0.1 Overview of the MINERνA Physics Program

The MINERνA neutrino scattering experiment [1] in the NuMI beam offers a unique opportunity to study a broad spectrum of physics topics. Of the physics topics of interest in the MINERνA program, several have not previously been studied in any systematic way, while others have only few results that are compromised by large statistical and systematic errors. The complete MINERνA physics program will consist of high-statistics studies of the following topics. These studies are important for both the elementary particle physics community as well as the nuclear physics community for which neutrino reactions provide information complementary to JLab studies in the same kinematic range.

- Precision measurement of the quasi-elastic neutrino–nucleus cross-section, including its E_ν and q^2 dependence, and study of the nucleon axial form factors. Over **300 K** events are expected in the fiducial volume in a four-year MINERνA run.

- Determination of cross-sections in the resonance production region for both neutral-current and charged-current interactions, including a study of isospin amplitudes, measurement of pion angular distributions, isolation of dominant form factors, and measurement of the effective axial-vector mass. A total of **470 K** one- and two-pion events make up the resonance sample.

- Precision measurement of coherent single-pion production cross-sections, with particular attention to target A dependence. Coherent π^0 production, especially via neutral-currents, is a significant background for next-generation neutrino oscillation experiments seeking to observe $\nu_\mu \to \nu_e$ oscillation. A sample of **20 K** CC events is expected off of a carbon target. The expected NC sample is roughly 1/2 the CC sample.

- Examination of nuclear effects in neutrino-induced interactions, including energy loss and final-state modifications in heavy nuclei, by employing targets of carbon, iron and lead. These nuclear effects play a significant role in neutrino oscillation experiments that measure ν_μ disappearence as a function of E_ν. In addition, it has recently been speculated that, for the same Q^2, shadowing with neutrinos can occur at much lower energy transfer (ν) than charged lepton scattering. This effect is in none of the currently employed event simulation Monte Carlos. With sufficient $\overline{\nu}$ running, a study of quark flavor-dependent nuclear effects will also be performed. Due to the different mix of quark flavors involved, this is another way in which neutrino and charged-lepton nuclear effects differ. MINERνA will collect over **700 K** CC events off of both iron and lead targets in addition to the sample off carbon.

- Clarification of the role of nuclear effects as they influence the determination of $\sin^2\theta_W$ via measurement of the ratio of neutral-current to charged-current cross-sections off different nuclei.

- The clarification of the W ($\equiv$ mass of the hadronic system) transition region wherein resonance production merges with deep-inelastic scattering. including tests of phenomenological characterizations of this transition such as quark/hadron duality. A sample of **500 K** multi (≥ 2) pion events is expected with W $\leq$ 2.0 GeV.

- With a sample of over **1 million** CC DIS events, a much-improved measurement of the parton distribution functions, particularly at large x_{Bj}, will be possible using a measurement of all three ν structure functions. Although we expect over **100 K** CC $\overline{\nu}$ events in the four year MINERνA ν run, an additional dedicated $\overline{\nu}$ run would be required for the three $\overline{\nu}$ structure functions to be measured with similar precision.

- Examination of the leading exponential contributions of perturbative QCD.
- With nearly **50 K** fully reconstructed exclusive events expected [2], precision measurement of exclusive strange- particle production channels near threshold, thereby improving knowledge of backgrounds in nucleon-decay searches, will be possible. Also, determination of V_{us}, and enabling searches for strangeness- changing neutral-currents and candidate pentaquark resonances will be undertaken. Measurement of hyperon-production cross-sections, including hyperon polarization, will be feasible with exposure of MINERνA to $\overline{\nu}$ beams.
- Improved determination of the effective charm-quark mass (m_c) near threshold, and new measurements of V_{cd}, $s(x)$ and, independently, $\overline{s}(x)$.

In addition to being significant fields of study in their own right, improved knowledge of many of these topics is essential to minimizing systematic uncertainties in neutrino-oscillation experiments. Following is a somewhat more detailed description of these topics that illustrate the potential of the MINERνA experiment.

