The MINERvA Neutrino Scattering Experiment at Fermilab

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Abstract. The MINERνA experiment at Fermilab is aimed at precision measurements of neutrino interactions in nuclei for energies up to a few GeV. MINERνA makes use of a fine-grained, fully active detector design and a range of nuclear target materials. The experiment began taking data in the NuMI neutrino beam at Fermilab in late 2009 and will collect data in both the neutrino and antineutrino configurations of the beamline.

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INTRODUCTION

MINERνA is a dedicated neutrino-nucleus scattering experiment currently running at the Fermi National Accelerator Laboratory, positioned just upstream of the MINOS near detector, in the Neutrinos from the Main Injector (NuMI) beamline [1]. The goal of the experiment is high-statistics, absolute measurements of inclusive and exclusive interaction rates for neutrinos and antineutrinos in the 1–20 GeV energy range. Further, by measuring rates on different atomic nuclei, from helium to lead, in the same detector and beam, MINERνA will be able to study nuclear effects in neutrino interactions.

The discovery of neutrino mass and mixing has led to an ambitious worldwide program of long baseline neutrino oscillation experiments. To increase event rates, especially over long baselines, these neutrino detectors tend to be composed of heavier nuclear targets such as carbon, oxygen, or iron. Precision measurements of oscillation parameters require an accurate reconstruction of the incoming neutrino energy from the visible energy left by charged particles created when the neutrino scatters off a nucleon within a nucleus in the detector. However, our understanding of basic neutrino-nucleus interactions is incomplete and this directly impacts how well we can measure oscillation effects. Detailed knowledge of inclusive and exclusive neutrino-nucleus cross sections and final state interactions within the target nucleus are important for determining the incoming neutrino energy and separating backgrounds from oscillation signal events.

Beyond the impact of effects in the dense nuclear medium for interpreting oscillation data, neutrinos offer a unique weak force probe for studying the structure of nuclear matter itself. Using its range of nuclear target materials, MINERνA will measure inter-

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[1] http://minerva.fnal.gov

action rates as a function of atomic mass (A) yielding the ratio of structure functions off nuclei. With this data, global fits will be able to extract nuclear parton distribution functions (nPDFs) of nucleons within a nucleus.[2] These data will be complimentary to the wealth of charged lepton scattering data off nuclei currently available.

THE MINERνA DETECTOR

To achieve the physics goals of the experiment, the MINERνA detector design has incorporated several basic features. Multiple nuclear targets were incorporated in such a way that events originating in different targets have similar acceptance in the detector. The detector has fine granularity in order to clearly identify the exclusive final states that create signals and backgrounds in coarse-grained oscillation detectors and to provide sufficient tracking resolution for resolving the target nuclei in interactions. Finally, the detector must be large enough in transverse extent (including side calorimetry) to contain the energy in an interaction for an accurate total energy measurement.

The MINERνA detector is comprised of 120 modules hung vertically and stacked along the beam direction. The modules are hexagonal in shape with an inner portion of segmented scintillator planes surrounded by an outer steel support frame. This frame is 56 cm wide and partially instrumented with scintillator to also serve as a containment calorimeter for hadrons. The majority of these modules contain two layers of segmented scintillator planes in different orientations (vertical, $\pm 60°$). Each plane is composed of 127 strips of extruded polystyrene scintillator that are triangular in cross section (17.0 mm height × 33.4 mm base). The triangular shape ensures energy deposition in two strips per plane for most particle paths, improving the position resolution of the reconstruction. A 1.2 mm diameter green wavelength shifting fiber down the middle of each strip guides the generated light to a single pixel of a 64 anode PMT. In the downstream portion of the detector, 10 modules also contain two lead sheets that are each 2 mm thick to provide electromagnetic calorimetry, and in the last 20 modules one plane of scintillator per module has been replaced by a 1 inch thick steel plate to serve as a hadronic calorimeter. Figure 1 shows a schematic drawing of the MINERνA detector. The MINOS detector, located just downstream of MINERνA and serving as a muon spectrometer for our reconstruction, is indicated in the figure as well.

Figure 2 shows a sample event display of a charge-current neutrino interaction occurring in the fully-active tracker region of MINERνA. The three orientations of scintillator planes (referred to as the X, U, and V views, respectively) are shown separately. The muon created in the interaction can be seen exiting the back of the detector where it enters the MINOS near detector and its energy and charge are measured. The multiple hadron tracks created in the interaction are contained within the MINERνA inner region or stopped in the outer calorimeter.

Distributed among fully-active modules in the upstream portion of the detector are 5

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[2] A proposal has recently been submitted to include running with a deuterium target in MINERνA as well, yielding A to deuterium structure function ratios and allowing the study of free-nucleon PDFs using neutrinos.

