MINERνA: A High-Statistics Neutrino Scattering Experiment using a Fine-Grained Detector in the NuMI Beam

Jorge G. Morfín[a]

[a]Fermi National Accelerator Laboratory,
P.O. Box 500, Batavia, IL,
60510

The NuMI Facility at Fermilab will provide an extremely intense beam of neutrinos making it an ideal place for high statistics (anti)neutrino-nucleon/nucleus scattering experiments. The MINERνA experiment at Fermilab is a collaboration of elementary-particle and nuclear physicists planning to use a fully active fine-grained solid scintillator detector. The overall goals of the experiment are to measure absolute exclusive cross-sections, nuclear effects in ν - A interactions and a systematic study of the resonance-DIS transition region including the extraction of high-x_{Bj} parton distribution functions at low Q^2.

1. Introduction

The upcoming neutrino oscillation experiments in the United States, Europe and Japan are driving the construction of new, very-intense neutrino beamlines required to achieve reasonable event rates at detectors located hundreds of kilometers away. These new beamlines will allow us to initiate a vigorous research program at a detector, located close to the production target, where event rates are much higher than at the previous generation of neutrino beam facilities. In addition, it is neutrino oscillation experiments, with their low-energy neutrinos and massive nuclear targets, which highlight the need for much improved knowledge of low-energy ν-Nucleus interactions.

At Fermilab, the new neutrino facility NuMI, designed for the MINOS neutrino oscillation experiment, will be based on the Main Injector (MI) accelerator. The neutrino beams from the MI yield several orders of magnitude more events per kg of detector and proton on target (POT) than the higher energy Tevatron neutrino beam. This highlights the major improvement of this next generation of neutrino experiments. One can now perform statistically significant experiments with much lighter targets than the massive iron, marble and other high-A detector materials used in the past. That these facilities are designed to study neutrino oscillations points out the second advantage of these neutrino experiments; an excellent knowledge of the neutrino beam will be required to reduce the beam-associated systematics of the oscillation result. This knowledge of the neutrino spectrum will also reduce the beam systematics in the measurement of neutrino scattering phenomena.

To take advantage of these major improvements in neutrino physics experimentation possible with the NuMI beam and facility, a collaboration of both elementary particle and nuclear physics institutions named MINERνA (Main Injector ExpeRiment: ν A) [1] has been formed. The collaborators from two Expressions of Interest (EOI) [2], which were submitted to the Fermilab PAC in December, 2002, have joined to prepare a full Proposal to be submitted to the Fermilab PAC in December, 2003.

2. The Fermilab NuMI Facility

The Fermilab NuMI facility is made up of the technical beamline components including target, two magnetic focusing horns, evacuated decay pipe, monitoring devices, shielding, the underground facilities to contain the beamline components and a large, on-site experimental detector hall ∼ 100 meters underground to contain the MINOS near detector. There is another, much more massive detector, 735 km away in Soudan, MN for oscillation studies by the MINOS experiment. The length of the target hall from target to decay pipe is 50 m, while the decay pipe and hadron absorber hall are 675 m long. Finally, there is a 240 m long dolomite (dirt) muon shield between the absorber and the near detector hall.

2.1. The NuMI Near Experimental Hall

This experimental hall is being constructed and completely outfitted for the MINOS near detector. The upstream end of the near detector hall is just over 1 km downstream of the target. The hall is 45 m long, 9.5 m wide and 9.6m high. There is a space upstream of the MINOS near detector amounting to, roughly, a cylinder 26 m long and 3m in radius for additional detector(s) which, were it desired, could use the MINOS near detector as an external muon identifier and spectrometer.

2.2. The NuMI Neutrino Beam

The neutrino energy distribution of the NuMI beam can be chosen by changing the distance of the target and second horn with respect to the first horn, as in a zoom lens. There are three standard configurations foreseen for the target and second horn called simply low-energy (le), medium-energy (me) and high-energy (he). The charged-current (CC) event rates for the three tunes are (per ton of detector and 10^{20} protons on target (POT)): le - 80K; me - 270K; he - 630K events. The neutrino energy distributions are shown in Figure 1. It is now expected that the Main Injector will deliver 2.5x10^{20} POT/year at the start of MINOS running, and build up to higher proton intensities if the necessary funds can be obtained. The CC event rates per ton (of detector) - year at startup of MINOS in 2005 and the possibly improved rate when a ν scattering experiment could control the beam are summarized in the following table:

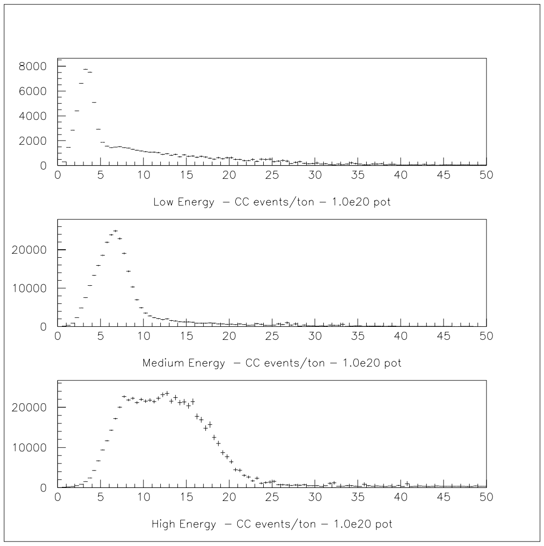

Figure 1. The neutrino event energy distribution for the three configurations of the NuMI beam corresponding to low-energy (le), medium-energy (me) and high-energy (he)

Event Rates per ton of detector per year

Beam	Total CC 2005	Total CC ∼ 2008/9
le	200 K	320 K
me	675 K	1080 K
he	1575 K	2520 K

To be conservative, for the rest of this paper event rates assuming **2.5x**$\mathbf{10^{20}}$ **POT/year** will be shown.

The energy of the beamline can also be chosen, essentially continuously, by simply varying the distance of target from the first horn and leaving the second horn fixed in the le position. These configurations are called "semi"-me/he beams. There is a loss of event rate with this procedure compared to also moving the second horn, and the most efficient energy tunes always will involve moving the second horn. For the MINOS experiment the beamline will be operating mainly in its lowest possible neutrino energy configuration to be able to reach desired low values of δm^2. However, to minimize systematics, there will also be running in the semi-me and semi-he configurations described above. For a possible MINOS running cycle consisting of 12 months le, 3 months semi-me and 1 month semi-he exposures, with the MI delivering 2.5x10^{20} POT/year, the sum would be order 430 K CC-events/cycle-ton. For a MINOS run consisting of two such cycles (32 months) the total CC event rate would be 860 K/ton. Of this rate, 140 K/ton would be quasi-elastic, 360 K/ton would be resonance/transition events and 360 K/ton would be deep-inelastic (DIS) with W $\geq$ 2 GeV and $Q^2 \geq 1.0$ GeV^2.

For a NuMI neutrino scattering experiment as prime user of the NuMI beam, the beamline would be run in the high-energy configuration with energies in the 5 - 25 GeV range. This configuration offers the ability to study neutrino interactions across an appreciable fraction of the x_{Bj} range at reasonable Q^2. With intensities of 1575 K CC events/ton, which is over a factor 100 more events than NuTeV, experiments could be performed on lighter targets with excellent statistics. A NuMI Neutrino Scattering Experiment, for example, running with the he-beam for a 1 year ν and a 2 years $\overline{\nu}$ period would accumulate 1575 K CC ν events/ton and 900 K CC $\overline{\nu}$ events/ton. Of these 900 K CC ν events/ton and 350 K CC $\overline{\nu}$ events/ton would be DIS.

The event rates for various scenarios are summarized in the following table giving events/ton-year where a "year" is defined as 2.5x10^{20} POT.

Event Rates per ton of detector

Run Period	Total CC	Elastic	DIS
MINOS: 3yr	860 K	140 K	360 K
he-ν: 1yr	1575 K	200 K	900 K
he-$\overline{\nu}$: 2yr	900 K	60 K	350 K

3. Neutrino Scattering Physics

A neutrino scattering experiment in the NuMI Near Experimental Hall will offer a unique opportunity to study a diverse array of physics topics. Most of these topics have either never been studied or the few results that do exist are plagued by large statistical and systematic errors. In addition to being significant fields of study in their own right, **many of these topics are essential to help minimize the systematics of neutrino oscillation experiments**.