0.1.1 Low-energy Neutrino Cross-sections

This is a topic of considerable importance to both present and proposed future (off-axis) neutrino oscillation experiments. With the statistics noted above, MINERνA will be able to measure these cross-sections with negligible statistical errors and with the well-controlled beam systematic errors needed for the MINOS experiment

0.1.2 Low-energy Neutrino Cross-sections: Quasi-elastic Scattering

Charged-current quasi-elastic reactions play a crucial role in both non-accelerator and accelerator neutrino oscillation studies. Cross-section uncertainties - often expressed as uncertainty in the value of the axial-vector mass - are a significant component in error budgets of these experiments. Currently available measurements of this cross-section are clustered below E_ν = 5 GeV with a few isolated measurements out to 12 GeV. The measurements have statistical errors of order (10-15)% plus another (10-20)% beam systematic error. A complete simulated analysis of the quasi-elastic channel in MINERνA has been carried out [3]. The efficiency and purity of the final sample are Q^2 dependent however, the average efficiency was 74% with a purity of 77%. The resulting sample is shown in Figure 1 a. MINERνA will measure the cross-section out to E_ν = 20 GeV with statistical errors ranging from $\leq$ 1% at low E_ν up to 7 % at E_ν = 20 GeV. The expected beam systematic error is (4-6)% due to more precise measurements of hadron production, the major source of uncertainty in predicting neutrino flux, from the currently running MIPP experiment [4].

There have been recent advances in the measurement of the vector component of elastic scattering from SLAC and Jefferson Lab. However, there is still an uncertainty in the large Q^2 behavior of G_E^p with differing experimental results depending on whether the extraction is based on cross-section or polarization techniques. For the axial-vector component of this channel, measurement of the neutrino quasi-elastic channel is the most direct way to improve our knowledge. MINERνA's ability to carefully measure $d\sigma/dQ^2$ to high Q^2 allows not only the investigation of the non-dipole component of the axial-vector form factor to an unprecedented accuracy, but also permits discrimination between the two alternative suggested high Q^2 behaviors discussed above. Figure 1 b shows the extraction of the axial-vector form factor from the quasi-elastic event sample accumulated over a 4-year MINERνA run. The data points are plotted as a ratio of F_A/F_A(Dipole) with the indicated assumptions. Also shown are the currently available values of F_A from early experiments. MINERνA will be able to

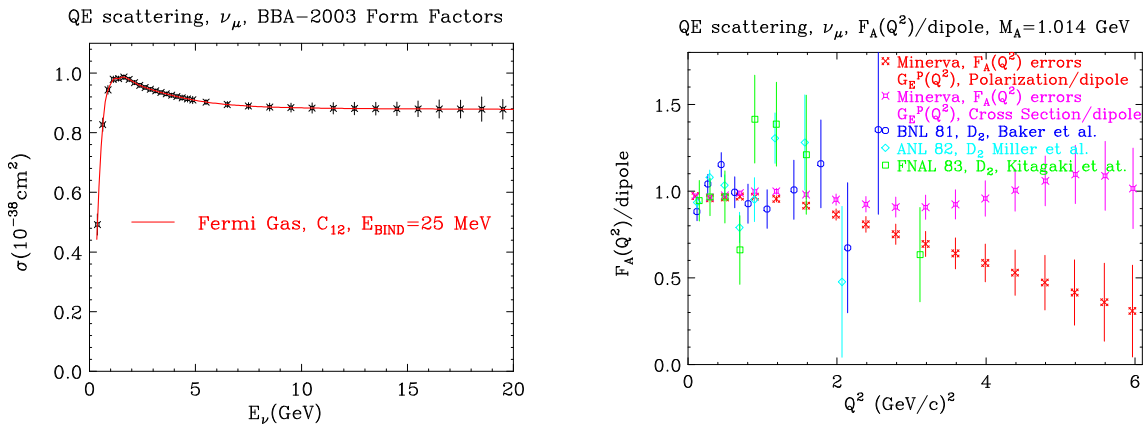

Figure 1: On the left is the cross section measurement for MINERνA assuming a 4-year run, statistical errors only, with M_A =1.00 GeV and the Fermi gas model. On the right is the projected results for MINERνA for two different assumptions: F_A/dipole=G_E^p/dipole from cross section and F_A/dipole=G_E^p/dipole from polarization. Also shown are the extracted values of $F_A(q^2)/dipole$ for deuterium bubble chamber experiments Baker *et al.* [5] and Kitagaki *et al.* [6].

