length of hadronic fluctuation \( L_c \) with the average distance between bound nucleons in the nucleus \( d \). For hadronic fluctuation of the vector current \( L_c \) is similar to the fluctuation time \( \tau \) from Eq. (9), where \( m \) is the mass of hadronic state in question. Coherent nuclear effects occur if the fluctuation time is large enough \( \tau > d \). This condition requires high energy transfer \( \nu \) and, as is clear from Eq. (9), the coherent region begins at lower energy for smaller masses \( m \). Since \( \tau < 2\nu/Q^2 \) for any intermediate state, the region of coherent nuclear effects is limited to small \( x \) for any \( Q^2 \). Nuclear shadowing saturates if \( L_c \gg R \), which happens at small \( x \), and the condition \( L_c \sim R \) defines the transition region with strong \( x \) dependence of the ratio \( \delta \sigma_A/\sigma_N \).

For the axial-vector current, the fluctuation time \( \tau \) is also given by Eq. (9). However, as argued in [97], the fluctuation and coherence lengths are not the same in this case. In particular, the coherence length is determined by the pion mass \( m_\pi \) in Eq. (9) because of the dominance of off-diagonal transitions like \( a_1 N \rightarrow \pi N \) in nuclear interactions. Since the pion mass is much smaller than typical masses of intermediate hadronic states for the vector current \( (m_\rho, m_\omega, \text{etc.}) \), the coherence length \( L_c \) of intermediate states of the axial current at low \( Q^2 \) will be much larger than \( L_c \) for the vector current. A direct consequence of this observation is early onset of nuclear shadowing in neutrino scattering at lower energy and \( Q^2 \) compared to charged-lepton scattering.

Figure 31 shows the calculated ratios of iron to nucleon and lead to carbon structure functions at two different \( Q^2 \) values as a function of \( x \). We also compare the nuclear shadowing effect for muon and neutrino scattering. The basic reason for the earlier onset of nuclear shadowing in neutrino scattering and different behavior in the transition region is the difference in correlation lengths of hadronic fluctuations between the vector and axial-vector currents. This is also illustrated by the observation that for a given \( Q^2 \) the cross-section suppression due to shadowing occurs for much lower energy transfer \( \nu \) in neutrino interactions than for charged leptons.

The relative nuclear shadowing effect for the structure function \( xF_3 \) should be substantially different than that of \( F_2 \) [98]. This is because \( xF_3 \) describes the correlation between the vector and the axial-vector current in neutrino scattering. In terms of helicity cross-sections, \( xF_3 \) is given by the cross-section asymmetry between the left- and right-polarized states of the virtual \( W \) boson. It is known that such a difference of cross-sections is strongly affected by Glauber multiple scattering corrections in nuclei. This leads to enhanced nuclear shadowing of \( xF_3 \).

The resulting ratio of lead and carbon structure functions are shown in Figure 32. Unlike nuclear effects at large Bjorken \( x \) (Figure 30), there are substantial, structure-function dependent nuclear effects at small \( x \). MINER\( \nu \)A can provide a unique tool to study these effects.
Figure 31: The ratio of iron to nucleon (upper row) and lead to carbon neutrino CC structure functions $F_2^\nu$ calculated at two different $Q^2$ within an approach based on PCAC and VMD (solid line). The dashed line shows similar ratios for the muon structure function $F_2^\mu$.

8.2.3 Determination of $\sin^2 \theta_W$

The rates of neutral-current (anti-)neutrino scattering are directly determined by $\sin^2 \theta_W$. Therefore the measurement of NC/CC ratios of neutrino cross-sections provides a valuable tool for determination of $\sin^2 \theta_W$. For an isoscalar target (e.g. the isoscalar combination of proton and neutron, or for deuterium) a relation between neutrino–antineutrino asymmetries in the NC and CC DIS cross-sections was derived by Paschos and Wolfenstein [99]

$$R^- = \frac{\sigma^\nu_{\text{NC}} - \sigma^{\bar{\nu}}_{\text{NC}}}{\sigma^\nu_{\text{CC}} - \sigma^{\bar{\nu}}_{\text{CC}}} = \frac{1}{2} - \sin^2 \theta_W,$$

(11)

where $\theta_W$ is the weak mixing angle. A similar relation also holds for the NC/CC ratio of structure functions

$$\frac{F^\text{NC}_3(x, Q^2)}{F^\text{CC}_3(x, Q^2)} = 1 - 2 \sin^2 \theta_W,$$

(12)

where $F^\text{CC}_3$ is the neutrino and antineutrino averaged structure function, $F^\text{CC}_3 = (F^\nu_3 + F^{\bar{\nu}}_3)/2$.