- quasi-elastic neutrino scattering and associated form-factors
- the poorly studied resonance production region for both neutral-current and charged-current interactions,
- the intriguing region where resonance production becomes deeply inelastic scattering
- nuclear effects in neutrino-induced interactions. In particular energy loss and final-state modifications in heavy nuclei as well as the study of quark flavor-dependence of these effects.
- nuclear effects in the of determination of $\sin^2\theta_W$ via measurement of the ratio of NC / CC to check the recent surprising NuTeV result [10]
- parton distribution functions (pdf), particularly in the high-x_{Bj} region
- leading exponential contributions of pQCD
- charm physics including the mass of the charm quark (m_c) to an order of magnitude better accuracy than current values, V_{cd}, s(x) and, independently, $\overline{s}$(x)
- strange particle production for V_{us}, flavor-changing neutral currents and measurements of hyperon polarization
- nuclear physics studies with neutrinos complementary to JLab studies in the same kinematic range.

3.1. Low-energy ν Cross Sections

This is a topic of considerable importance to both present and proposed future (off-axis) neutrino oscillation experiments. The available measurements from early experiments at ANL, BNL, CERN and FNAL of both total and exclusive cross-sections all have considerable errors due to low statistics and large systematic errors, including lack of knowledge of the incoming flux [3]. A working group [4] to assemble all available data on ν and $\overline{\nu}$ cross sections and to determine quantitative requirements for new experiments has been established.

As will be discussed in the section on detectors, there is also growing interest in providing LH_2 and LD_2 targets for measurement of these cross sections off protons and neutrons in addition to nuclear targets such as C, Fe and Pb at the NuMI facility.

3.1.1. Resonance Production and Quark-Hadron Duality

As mentioned, there is very little data on neutrino resonance production. Neutrino monte carlo programs trying to cover this kinematic region have been using early theoretical predictions by Rein and Sehgal [5] or results from electro-production experiments. Recently Lee and Sato [6] have produced a model for the weak production of the Delta resonance. Paschos and collaborators [7] have also contributed to this study. Recent work at Jefferson Lab [8] shows strong support for quark-hadron duality which relates the average of resonance production cross sections to the F_2 structure function. How to incorporate this into neutrino monte carlos is currently being discussed. An analysis by Bodek and Yang [9] seems to offer a very promising procedure for fitting F_2 in the low Q^2-high x region. Extrapolating their results through the resonance region yields values of F_2 consistent with duality arguments and the Jefferson Lab results mentioned above.

3.2. Studying Nuclear Effects with Neutrinos

Nuclear effects in DIS have been studied extensively using muon and electron beams but have only been glanced at for neutrinos in low-statistics bubble chamber experiments. High statistics neutrino experiments have, to date, only been possible using heavy nuclear targets such as iron-dominated target-calorimeters. For these experiments, results from eμ - A analyses have been applied to the results. However, there are strong indications that the nuclear corrections for e/μ - A and ν - A are different. A neutrino scattering program at NuMI would provide experimental conditions where a systematic, precision study of these effects would be possible by using a variety of heavy nuclear targets as well as, eventually, H_2 and D_2 targets.

3.3. Strange Particle Production by ν and $\overline{\nu}$

As pointed out by Solomey [11] the measurement of both charged and neutral current strange particle production cross sections would yield new information on the six form factors as well as a very clean measurement of V_{us}. In addition, the search for strangeness-changing neutral currents (SCNC) is important as an indication of new physics. This experiment could significantly extend the limit on this process or, perhaps, discover evidence for the existence of SCNC. The question of hyperon polarization is still somewhat troublesome when comparing theory to experiment. The production of hyperons by neutrinos would yield new more accurate information on hyperon polarization with a very different set of systematic errors.

3.4. Extracting Parton Distribution Functions

Neutrinos have long been a particularly successful probe of nucleon structure. One of the obvious reasons for the significance of neutrino results in the extraction of parton distribution functions is the neutrino's ability to directly resolve the flavor of the nucleons constituents: ν interacts with d, s, $\overline{u}$ and $\overline{c}$ while the $\overline{\nu}$ interacts with u, c, $\overline{d}$ and $\overline{s}$. This unique ability of the neutrino to "taste" only particular flavors of quarks enhances any study of parton distribution functions. The study of the partonic structure of the nucleon, using the neutrino's weak probe, would complement the on-going study of this subject with electromagnetic probes at Jlab as well as earlier studies at SLAC, CERN and FNAL.

The QCD evolution of parton distribution functions takes high-x pdf's at low Q and evolves them down to moderate-and-low-x at higher Q. This obviously means that one of the larger contributions to background uncertainties at LHC measurements will be the very poorly known high-x pdf's at the lower Q values open to NuMI neutrino beams. The current problem is accumulating sufficient statistics at high-x off of light targets to extract the pdf's. The NuMI beam will yield the necessary statistics to start addressing this major concern.