measure the axial nucleon form-factor with precision comparable to vector form-factor measurements at JLab. Combining these MINERνA measurements with present and future Jefferson Lab data will permit precision extraction of all form factors needed to improve and test models of the nucleon.

0.1.3 Low-energy Neutrino Cross-sections: Resonance Production

Neutrino Monte-Carlo programs, trying to simulate this kinematic region, have used early theoretical predictions by Rein and Sehgal [7] or results from electro-production experiments since existing data on neutrino resonance-production is insufficient for the task. It is noteworthy that the theoretical and experimental picture of the resonance and transition regions are far more obscure than the quasi-elastic and deep-inelastic scattering (DIS) regions which border it. Since the event samples of present and proposed neutrino oscillation experiments fall inside this poorly-understood resonance region, resonant pion production is an important source of background in neutrino oscillation searches. This kinematic region will be carefully examined by MINERνA.

Analysis of resonance production in MINERνA [8] will focus on several experimental channels including inclusive scattering in the resonance region ($W < 2$ GeV) and exclusive charged and neutral pion procuction. Analysis efforts thus far have focused on understanding the performance of MINERνA for inclusive resonance prodcution [9], particularly near the $Delta(1232)$ resonance. This analysis indicates that the resolutions of W is about 100 MeV in the region of the Δ and the Q^2 resolution is better than 20%. Despite this resolution smearing and smearing introduced by fermi-motion, as most of the scatterings take place on bound nucleons in carbon, the Δ peak is still clearly visible in the W yield spectrum when using the reconstructed kinematics.

Analysis methods are being developed to use the tracking capability of MINERνA to improve the

kinematic determination of resonance events, which typically have low multiplicity. This is expected to help the reconstruction of W in the neighborhood of the Δ resonance as well as permit the reconstruction of exclusive resonance events.

0.1.4 Low-energy Neutrino Cross-sections: Coherent Pion Production

Both charged- and neutral-current coherent production of pions result in a single forward-going pion with little energy transfer to the target nucleus. In the neutral-current case, the single forward-going π^0 can mimic an electron and be misinterpreted as a ν_e event. Existing cross-section measurements for this reaction are only accurate to $\sim$ 35% and are only available for a limited number of target nuclei in the few-10 GeV region [10].

The MINERνA experiment, with its high statistics and variety of nuclear targets, will greatly improve our experimental understanding of coherent reaction processes. A complete simulated analysis of the charged-current coherent production channel has been carried out [11]. The kinematic cuts employed reduced the background by three orders of magnitude while reducing the signal by a factor of three.

Figure 2 a shows the precision of the resulting sample of the MINERνA measurement of the charged current coherent pion production cross-section as a function of neutrino energy after projected background subtraction. The errors are statistical only. Here it is assumed that the measured value is that predicted by Rein-Seghal [12]. Also plotted are the only currently available measurements in this kinematic region showing their total errors.

The MINERνA sample of charged current coherent events can be used to study the differential cross sections for coherent scattering. Comparions of the overall rates of neutral and charged current production, as well as comparison of the pion energy and angular distributions from NC and CC events will also provide useful tests of the various models. For several recent models, the prediction for the NC/CC ratio in coherent scattering differs by around 20% [12, 13].

Another task for MINERνA will be comparison of reaction rates for lead, iron and carbon. 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 [14]. No experiment to date has been able to perform this comparison. Figure 2 b illustrates the broad range in A to be covered by MINERνA's measurement of the coherent pion cross-section. The shaded band is the range in A covered by existing experiments.

