Status of the MINERνA Experiment at Fermi National Laboratory

Vittorio Paolone
On behalf of The MINERνA Collaboration[a]

Department of Astronomy and Physics, University of Pittsburgh,
Allen Hall, 3941 O'Hara St.
Pittsburgh, PA 15213, U.S.A.
E-mail: paolone@fnal.gov

ABSTRACT

MINERνA is a detector designed to precisely study ν-nucleus interactions in the 1-20 GeV energy range in the NuMI high-intensity neutrino beam at the Fermi National Accelerator Laboratory. MINERνA will improve our knowledge of neutrino cross sections at low energy and low Q^2, and of the A-dependence in interactions. These data will be interesting in their own right, and will be important to reduce systematic errors in oscillation experiments. Preliminary results for anti-neutrino Charged Current Quasi-Elastic interactions are presented.

1. Introduction

MINERνA (**M**ain **IN**jector **E**xperiment for **ν-A**) is a few-GeV scattering experiment at Fermilab, optimized to study neutrino interactions across a variety of scattering regimes and target A values in the intense NuMI (Neutrinos at the Main Injector) beam. Large statistics data samples with active high resolution tracking combined with calorimetry will allow cross-section measurements with improved precision to advance low-energy neutrino physics in general, and provide input to neutrino interactions for long baseline oscillation experiments in particular.

2. Motivation

Neutrino oscillation physics is now in an era of precision measurements. Most accelerator based neutrino oscillation experiments employ neutrino beams with energies in the 1-20 GeV range. It is precisely in this regime where neutrino cross sections are poorly measured. Previous measurements suffered from both low statistics and large uncertainties on the flux, resulting in large systematic errors for absolute cross sections. Therefore MINERνA results will be important for present and future neutrino oscillation experiments, where cross-sections, final state topologies, and nuclear effects are all important in calculating incoming neutrino energy and in separating backgrounds from the oscillation signal. Recall that oscillation probability depends

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

on E_ν, the neutrino energy. For a ν_μ disappearance experiment, the two-flavor disappearance relation is show in Eq. 1:

$$P\left(\nu_\mu \rightarrow \nu_\mu\right) = 1 - \sin^2\left(2\theta_{23}\right)\sin^2\left(\frac{1.27\Delta m_{23}^2(eV^2)L(km)}{E_\nu(GeV)}\right) \quad (1)$$

To extract Δm^2, experiments must measure the correct energy of the interaction. Visible energy however is a function of flux, cross-section, and detector response. In addition because the neutrino interacts in dense nuclear matter, final state interactions (absorption, re-scattering and re-interactions) play a significant role in the observed final state particles. For appearance type neutrino oscillation experiments such as $\nu_\mu \rightarrow \nu_e$ searches, background processes producing electromagnetic final states must be understood. Specifically the NC π^0 production cross sections on varying A target materials and the intrinsic ν_e content of the beam will need to be measured.

3. MINERνA Detector

The MINERνA detector shown in Fig. 1, is a fine-grained tracking calorimeter with a fully active solid-scintillator Tracker forming the bulk of the Inner Detector (ID). Upstream of the Tracker is an area of nuclear targets - He (not shown), carbon, iron, and lead, interleaved with tracking planes. The downstream part of the ID contains Electromagnetic CALorimeter (ECAL) and Hadronic CALorimeter (HCAL). The ID is surrounded by side ECAL and side HCAL. The downstream MINOS Near Detector will serve as a muon spectrometer for MINERνA. A summary of the detector capabilities are:

- Good tracking resolution (∼3 mm).
- Calorimetry for both charged hadronic particles and EM showers.
- Timing information (few ns resolution).
- Containment of events from neutrinos less than 10 GeV (except muon).
- Muon energy and charge measurement from MINOS.
- Particle ID from dE/dx and energy+range (no charge determination except muons entering MINOS).