If only the contributions of light quarks are taken into account, the PW relationship is a direct result of isospin symmetry. This ensures that various strong interaction effects, including nuclear effects,
cancel out in $R^-$ for an isoscalar target, making Eq. (11) a powerful tool for measurement of the mixing angle in neutrino scattering.

The targets used in neutrino experiments are usually heavy nuclei, such as iron in the NuTeV experiment [100]. Heavy nuclei typically have an excess of neutrons over protons and therefore are not isoscalar targets. For a non-isoscalar target the relations (11) and (12) are violated by contributions from isovector components of nuclear parton distribution functions. Nuclear corrections to relations (11) and (12) were recently studied in [101, 102, 103], which showed that nuclear effects enter through non-isoscalar effects in the target. These studies suggest that nuclear corrections should be greatly reduced for isoscalar targets like carbon. MINERνA, with its lead, iron, and carbon targets, can directly measure the NC/CC ratio for several nuclear targets to explore these effects experimentally.

8.3 Final-state Interactions

8.3.1 Overview

Interactions of few-GeV neutrinos with nuclei often produce resonances which decay to pions. Any attempt to reconstruct the incident neutrino energy based on the total observed energy must account for pion interactions within the target nucleus. Existing neutrino interaction Monte Carlos (such as INTRANUKE [104]) handle intra-nuclear pion interactions crudely and have generally not incorporated the latest knowledge of pion interactions.

The concern is mainly with pions in the 100–500 MeV range, where the interaction cross-sections are highest. In this range the pion/nucleon cross-section is dominated by the strong $\Delta(1232)$ resonance. The $\Delta$ is a fairly narrow (about 100 MeV) resonance, and the pion-nucleon cross-section reflects this, with a peak near 200 MeV pion energy which drops quickly above and below this. The pion/nucleus cross-section exhibits a similar behavior, with a less pronounced drop-off at higher energy. The charged-pion/nucleus cross-section has four important components in the intermediate energy range: elastic scattering (nucleus left in the ground state), inelastic scattering (nucleus left in an excited state or nucleon knocked out), true absorption (no pion in the final state), and single charge exchange (neutral pion

Figure 32: The ratio of lead to carbon neutrino charged-current structure functions $F_2$ calculated in an approach based on PCAC and VMD at two different $Q^2$ (solid line). The corresponding ratio for $xF_3$ is shown by the dashed curve.
in the final state).

Neutrino detectors are mainly iron (absorber), oxygen (water) and carbon (scintillator). The total pion–carbon cross-section is 600 mb, with elastic and inelastic cross-sections about 200 mb each, and absorption about 160 mb. The total pion-iron cross-section is about 1700 mb, with elastic and absorption about 600 mb each, and inelastic about 400 mb. Cross-sections for positive and negative pions are nearly the same because nuclei contain about the same number of protons and neutrons. These very large cross-sections mean that many pions will undergo some nuclear reaction within the target nucleus. In elastic and most inelastic reactions the scattered pion will not, because of its small mass, lose much energy. However, absorbed pions will lose all of their kinetic and mass energy. Of the four components of this intra-nuclear cross-section, the absorption probability within the interaction nucleus is roughly 30%. Figure 33 [113] shows absorption cross-sections for various nuclei as a function of pion energy.

![Figure 33: The absorption cross-sections for various nuclei as a function of pion energy.](image)

Pion absorption cannot occur on a single nucleon due to energy and momentum conservation. The simplest absorption mechanism is on two nucleons. Because absorption appears to proceed mainly through $N-\Delta$ intermediate states, an isospin zero (np) pair is the primary candidate. Such an absorption for a positive pion would give two energetic protons whose kinetic energy nearly equaled the total pion energy. However, early studies of pion absorption found this was not the most probable mechanism.