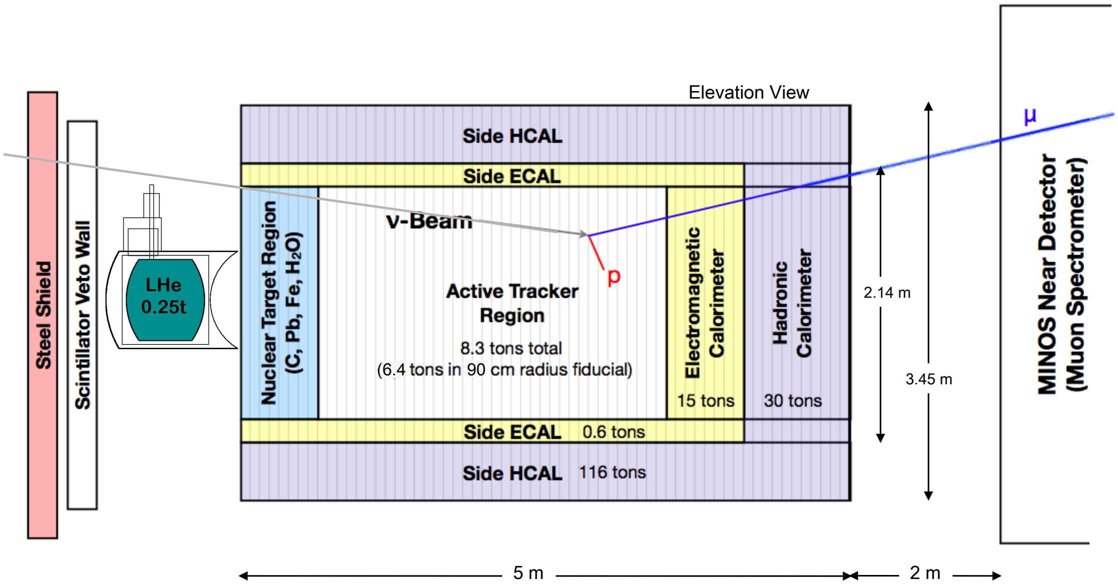

FIGURE 1. Schematic section view of the MINERνA detector. The beam enters from the left at a downward angle of about 3 degrees. The nuclear targets, both cryogenic and solid, are located at the front of the detector followed by a fully-active, finely-segmented scintillator region. The electromagnetic and hadronic calorimeter portions of the detector are indicated.

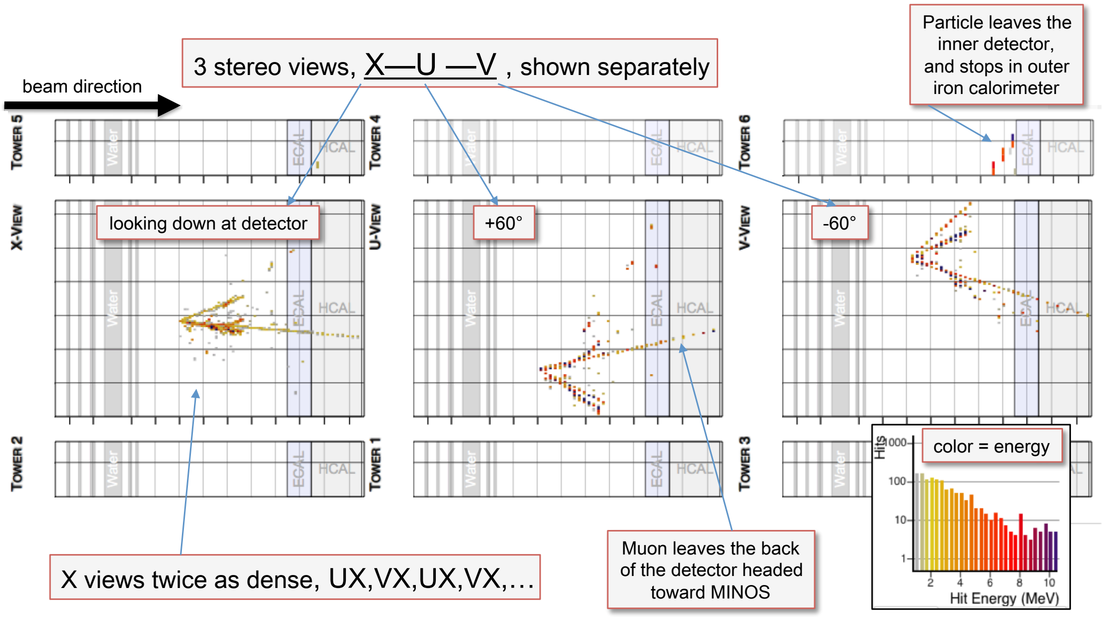

FIGURE 2. MINERνA detector event display showing a charged-current interaction candidate from data. The three orientations of planes (X,U,V) are shown in separate panels. Hits in the inner fully-active and outer calorimeter regions of the detector are shown. The amount of energy deposited in each strip is indicated by the color.