The active detector elements are solid-scintillator strips of triangular cross-section (3.3 cm base, 1.7 cm high), arranged in planes where neighboring strips alternate orientation with respect to the beam. Charge sharing between neighboring strips allows one to achieve a spatial resolution of ∼3 mm as shown in Fig. 2. Scintillation light due to a charged particle traversing the scintillator is collected by a wavelength

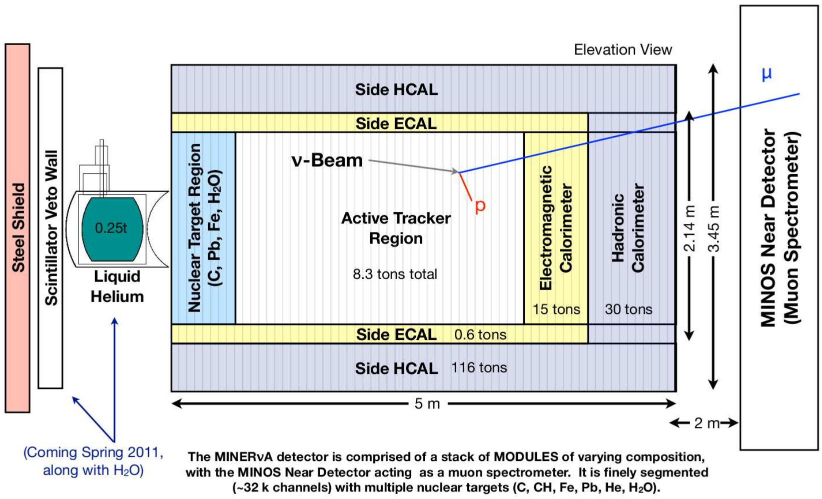

Figure 1: Schematic of the MINERνA detector.

shifting fiber located at the center of each strip, and routed through clear optical fibers to M64 Hamamatsu photo-multiplier tubes (PMT). The electrical signals from Front End Boards mounted on top of each PMT box are readout via the data acquisition system. The detector consists of hexagonal modules containing one or two active planes mounted on a steel frame. The orientation of strips in the planes can be vertical (X), +60 (U), or -60 (V) (see Fig. 3). Four types of modules were built: (i) tracker modules, strip orientations X+U, X+V; (ii) ECAL with Pb+X+U, Pb+X+V (0.2 cm thick Pb sheets); (iii) HCAL with Fe+X, Fe+U, Fe+V (2.54 cm thick steel plates) and (iv) Target modules of differing A values as shown in table 1. All modules were scanned with Cs-137 source in order to measure position of all strips, to obtain the attenuation curve for each strip, and to localize anomalies in the response of the scintillator/fiber system.

3.1. FNAL NuMI Beamline

MINERνA utilizes the intense NuMI (Neutrinos at the Main Injector) beam running at FNAL. FNAL's Main Injector accelerates protons up to 120 GeV which then impinge onto a carbon target with 35×10^{12} protons on target(POT) per spill. The spill repetition rate is $\sim$0.5 Hz and hence a beam power of 300-350 kW is generated. The pions produced by the proton interactions on the carbon target are focused by two horns and allowed to decay in a 675 meter decay pipe. Undecayed pions are absorbed in the hadron absorber just downstream of the decay region and the decay muons are absorbed in the following 240 meters of rock before reaching the detec-

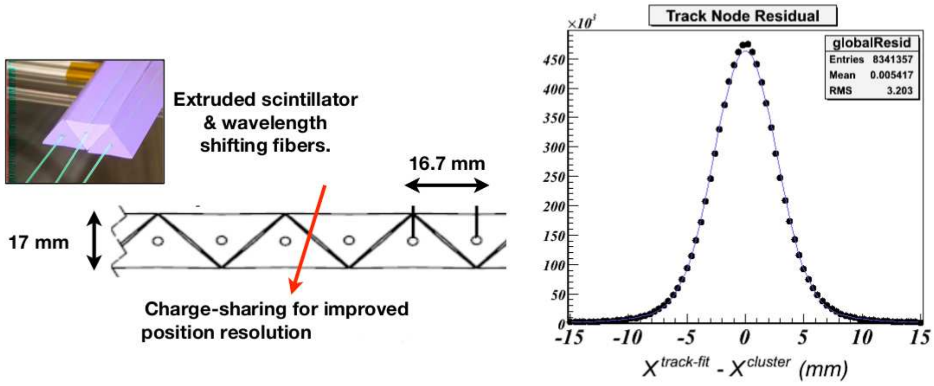

Figure 2: Shown is the triangular scintillator strip arrangement. Groups of 127 strips form a plane. Tracking residuals between a fitted position along a track and the charge-weighted hit in that plane for a sample of through-going muons is also shown. The fitted sigma for the residuals is 2.65 mm.