In the 1990’s two large solid angle detectors, the LAMPF BGO Ball and the PSI LADS detector, were built to study pion absorption. The somewhat surprising result from both experiments was that pion absorption is dominated by three body absorption [105]. For positive pions, the absorption on a $pnn$ triplet (leading to a $ppn$ final state) was the most common. This was observed even in $^4$He. The absorption in heavier nuclei also appears to proceed mainly through a three-body mechanism,
although increased initial state interactions (pion re-scattering) and final-state interactions (nucleon re-scattering) result in four to five nucleons being emitted. Typically the final-state contains more neutrons than protons. The absorption process, which is still not well understood theoretically, largely fills the available phase space thus giving a wide range of nucleon energies with little angular dependence. Because much of the energy is in neutrons, the visible energy is well below the total pion energy. Even in carbon more than half the energy is lost to unobserved particles, a fraction which increases with pion energy and with $A \[106\]$. 

The situation is worse for negative pions. Charge symmetry would indicate that the primary absorption should be on a $ppn$ triplet leading to a $pnn$ final state. In this case, most of the pion energy would be in neutrons, and hence effectively invisible. However, if the interaction vertex and one proton energy is known, and the angles of the outgoing neutrons are known, the total energy of the three nucleons can be estimated. Monte Carlo studies with realistic absorption models will be needed to determine the accuracies of such estimates.

Although neutral pions escaping the nucleus will decay, usually to two photons, the mean distance traveled before decay is a few nanometers, much greater than the size of the nucleus. Thus the absorption of neutral pions in the interaction nucleus must also be accounted for in any study of resonance production.

For MINER$\nu$A, studies with INTRANUKE have begun to explore the sensitivity to the probability of pion absorption in the interaction nucleus. Monte Carlo routines are being modified to treat pion absorption more realistically. Unfortunately there are essentially no measurements of pion absorption above 500 MeV. The fine spatial resolution and $4\pi$ acceptance of MINER$\nu$A will allow study of these interactions, especially in carbon.

### 8.3.2 Nuclear transparency

A second nuclear interaction process which affects the observed energy is final state interaction of a nucleon in the struck nucleus. An outgoing nucleon has a substantial probability of interacting in the nucleus. These probabilities have been measured, most recently at Jefferson Lab, with some precision. The experiments used $(e, e'p)$ coincidence reactions, and the cross-section for finding the scattered electron in the quasi-elastic peak was compared to the cross-section for finding the coincident proton.

Unlike pion absorption, there is little available information on what happens to the scattered nucleon. Of course, most either scatter from a single nucleon quasi-elastically or produce a pion (for protons above 600 MeV). Improving Monte Carlo routines to model this interaction should allow us to better estimate the total final state energy. As for pion absorption, the good resolution, neutron detection capability, and full solid angle coverage of MINER$\nu$A should allow measurement of the actual final states and help constrain the Monte Carlo models.

### 8.4 Nuclear Effects in MINER$\nu$A

To study nuclear effects in MINER$\nu$A, carbon, iron and lead targets will be installed upstream of the pure scintillator active detector. The currently preferred configuration involves a total of 9 planes, with each plane divided transversely into C, Fe and Pb wedges. As one proceeds from upstream to downstream, the C, Fe and Pb targets exchange (rotate) positions. A scintillator module of four views (X,U,X,V) separates each of the planes. The total mass is over 1 ton of Fe and Pb and somewhat over 0.5 ton of C. Since the pure-scintillator active detector acts as an additional 3-5 ton carbon target (CH),
The expected event sample per target with $Q^2 \leq 0.4 \text{GeV}^2$ and $\nu \geq 6 \text{GeV}$.

![Figure 34: The expected event sample per target with $Q^2 \leq 0.4 \text{GeV}^2$ and $\nu \geq 6 \text{GeV}$.](image)

the pure graphite (C) target is mainly to check for consistency. For the standard four-year run described in the proposal, MINER$\nu$A would collect over 740 K events on Fe and Pb, 430 K events on C as well as 2.3 M events on the scintillator in the fiducial volume.