0.1.5 Neutrino Induced Nuclear Effects

In most neutrino scattering experiments, including neutrino oscillation experiments, massive nuclear target/detectors are necessary to obtain useful reaction rates. Analysis of neutrino reactions within nuclear media requires an understanding of certain processes, so-called "nuclear effects". There are two general categories of such effects:

- The neutrino interaction probability on nuclei is modified relative to that for free nucleons. Nuclear effects of this type have been extensively studied in deep-inelastic scattering (DIS) measurements of structure functions using muon and electron beams, but have not been studied with neutrinos. Depending on the kinematic region in question, these nuclear effects are expected to be quite different for neutrinos. In particular, the shadowing phenomena is expected to be very different for neutrinos as compared to muon or electron induced interactions [22]. As explained in reference [26], for a given Q^2, the reduction in observed cross-section (shadowing) occurs for

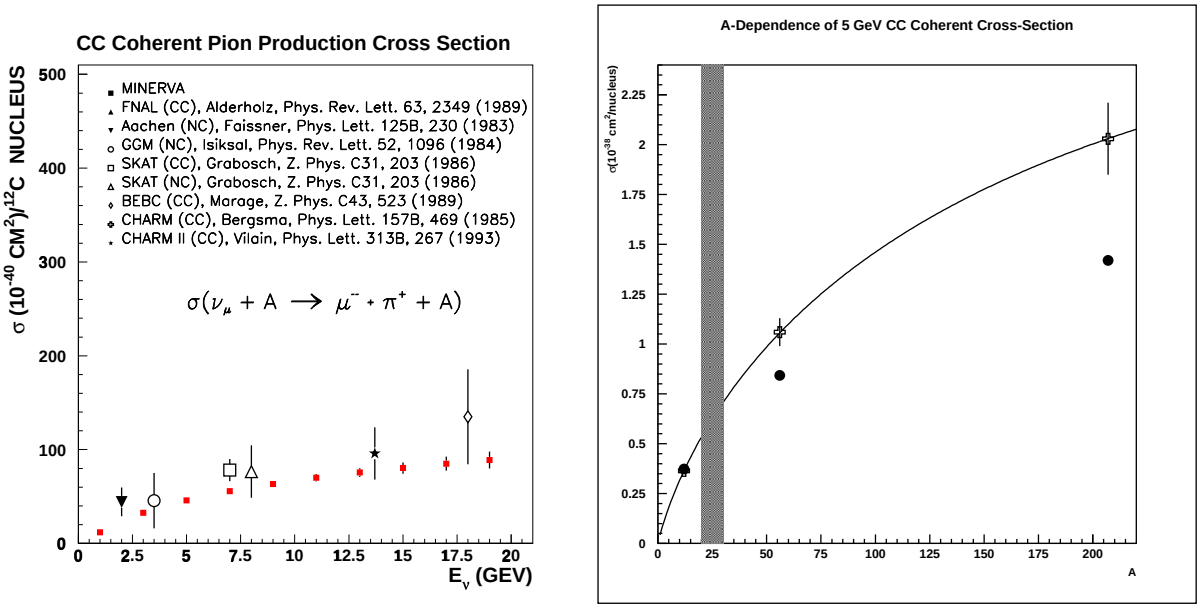

Figure 2: On the left is the cross section measurement for MINERνA assuming a 4-year run, statistical errors only, compared with existing published results. On the right is the range of A-dependent measurements of the coherent-pion cross-section to be measured by the MINERνA experiment compared to the range of exisitng data shown by the shaded band.

much lower energy transfer ν in neutrino interactions than for charged lepton interactions. This is an important and, until MINERνA studies this, an unmeasured effect.

- The resulting final state may undergo final state interactions (FSI), including re-scattering and absorption; these interactions may significantly alter the observed final-state configuration and measured energy. These effects are likely to be sizable for neutrino energies producing a large fraction of elastic and resonant final states [24] as in current and planned neutrino oscillation experiments.