With the high statistics foreseen at NuMI as well as the special attention to minimizing neutrino beam systematics, it should be possible for the first time to determine the separate structure functions $2F_1^{\nu N}(x,Q^2)$, $2F_1^{\bar{\nu} N}(x,Q^2)$, $F_3^{\nu N}(x,Q^2)$ and $F_3^{\bar{\nu} N}(x,Q^2)$ where N is an isoscalar target including, eventually, deuterium.

If we concentrate on the region of high x, the uncertainties in current nucleon parton distribution functions are of two types: the ratio of the light quark pdf's, $d(x)/u(x)$, as $x \rightarrow 1$ and the role of leading power corrections (higher twist) in the extraction of the high x behavior of the quarks.

Analyses of present leptoproduction data sets that used hydrogen and deuterium targets have been unable to **precisely** pin down the high-x behavior of $d(x)/u(x)$. An analysis by Bodek and Yang [12] indicated that the $d(x)/u(x)$ quark ratio approaches 0.2 as $x \rightarrow 1$. However global QCD analyses of experimental results, such as the CTEQ fits [15], do not indicate the need for this higher value of $d(x=1)/u(x=1)$. Besides the statistical and experimental uncertainties in the existing data sets, a complication with past analyses was the need to model nuclear binding effects in the deuterium target which was used. These issues could be avoided with a high statistics exposure to a H_2 target which could directly measure the $d(x)/u(x)$ ratio in protons as $x \rightarrow 1$ from the ratio of neutrino-proton to antineutrino-proton cross sections. Such a measurement would require only a small correction for the residual sea quark contributions at high x.

The measurement of quark densities at high x is closely related to the question of the leading power corrections known as "higher twist effects". The n^{th} order higher twist effects are proportional to $1/Q^{2n}$ and reflect the fact that quarks have transverse momentum within the nucleon and that the probe becomes larger as Q^2 decreases, thus increasing the probability of multi-quark participation in an interaction. As was the case with the d/u ratio, different analyses of higher twist corrections in current data leave some unresolved issues that would benefit from new experimental information.

The only actual measurements of higher-twist term in neutrino experiments have been two low-statistics bubble chamber experiments: in Gargamelle [16] with freon and in BEBC [13] with NeH_2. Both bubble chamber analyses are complicated by nuclear corrections at high-x. However, both analyses found a twist-4 contribution that is smaller in magnitude than the charged leptoproduction analysis and, most significantly, is preferentially negative.

4. A Staged Detector Concept

The detector studies for a dedicated NuMI ν scattering experiment are being carried out by the MINERνA collaboration. In order to perform the full spectrum of physics outlined in this paper, the target/detector must eventually be able to:

- identify muons and measure their momentum with high precision
- identify individual hadrons and π^0 and measure their momentum
- measure the energy of both the hadronic and electromagnetic shower with reasonable precision
- minimize migration of neutral-current $\leftrightarrow$ charged current event classifications
- accommodate other nuclear targets.

These goals can be met in a staged approach to detector development and installation. For initial running in a parasitic mode with the MINOS experiment and a subsequent run with a he ν exposure, the physics goals can be met by a comparatively compact active target/detector [14] consisting of a central section of essentially solid scintillator bars. This central detector is surrounded on all sides by an electromagnetic calorimeter, a hadronic calorimeter and a magnetized muon-identifier / spectrometer. The detector would have the approximate overall shape of a hexagon (to enable 3 stereo views) with 4 m across-section and 3m length. The fiducial volume would be 3 tons of scintillator. At the upstream end of the detector would be nuclear targets consisting of 1-2 tons of C, Fe and Pb. Significant granularity and vertex-reconstruction accuracy can be achieved by the use of triangular shaped plastic scintillator(CH) bars with 3 cm base, 1.5 cm height and length up to 4.0 m with a fiber down the center of the bar for readout. Recent work at the Fermilab Scintillator R&D Facility has shown that using light division across triangularly shaped scintillator strips of this size can yield measuring precisions of a few mm. The orientation of the scintillator strips are alternated so that tracking can be performed. .

Following the downstream end of the central detector would be an electromagnetic calorimeter. The MINERνA detector would be placed as close as possible to the upstream face of the MINOS near detector in order to use the magnetic field and steel of the MINOS near detector as a muon identifier and spectrometer for the energetic forward going muons and hadron energy leaving the MINERνA detector.

With such a detector, for the initial multiple-energy MINOS run mentioned earlier, two such cycles ($\sim$ 3 years running) would result in **2.6 M events** in the fiducial volume of the scintillator while for a 1 year he-configuration ν run, the corresponding statistics would be **4.9 M events**.