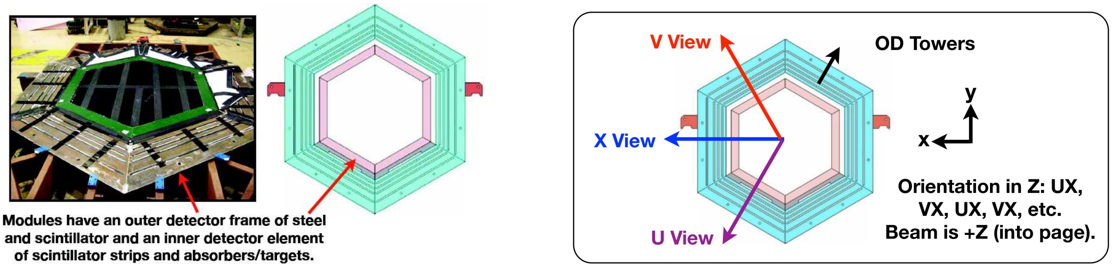

Figure 3: Plane structure is illustrated at the left. The three orientations for strips in scintillator planes are "U" , where the strips are oriented perpendicular to $-\left(60^0\right)$, "X" (strips oriented vertically), and "V", where the strips are oriented perpendicular to $\left(60^0\right)$.

Table 1: MINERνA nuclear targets: types and masses. The scintillator tracker mass includes the full longitudinal span. For most analyzes, the fiducial mass will be approximately five tons.

Target	Fiducial Mass (90 cm radius cut)
Scintillator Tracker (CH)	6.43 tons
Carbon (Graphite)	0.17 tons
Helium	0.25 tons
Water	0.35 tons
Iron	0.97 tons
Lead	0.98 tons

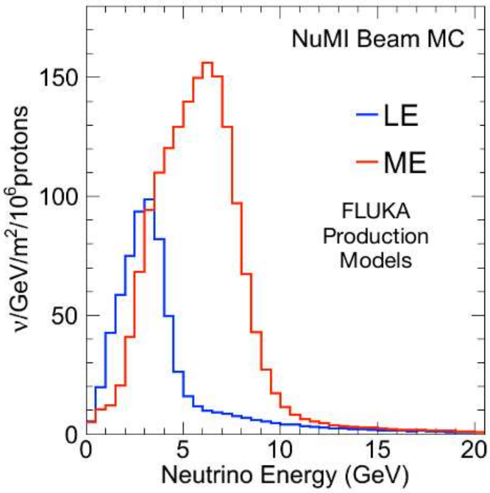

Figure 4: Neutrino Spectra for the Low Energy (LE) and Medium Energy (ME) beam tunes.

tor hall. Extensive instrumentation is used to monitor the proton, produced hadron and muon beams. Different energy tunes are available by varying the location of target and horns. The two main configurations are know as the Low Energy (LE) and Medium Energy (ME) beam tunes. The neutrino energy spectra for both the LE and ME beam are shown in Fig. 4. In addition the NuMI target is mounted on a rail drive for variable positioning and therefore allowing for easy energy tuning. NuMI also allows for neutrino or anti-neutrino beam running by sign selecting pions by setting the magnetic horn current direction.

The total error on absolute cross section measurements will be dominated by the systematic error on the determination of the neutrino flux. Past experiments in wide band beams were limited by $\sim$30% uncertainties in flux. One of the largest uncertainties when estimating the neutrino flux is the hadron production spectra at the target. By utilizing the NuMI neutrino energy tuning of the beam-line, it is possible to fit for the various hadron production parameters in the MC. This can be done by

Table 2: Charged-current inclusive event rates in the current data sample. (GENIE 2.6.2 Generator raw events, not acceptance corrected.)