8.4.1 Measuring modified interaction probabilities

To measure this nuclear effect, the cross-section and resulting structure functions $F_2(x,Q^2)$ and $xF_3(x,Q^2)$ will be measured for the three target nuclei of C, Fe and Pb. For the standard 4-year run we expect around 740 K events per target distributed in $x$ depending on the $W$-region in question. For an A-dependent comparison in the DIS region ($W \geq 2 \text{ GeV}$ and $Q^2 \geq 1 \text{ (GeV/c)^2}$) we would have 330 K events per target with 66 K events per target in the shadowing region ($x \leq 0.1$) and 20 K events per target in the high-$x$ region ($x \geq 0.5$).

To study the axial-vector nuclear shadowing effects expected at low $Q^2$ (non-DIS events) and low $\nu$ we will have 133 K events per target with $Q^2 \leq 1.0 \text{ (GeV/c)^2}$ and $x \leq 0.1$. For example, the expected distribution of events with $Q^2 \leq 0.4 \text{ (GeV/c)^2}$ and $\nu \geq 6 \text{ GeV}$ (the region where the largest differences from charged-lepton shadowing are expected) is shown in Figure 34. With these samples, MINER$\nu$A can measure the expected difference in lead to carbon shadowing for charged leptons compared to neutrinos to just under three standard deviations (statistical).

8.4.2 Measuring final state interactions

The NEUGEN Monte Carlo has been used to study MINER$\nu$A’s sensitivity to nuclear effects. Nuclear effects in NEUGEN are controlled by the INTRANUKE processor. This processor incorporates a probability for pion absorption based on earlier electroproduction absorption studies and lower-statistics Ne/H$_2$ neutrino bubble chamber data. The observed phenomenon of hadron formation length, which increases the transparency and reduces final-state interactions, is incorporated. The particular model used
for pion absorption, which is currently being improved and updated, assumes that absorption eliminates
a pion and the resulting nucleons are themselves either absorbed in the nucleus or are too low in energy
to be observed.

To determine MINERνA’s sensitivity to the predictions of this model, the assumed probability for
pion absorption in INTRANUKE has been increased by three standard deviations and then decreased by
the same amount, which essentially turns off pion absorption completely. The multiplicity and a simple,
crude estimate of the visible hadron energy have been examined under these extreme conditions. Other
nuclear effects such as intra-nuclear scattering and hadron formation length have not been altered from
their nominal values. Figure 35 shows both the true and reconstructed multiplicity distributions for
carbon. Unfortunately, the available tracking software fails to reconstruct many of the tracks. We
expect this problem to be resolved when full pattern recognition and a more robust tracker become
available. For the present study, we will use the true multiplicities.

![Figure 35: The shift in the true and reconstructed multiplicity distributions between the two values
assumed for pion absorption on carbon described in the text.](image)

The next series of figures show the predicted “asymmetry” of the true multiplicity and visible hadron
energy. The asymmetry is defined as the percentage change under these extreme assumptions. That
is, the bin contents at plus three standard deviations minus the bin contents at minus three standard
deviations, divided by bin contents at minus three standard deviations. Figure 36 shows the asymmetry
of the true multiplicity for carbon and iron. There is a dramatic effect for carbon, as the high absorption
value increases the number of 0-track events by over a factor of six compared to the no-absorption case.
This is because the other nuclear effects, being unchanged, are minimal for carbon. Since intra-nuclear
rescattering increases as $A^{1/3}$ and the suppression due to hadron formation length decreases as $A^{1/3}$,
non-absorption nuclear effects are minimal for carbon and already sizable for lead. If this model is
realistic, the carbon multiplicity distribution should be quite sensitive to the probability of absorption.

Final determination of the visible hadronic energy will be an involved process for this experiment.
For now, we use the most primitive estimate of this quantity, an uncorrected version derived from the
total light output of the hadron shower. In the real data analysis this can be refined through measure-
ments of stopping/decaying particles. With this crude estimate, the change in hadron energy for iron and lead are shown in Figure 37. There is a significant increase in the number of events with \( E_H \) less than 3 GeV and a corresponding decrease in the number of events with higher \( E_H \), as one would expect. MINERνA will collect several times these statistics and should be able to measure this effect at even higher hadron energy.