The statistics from the first 3-year MINOS run would be adequate to perform many of the physics topics listed in this paper although some would be limited by the kinematic reach of the neutrino beam energies used for MINOS running. In addition, all studies involving $\overline{\nu}$ statistics would be somewhat limited with the currently envisioned MINOS exposure, which has minimal $\overline{\nu}$ running.. To realize the **full potential** of the NuMI facility for a ν scattering experiment, the impressive statistics and kinematic reach of a he-beam ν and $\overline{\nu}$ runs would be required.

In a subsequent stage it would be most beneficial, for all physics topics of interest, to have a low-A target, preferably H_2 or D_2. An investigation of the technical and safety challenges of such a target is currently underway at Fermilab and a report [17] indicates that there are no real technical challenges in fabricating or efficiently operating a large LH_2 or LD_2 target. The main effort (and expense) for such a facility would be in satisfying safety requirements. For a fiducial volume with r = 80 cm. and l = 150 cm. we would expect 350 K CC events in LH_2 and 800 K CC events in LD_2 per year of he-ν running.

REFERENCES

1. The MINERνA Collaboration consists of groups from the following institutions: Argonne National Lab, U Athens, U California/Irvine, U Colorado, U Dortmund, Duke U, Fermilab, Hampton U, IL Inst. Tech., Inst. for Nuc. Research - Moscow, James Madison U, Jefferson Lab, U Minnesota, U Pittsburgh, U Rochester, Rutgers U, U S. Carolina, Tufts U.
2. The two EOIs combined to form the MINERνA proposal can be found on the MINERνA home page at: http://www.pas.rochester.edu/ ksmcf/minerva/
3. A. Vovenko, "Total cross sections and structure functions for neutrino interactions in 3-30 GeV energy range and near plans for 1-5 GeV energy range", submitted to the Proceedings of NuInt01 : The First International Workshop on Neutrino-Nucleus Interactions in the Few GeV Region, (2002).
4. A recent working group coordinated by Hugh Gallagher and Costas Andreopoulos is attempting to gather all existing neutrino scattering data.
5. D. Rein and L. M. Sehgal, Annals Phys. **133**, 79 (1981).
6. T. S. Lee and T. Sato Few Body Syst. Suppl. **15**, 183 2003
7. E. A. Paschos, L. Pasquali and J. Y. Yu, Nucl. Phys. B **588**, 263 (2000) and E. A. Paschos, J. Y. Yu and M. Sakuda hep-ph/0308130.
8. S. Wood, "Resonance Region to DIS, Quark-

Hadron Duality", submitted to the Proceedings of NuInt01 : The First International Workshop on Neutrino-Nucleus Interactions in the Few GeV Region, (2002).

9. A. Bodek and U. K. Yang, arXiv:hep-ex/0203009.
10. G. P. Zeller *et al.* [NuTeV Collaboration], Phys. Rev. Lett. **88**, 091802 (2002) [arXiv:hep-ex/0110059].
11. N. Solomey, "Physics prospects with an intense neutrino experiment," arXiv:hep-ex/0006021 and "Neutrino Interactions-Strange Particle Production", contribution to the Workshop on New Initiatives for the NuMI Neutrino Beam, Fermilab, 2002.
12. U. K. Yang and A. Bodek, Phys. Rev. Lett. **82**, 2467 (1999) [arXiv:hep-ph/9809480].
13. K. Varvell *et al.* [BEBC WA59 Collaboration], Z. Phys. C **36**, 1 (1987).
14. The original design of this "pure scintillator" detector resulted from a study for physics at Fermilab with a new high-intensity booster. J. Arrington, R. Holt, D. Potterveld and P. Reimer from Argonne National laboratory, along with the author, were involved in the original concept of this detector.
15. H. L. Lai *et al.*, Phys. Rev. D **51**, 4763 (1995) [arXiv:hep-ph/9410404].
16. H. Deden and et al., [Gargamelle Neutrino Collaboration], "Experimental Study Of Structure Functions And Sum Rules In Charge Changing Interactions Of Neutrinos And Anti-Neutrinos On Nucleons," Nucl. Phys. **B85**, 269 (1975).
17. J. Kilmer and T. J.Sarlina, "Technical and Safety Considerations of Large Cryogenic Liquid Targets at the NuMI Near Hall" contribution to the Workshop on New Initiatives for the NuMI Neutrino Beam, Fermilab, 2002