Material	1.2×10^{20} POT (LE ν Mode)	1.2×10^{20} POT (LE $\bar{\nu}$ Mode)
Coherent Pion Production	4k	3k
Quasi-Elastic	84k	46k
Resonance Production	146k	62k
Deep Inelastic Scattering	168k	19k
Carbon Target	10.8k	3.4k
Iron Target	64.5k	19.2k
Lead Target	68.4k	10.8k
Scintillator (CH) Tracker	409k	134k

varying the focusing horn current (to focus pions of different P_T) and by varying the position of the target (to focus pions of different $x_F = P_Z/P_T$). MINERνA's goal is to achieve a 7% error in flux shape and a 10% error in absolute normalization.

4. Data Collection Timeline

MINERνA began taking neutrino data with the full detector in March 2010. At this time the NuMI beam line was set in the forward horn current (FHC) low energy mode, focusing π^+ mesons therefore producing a neutrino beam. A total of 1.2×10^{20} POT were recorded during this period. Reversing the horn current (RHC) focuses π^- mesons and therefore produces the anti-neutrino beam. Presently (as of March 2011) another 1.2×10^{20} POT of low energy anti-neutrino data has been collected. Starting in May 2011, MINERνA will resume low energy neutrino running. Before taking data in March 2010, and when the fraction of the assembly of the detector reached 55% (Frozen Detector), an initial anti-neutrino run of 0.8×10^{20} POT was recorded. Preliminary results from this run will be presented here. Table 2 shows raw MC event generator estimates for the event rates in the collected full detector data samples. Our MC event generator is GENIE 2.6.2 [b]. For the future, the run plan in neutrino mode is 4.9×10^{20} POT in the low-energy (LE) beam configuration (March, 2010 to mid 2012) and 12×10^{20} POT in medium-energy (ME) mode (beginning in 2013).

4.1. Detector Performance

Since November 2010 detector live-time has been in excess of 98% as shown in

[b] GENIE, http://www.genie-mc.org 2011

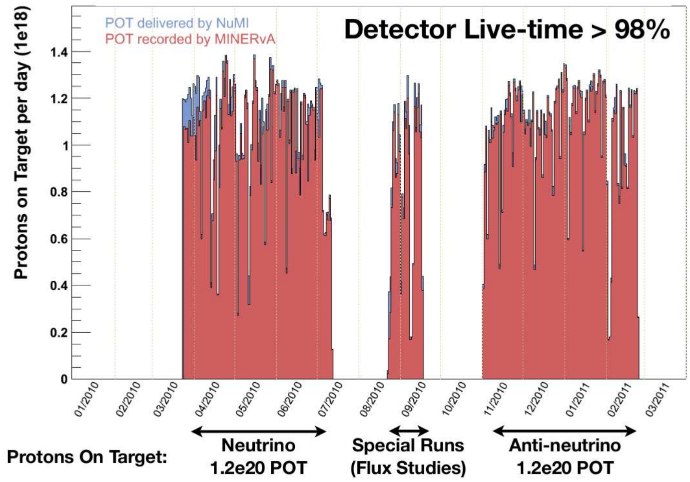

Figure 5: Detector live-time as a function of time.