Since the incoming neutrino energy is not known \textit{a priori}, the measured muon kinematics will be tested as a basis for comparing the visible hadron shower across nuclear targets to determine whether a nuclear correction-factor can be parameterized as a function of the observed muon angle and energy. The muon is relatively free from nuclear dependent effects and serves well as an \( A \)-independent normalization. For example, the quantity:

\[
Q' = E_\mu \sin^2(\theta/2)
\]  

(13)

is representative of the 4-momentum transfer to the nucleon or quark (divided by \( E_\nu \)) and reflects the energy-momentum transferred to the hadronic vertex. The distribution of events in this quantity is peaked toward low \( Q' \), with half the events below \( Q' = 1.0 \) GeV.
Figure 37: The fractional change in the visible hadron energy distributions between the two values of pion absorption on iron (left) and lead (right), as discussed in the text.
Part II
The MINER$\nu$A Project
9 NuMI Beam and Hall

MINER$\nu$A will run in the NuMI beamline, and be sited in the hall which currently houses the MINOS near detector. The NuMI beam is the most intense high-energy neutrino beam available today, and because of the available space, the hall itself is an ideal environment for neutrino experiments. It provides a well-shielded area with sufficient infrastructure to support MINOS as well as other neutrino experiments.

9.1 The MINOS Near Detector Hall

The MINOS Near Detector Hall[152] is a fully-outfitted experimental facility that can accomodate MINER$\nu$A with a limited number of additions to the infrastructure.

The hall is 45 m long, 9.5 m wide, 9.6 m high, with its upstream end just over 1 km from the NuMI target, at a depth of 106 m below grade. The MINOS near detector has been installed at the downstream end of the hall, and there is free space upstream amounting to, roughly, a cylinder 26 m in length and 3 m in radius. The neutrino beam centerline descends at a slope of 3.3° and enters the MINOS detector at a height of 3 m from the floor.

Ground water is pumped from the NuMI/MINOS complex at a rate of approximately 270 gallons (980 l) per minute. The hall floors and walls are occasionally damp in places, and a drip cover will be used to protect MINER$\nu$A from moisture. The air is held at a temperature between 60° F and 70° F (15° C and 21° C), and 60% relative humidity.

9.1.1 Utilities

The MINOS Service Building on the surface houses the access shaft to the Near Detector Hall and is the entry point for electrical, cooling, and data services to the hall. A 15-ton capacity crane, with a hook height of 18.5 feet (5.66 m), was used to lower the 3.47 ton MINOS detector planes to the hall. MINOS planes were moved within the hall using an overhead 15-ton crane, with 22 foot (6.7 m) hook height and a coverage along the beam axis of approximately 40 m.

Quiet power to the hall is provided by a 750 KVA transformer at the surface, which branches to a 45 KVA transformer for the muon monitoring alcoves, and two 75 KVA transformers for the Near Detector hall. The power needs of the MINOS detector account for the capacity of the 4 panelboards served by the two 75 KVA transformers, so additional panelboards for MINER$\nu$A will be installed by Fermilab. The estimated power consumption of MINER$\nu$A’s electronics is less than 5000 W. The overall capacity for this additional load exists within the MINOS hall.

MINER$\nu$A’s main non-quiet power need is for the magnet coils, with an estimated ohmic power loss of 30 kW. The MINOS magnet coil power supply is served by a 480 V line with 400 A capacity, but requires less than 80 kW of power. This should leave ample capacity for the addition of a power supply for the MINER$\nu$A coil on the same line.

The heat sink for the MINOS LCW cooling circuit is the flux of ground water collected in the MINOS sump. This cooling is adequate for MINOS, with an output water temperature of 70° F. This should be sufficient to absorb the heat load of the MINER$\nu$A magnet, but would likely be too warm to effectively cool the power supplies for MINER$\nu$A’s electronics. The relatively low heat load of the MINER$\nu$A electronics would likely be absorbed without problem by the MINOS hall air conditioning.
9.1.2 Detector placement

MINER$\nu$A will be placed 1.75 m upstream of MINOS. This will leave sufficient work space between the two detectors and will avoid interfering with the MINOS coil, which extends approximately 1.5 m upstream of MINOS, to the lower right in the view of Figure 38. To have the beam axis intersect the detector axis close to the center of the active plastic target, the lowest corner of MINER$\nu$A will be placed 1.10 m above the hall floor. The beam centerline would enter the detector at an elevation of 3.4 m from the floor (Figures 39 and 40).