TABLE 1. Nuclear target masses in MINERνA.

Target	Fiducial Mass*
Polystyrene Scintillator (C_8H_8)	6.43 tons
Helium	0.25 tons
Carbon (graphite)	0.17 tons
Iron	0.97 tons
Lead	0.98 tons

* within a 90 cm radius cylinder

planes of solid nuclear targets. Their locations are indicated in Fig. 2 by the thin grey bands in the front 1/3 of the detector. Recently installed upstream of the first module is a cryogenic tank that will be filled with liquid helium[3]. Table 1 shows the masses of each nuclear material within a 90 cm radius cylinder along the axis of the detector. Also, as indicated in Fig. 2, space has been reserved to install a thin tank of water in the future.

RUN PLAN AND STATUS OF DATA TAKING

The MINERνA data taking plan includes two distinct periods. Currently, the experiment is running in the "low-energy" phase. After a modification of the NuMI complex, the neutrino flux will shift to higher energies and higher intensity for the NOνA [2] oscillation experiment beginning in 2013. The different fluxes are shown according to the NuMI beamline Monte Carlo simulation in the left panel of Fig. 3. The exposure goals of the experiment are:

- 4.0×10^{20} protons on target in the current, low-energy, neutrino beam configuration
- 12.0×10^{20} protons on target in the higher-energy beam configuration during NOνA running
- 0.9×10^{20} protons on target of variable beamline configuration data for performing studies of the neutrino flux [3]

The right panel of Fig. 3 shows that, through February 2011, approximately equal exposures, 1.2×10^{20} protons on target, in the neutrino and antineutrino beams have been collected. Table 2 lists the number of expected charged-current interactions in this data set according to the Monte Carlo simulation.

DETECTOR CALIBRATION AND TRACK RECONSTRUCTION

The purpose of the fully-active, fine-grained detector design for MINERνA is to enable the identification of particular exclusive final states and to achieve excellent position and energy resolution when reconstructing neutrino interactions.

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[3] The cryogenic target was not installed during the November, 2009 to February, 2011 data taking period.

TABLE 2. Charged-current event rates in MINERνA for the listed exposures in neutrino mode and antineutrino mode running of the NuMI beamline. The rates listed were determined using the GENIE [4] neutrino event generator (version 2.6) and do not include corrections for reconstruction efficiencies or acceptance in MINERνA.

	1.2×10^{20} POT LE ν mode	**1.2×10^{20} POT LE $\bar{\nu}$ mode**
Total Charge-Current Events:		
Scintillator	409k	134k
Graphite	11k	5k
Iron	65k	20k
Lead	68k	17k
Events by channel in scintillator:		
Deep inelastic scattering*	167k	19k
Resonance production	146k	62k
Quasi-elastic	84k	46k
Coherent pion production	4k	3k

* Defined as $Q^2 > 1, W > 2$

To achieve these goals, a detailed chain of energy calibration steps are carried out for all data. Readout channel pedestals and individual PMT channel gains are monitored continuously through the run using a sample of unbiased triggered events recorded between neutrino beam spills and an *in situ* light injection system, respectively. The signal attenuation was mapped out along the full length of each scintillator strip in the detector using a gamma-ray source prior to installation; these measurements are used to correct the signals read out at the end of each strip during data taking.

The NuMI beamline supplies a useful *in situ* calibration sample. Neutrinos undergoing charged-current interactions in the rock surrounding the detector hall create muons which can enter the detector. Since the beginning of data-taking, well over 1 million of