It is important to note that the hadron shower observed in neutrino experiments is the **convolution** of these two effects. The FSI are dependent on the produced final state that, even off single nucleons, is different for neutrino and charged-lepton final states. In addition, the suppression or enhancement of the production of particular initial final states by nuclear effects is again different for neutrinos as compared to charged leptons. For these reasons, results of nuclear effects studies using charged leptons can not be simply applied to neutrino nucleus interactions.

To study these combined nuclear effects in MINERνA, carbon, iron and lead targets will be installed upstream of the pure scintillator active detector. To measure the overall result of these combined effects [23], the observed hadron energy and multiplicity will be measured off of C, Fe and Pb targets as a function of muon variables to determine an A,P$_\mu$ correction factor to be applied to visible hadron energy of CC events.

0.1.6 The Perturbative - Non-Perturbative Interface and Deeply Inelastic Scattering

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 elementary particle and nuclear physics. A

major obstacle arises from the fact that the degrees of freedom observed in nature (hadrons and nuclei) are totally different from those appearing in the QCD Lagrangian (current quarks and gluons). Making the transition from quark and gluon to hadron degrees of freedom is therefore the key to our ability to describe nature from first principles.

Experimentally, understanding this transition requires reliable data in three kinematic regimes: in the scaling domain of high Q^2 deep inelastic scattering; in the hadronic region of resonances and quasi-elastic scattering; and, perhaps most importantly, in the moderate Q^2 region between the two, where the transition is made manifest most dramatically. MINERνA is uniquely situated to address this compelling topic for the first time with neutrinos with measurements that will span all three regimes, and provide reliable data in the crucial transition region [15].

Despite the apparent dichotomy between the partonic and hadronic regimes, in nature there exist instances where the behavior of low-energy cross sections, averaged over appropriate energy intervals, closely resembles that at asymptotically high energies, calculated in terms of quark-gluon degrees of freedom. This phenomenon is referred to as *quark-hadron duality*, and reflects the relationship between confinement and asymptotic freedom, and the transition from perturbative to nonperturbative regimes in QCD. In electron–nucleon scattering, quark-hadron duality links the physics of resonance production to the physics of scaling, and is the focus of subtantial renewed interest in understanding the structure of the nucleon [16, 17, 19, 18]. For example, there are over 10 approved experiments at Jefferson Lab which address this topic.

Weak currents can provide complementary information on the quark structure of hadrons, not accessible to electromagnetic probes. In particular, neutrino-induced reactions can provide important consistency checks on the validity of duality. While deep inelastic neutrino structure functions are determined by the same set of universal parton distribution functions as in charged lepton scattering, the structure of resonance transitions excited by neutrino beams is in some cases strikingly different to that excited by virtual photons. Although on general grounds one may expect that a duality should also exist for weak structure functions [20], the details of how this manifests itself in neutrino scattering may be quite different from that observed in electron scattering. MINERνA specifically designed to measure low-energy neutrino-nucleus interactions accurately over both the resonance and deep inelastic regimes, will be an exceptional tool for the study of duality with the weak current [21].

Once in the perturbative QCD regime, the evolution of parton distribution functions takes high-x$_{Bj}$ pdf's at low Q^2 and evolves them down to moderate-and-low x at higher Q^2. This means that one of the larger contributions to background uncertainties at, for instance, LHC measurements will be the very poorly known high-x pdf's at the lower Q^2 values open to NuMI neutrino beams. MINERνA will sit in the optimal kinematic region and will yield the necessary statistics to start addressing this major concern.

Finally, it is important to note that the moments of structure functions are a subject of attention in lattice QCD simulations. Comparisons of the experimental moments with those calculated on the lattice over a range $Q^2 \approx$ 1–10 GeV^2 will allow one to determine the size of higher twist corrections and the role played by quark-gluon correlations in the nucleon. For the experimental moments, an appreciable fraction of the strength resides in the nucleon resonance region. Therefore, while a broad range in x is required at fixed Q^2 values to obtain the moments, precise resonance region data are imperative. Moreover, lattice calculations are in moments of pdf's as well as structure functions, requiring flavor decomposition. For all of these reasons, MINERνA will also provide a vital comparison with results from lattice QCD.