MINER$\nu$A will impinge slightly on a “stay clear” egress space for the lower MINOS detector electronics racks. This will be resolved by extending the upstream part of the MINOS electronics platform and moving the stairs farther upstream.

Figure 38: View of the proposed MINER$\nu$A detector, and the MINOS detector, looking downstream.

9.1.3 Impact on MINOS

The impact on MINER$\nu$A’s heat load and power consumption on MINOS can be made negligible through relatively minor additions to the hall infrastructure. Presence of the detector in the neutrino beam will cause an increase in the rate of activity in the MINOS detector, particularly in the first 20 planes forming the MINOS veto region. Given MINER$\nu$A’s design, the expected event rate in the detector is $\approx 1.4$ charged-current interactions per $10^{13}$ protons on target (POT). For a spill of $2.5 \times$
Figure 39: Plan view of MINERvA (purple outline near top of figure).
Figure 40: Front view of MINERνA.
POT this corresponds to 3.4 charged-current events, plus an additional 1.0 neutral-current event per spill. Since the vectors of all particles leaving MINERνA with a trajectory heading towards MINOS will be made available when MINERνA is taking data, this rate should be manageable.

9.2 The NuMI Beam and MINERνA Event Sample

The NuMI neutrino beam is produced from $\pi$- and $K$-decay in a 675 m decay pipe beginning 50 m downstream of a double horn focusing system. At the end of the decay pipe a 10 m long hadron absorber stops the undecayed secondaries and non-interacting primary protons. Just downstream of the absorber, 240 m of Dolomite is used to range out muons before the $\nu$ beam enters the Near Detector Hall. Figure 41 shows the beamline and hall layout.

![Diagram of NuMI beamline components and near detector hall](image)

Figure 41: Layout of NuMI beamline components and near detector hall (not to scale).

9.2.1 Energy options

The neutrino energy spectrum of the NuMI beam can be adjusted by changing the distances of the target and second horn from the first horn, as in a zoom lens. The three configurations result in three beam energy tunes for the low- (LE), medium- (ME), and high-energy (HE) ranges respectively. However, to switch from one beam mode to another requires down-time to reconfigure the target hall and a loss of beam time. An alternative which allows the peak energy to be varied is to change the distance of target from the first horn and leave the second horn fixed in the LE position. This can be accomplished remotely with a maximum target excursion of -2.5 m upstream of the first horn from its nominal low-energy position. Moving the target -1.0 m results in a “semi-medium” energy beam tune (sME), and -2.5 m produces a “semi-high” energy beam (sHE). These semi-beam configurations are less efficient and result in lower event rates than the ME and HE beams. A considerably more efficient sHE beam is possible with three-day downtime to move the target to its normal HE position of -4.0 m. This more efficient sHE(-4.0) beam would yield over 50% more events than the sHE(-2.5) beam. For MINOS, the beamline will be operating primarily at its lowest possible neutrino energy setting, to reach the lowest values of $\Delta m^2$. However, to minimize systematics, MINOS will also run in the sME and sHE configurations. The neutrino energy distributions for the LE, sME, and sHE running modes are shown in Figure 42.
Figure 42: Neutrino energy distribution for charged-current interactions in three configurations of the NuMI beam corresponding to low-energy (LE), medium-energy (sME) and high-energy (sHE).

9.2.2 MINER$\nu$A event rates

Table 6 shows charged-current interaction rates per $10^{20}$ protons on target (PoT) per ton for different beams. The expected rates are about 20% lower than quoted in our November 2003 proposal, due to new hadron production spectra from the SPY experiment\cite{157} recently incorporated in the NuMI beam Monte Carlo.