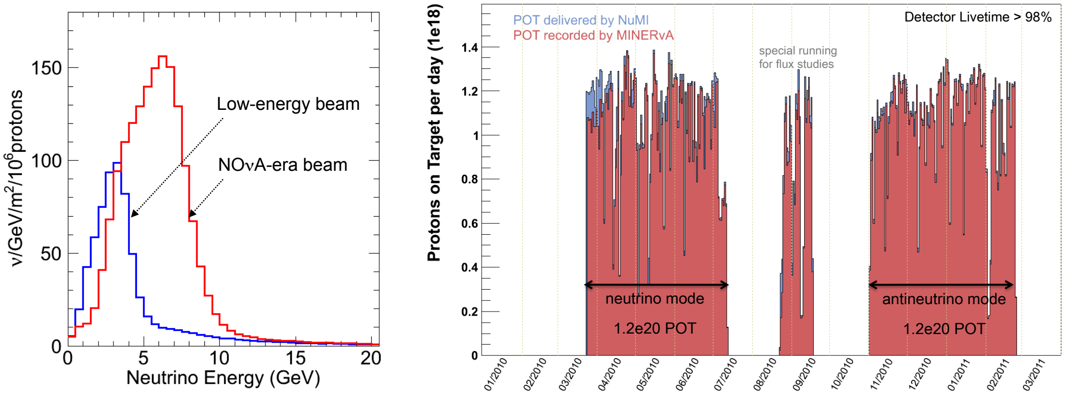

FIGURE 3. Predicted neutrino flux at the MINERνA detector in the current, low-energy configuration of the NuMI beamline (blue) and the higher energy beam configuration to be used during shared running with NOνA (red) starting in 2013 (left). Protons on target delivered to the NuMI beamline during the MINERνA run between March, 2010 and February, 2011, all in the low-energy beam (right).

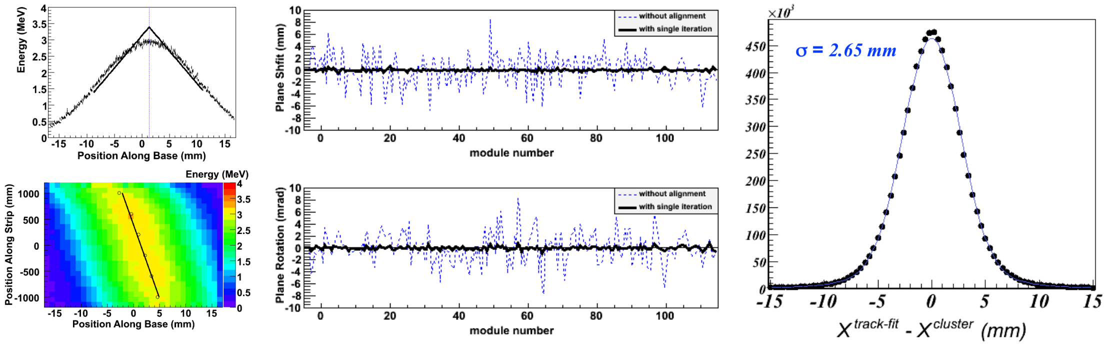

FIGURE 4. Detector alignment and tracking position resolution. The left column demonstrates the method of using the relationship between the signal pulse height and the track path length to measure the offset and rotation of each plane. The center figures show the measured detector offsets (blue curves) and the result of applying the detector alignment corrections using this method (black curves). The right panel shows the position resolution along muon tracks using the Kalman Filter and after detector alignment, σ = 2.65 mm.

these "rock muons" have passed though MINERνA. This sample of minimum ionizing tracks can be used to measure any remaining variation in the energy response of the 27,178 scintillator strips in the inner detector as well as to tune the overall energy scale in the reconstruction.

Scintillator planes in MINERνA are arranged in a UX-VX-UX-VX... pattern throughout the detector. The z-direction is taken to be along the axis of the detector from the upstream to the downstream end with respect to the neutrino beam. Therefore, the set of planes in each view provide a 2-dimensional path measurement for any charged particle passing through a sufficient portion of the detector along the detector axis (XZ, UZ, or VZ). The 2D segments can then be merged to form the 3-dimensional path of the particle. A Kalman Filter [5] approach is used to determine the track parameters at each point along the path. The tracking efficiency for muons is $> 95\%$ using this method.

The rock muon sample described above has also been used to measure the relative shifts and rotations of the 214 scintillator planes as installed in the detector. Taking advantage of the triangular shape of the strips, we can use the relationship between the pulse height of the signal recorded and the path length of the fitted muon track passing through that strip. Expecting the largest pulse height to be at the center of each strip, one can measure any offset from the nominal position in the geometry description of the detector. Figure 4 shows an example of this technique for one plane in the upper left panel. Dividing each plane into six regions along the length of the strips, one can repeat this measurement in each region and clearly see small rotations of each plane away from the nominal orientations (0°, ±60°). This is shown for one plane in the lower left panel. The measured plane shifts and rotations before and after applying the correction to the geometry description are shown in the center panels. These corrections result in a tracking position resolution better than 3 mm along muon tracks as indicated in the right panel of Fig. 4 showing the residuals between fitted track positions and the measured cluster locations.

This high resolution, high efficiency muon track reconstruction is already being used to study charged-current neutrino interactions in the iron and lead nuclear targets [6] and charged-current quasi-elastic antineutrino interactions in the plastic scintillator [7]. Both of these analyses have been presented at this workshop.

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