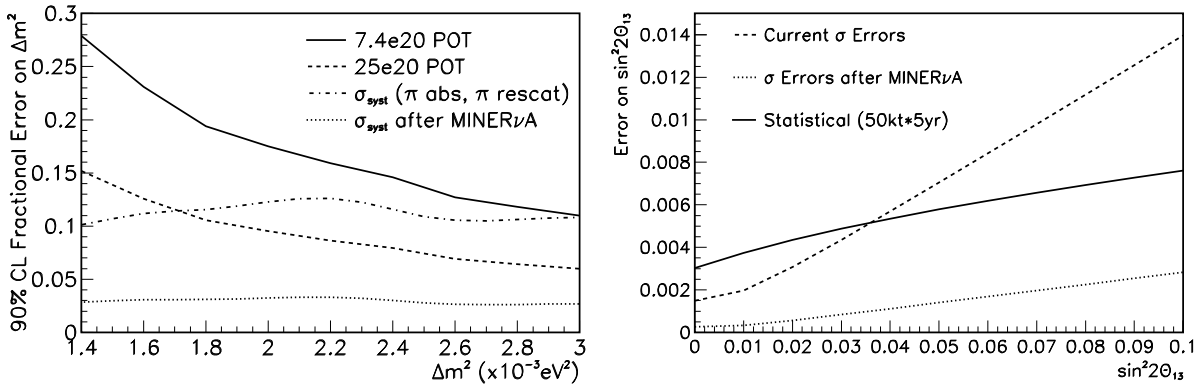

Figure 3: Left: Fractional size of the 90% confidence level region at $\sin^2 2\theta_{23} = 1$, assuming the uncertainties for nuclear effects are those described in the text, and assuming a 0.5 GeV muon momentum cut. Right: Statistical error, current cross section systematic errors, and post-minerva cross section systematic errors on NOνA measurement of $\sin^2 2\theta_{13}$ as a function of $\sin^2 2\theta_{13}$.

0.1.7 The Impact of MINERνA's Results on Neutrino Oscillation Studies

The MINERνA study of both nuclear effects and low-energy neutrino cross-sections has direct and important applications to neutrino oscillation experiments such as the MINOS ν_μ disappearance experiment and the future T2K and NOνA ν_e appearance experiments.

For the MINOS experiment, for a givien initial state neutrino energy, the final observed state may have a significantly lower visible energy [27, 28]. Since the determination of Δm^2 depends on knowledge of the **initial** E_ν, understanding this energy distortion is crucial for a precise Δm^2 determination. For the T2K and NOνA ν_e experiments, precise knowledge of the coherent and resonant π^0 background is essential. To better understand how MINERνA's results would help neutrino oscillation experiments, a preliminary quantitative study [29] has been performed.

Figure 3 shows two examples of how MINERνA can help oscillation experiments. The left plot shows the statistical error for MINOS on the Δm^2_{23} measurement as a function of Δm^2, as well as the systematic uncertainty assuming the current minimal knowlege of nuclear effects in neutrino scattering, given errors in both pion absorption and rescattering in the nucleus. The right plot shows the statistical and systematic error on $\sin^2 2\theta_{13}$ for NOνA as a function of $\sin^2 2\theta_{13}$. Two different systematic uncertainties are shown: one is assuming the current set of uncertainties on cross sections, the second is assuming the uncertainties expected after MINERνA runs.

It is clear from even these preliminary studies that the MINERνA experiment will play a very important role in helping the current and future precision oscillation experiments reach their ultimate sensitivity. In order to get the most precise values of Δm^2_{23} (which eventually is used to extract mixing angles and the CP-violating phase) we must must better understand and quantify the processes that occur between the interaction of an incoming neutrino and the measurement of outgoing particles in the detector. Extracting the mixing parameters such as θ_{13} and ultimately the neutrino mass hierarchy and CP violation requires much better understanding of resonant cross sections. Precise measurements of nuclear effects and exclusive cross sections will lay an important foundation for the study of neutrino oscillations that is in the middle of making order of magnitude leaps in both statistics and sensivitity.

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