The same beam configurations with horn-currents reversed focus $\pi^-$ to create anti-neutrino beams. Rates for $\bar{\nu}_\mu$ charged-current interactions from anti-neutrino configurations (LErev, MErev, and HErev) are of great interest but have not yet been calculated with the new hadron production spectra. Running in these reversed ($\bar{\nu}$) modes would be highly desirable for MINER$\nu$A’s physics program.

<table>
<thead>
<tr>
<th>Beam</th>
<th>CC $\nu_\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LE</td>
<td>60 K</td>
</tr>
<tr>
<td>sME</td>
<td>132 K</td>
</tr>
<tr>
<td>sHE</td>
<td>212 K</td>
</tr>
</tbody>
</table>

Table 6: MINER$\nu$A charged-current interactions per ton, per $10^{20}$ protons on target.

9.2.3 Baseline MINOS run plan

Table 7 shows the expected protons on target over a hypothetical four-year MINOS run. For this scenario, the total integrated rate in MINER$\nu$A would be 745 K $\nu_\mu$ charged-current interactions per ton. Table 9.2.3 shows the MINER$\nu$A sample (per ton) for different processes, assuming $9 \times 10^{20}$ protons on target.
<table>
<thead>
<tr>
<th>year</th>
<th>total PoT</th>
<th>LE</th>
<th>sME</th>
<th>sHE</th>
<th>LRev</th>
<th>MRev</th>
<th>HRev</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>3.0</td>
<td>3.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2007</td>
<td>4.0</td>
<td>3.0</td>
<td>0.7</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2008</td>
<td>4.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>2.5</td>
<td>1.0</td>
<td>0.5</td>
</tr>
<tr>
<td>2009</td>
<td>4.0</td>
<td>1.0</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Total</td>
<td>15.0</td>
<td>7.0</td>
<td>1.2</td>
<td>0.8</td>
<td>3.0</td>
<td>1.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Table 7: Hypothetical proton luminosity scenario for a four-year run.

<table>
<thead>
<tr>
<th>Process</th>
<th>CC/ton</th>
<th>NC/ton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quasi-Elastic</td>
<td>82 K</td>
<td>27 K</td>
</tr>
<tr>
<td>Resonance</td>
<td>156 K</td>
<td>48 K</td>
</tr>
<tr>
<td>Transition</td>
<td>164 K</td>
<td>52 K</td>
</tr>
<tr>
<td>DIS</td>
<td>336 K</td>
<td>98 K</td>
</tr>
<tr>
<td>Coherent</td>
<td>7 K</td>
<td>3.3 K</td>
</tr>
<tr>
<td>Total (ν)</td>
<td>745 K</td>
<td>228 K</td>
</tr>
</tbody>
</table>

Table 8: MINERνA samples per ton for various processes, assuming $9 \times 10^{20}$ PoT. The detector fiducial mass is 3–5 tons Carbon, 1 ton Iron, and 1 ton Lead.

### 9.2.4 Precision of neutrino flux prediction

One of MINERνA’s significant advantages over previous wide-band neutrino scattering experiments will be better knowledge of the neutrino flux and energy spectrum. Since the NuMI beamline is designed for the MINOS oscillation experiment, considerable effort has been devoted to control of beam-related systematic uncertainties.

The largest source of uncertainty in the neutrino energy spectrum arises from the hadron ($\pi^\pm$ and $K$) production spectra. To reduce this uncertainty, a dedicated Fermilab experiment called MIPP (E-907)[158, 155] is directly measuring these hadron production spectra for various nuclear targets. One of the E-907 measurements will expose of the NuMI target itself to the 120 GeV Main Injector proton beam. Using the NuMI target material and shape, E-907’s data will include secondary and tertiary hadron production, which significantly modified the spectra relevant for neutrino production. With input from E-907, the absolute neutrino flux and energy spectrum should be known to $\approx 3–5\%$.

For the absolute flux of neutrinos, a second uncertainty concerns the number of protons on target. With the planned NuMI primary proton beamline instrumentation[159], the number of protons on target will be known to within $(1 – 3)\%$, the range being determined by control of the drift in the proton beam toroid devices.

To summarize, the energy spectrum of the NuMI beam should be known to $(3 – 5)\%$ and the absolute flux should also be known to $(3 – 5)\%$.