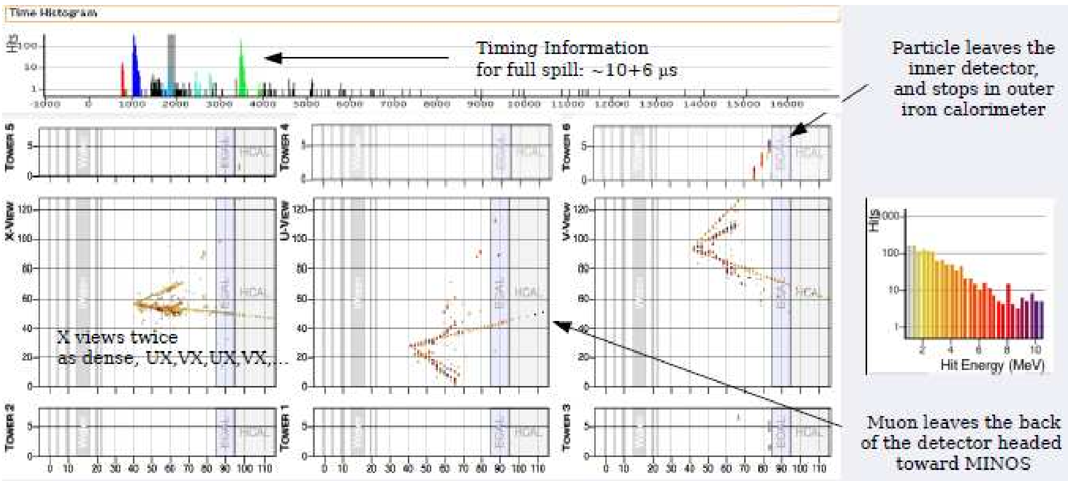

Figure 6: A charged-current interaction candidate event display from data.

Fig. 5. From live channel and occupancy plots only a small fraction (<0.1%) of the total ∼32K channels are not functioning. Shown in Fig. 6 is a sample charged-current interaction candidate event from the data. ADC and TDC information is buffered from each spill and read-out at the end of the spill allowing similar times to be bunched together to generate different time slices (events) within the several microsecond beam window.

5. Preliminary Results: Anti-neutrino Charged Current Quasi-elastic Interactions

Charged current quasi-elastic (CCQE) events ($\bar{\nu} + p \rightarrow \mu^+ + n$) exhibit a rela-

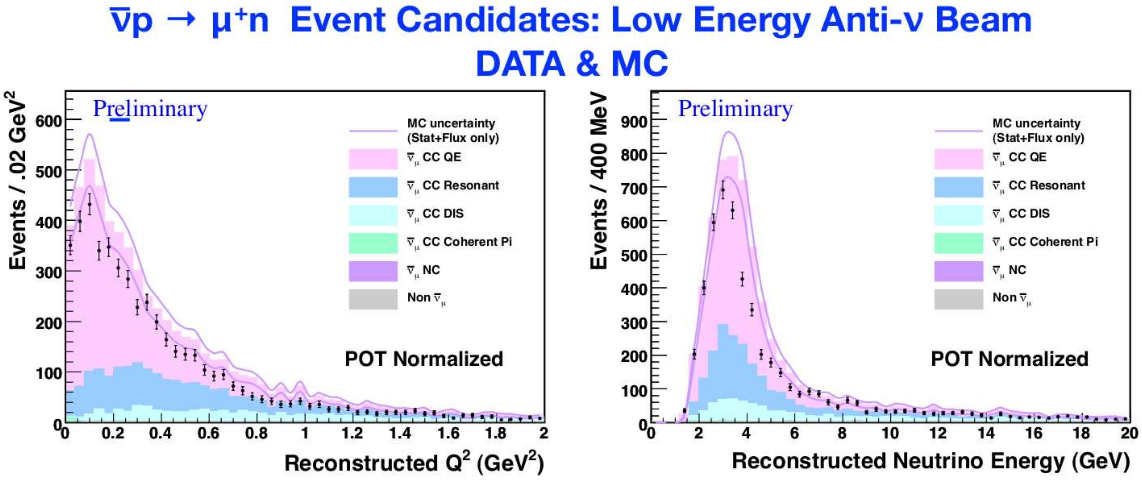

Figure 7: $\bar{\nu}$ data and simulation comparisons in reconstructed energy and Q^2 assuming charged-current quasi-elastic hypothesis.

tively large cross-section at the energies of the NuMI Low Energy (LE) beam configuration and a simple event topology. Often the muon is the only particle visible and relatively easy to identify and measure (direction and momentum). A preliminary analysis using the partially completed detector (Frozen Detector) and 4×10^{19} protons on target (POT) in the RHC LE beam configuration is presented. The fiducial mass in the active tracker region used for this analysis was 2.86 tons of plastic scintillator.

The sample criteria required a μ^+ originating in the fiducial MINERνA tracker volume and matched in the MINOS Near-Detector. Using the QE hypothesis, one can then reconstruct the neutrino energy and four-momentum transfer with only the muon information. Additionally very little observed extra energy in the event was allowed. A maximum observed energy cut based on a simple function of Q^2 outside of a 5 cm radial cylinder around the track and within a 100 ns time window was applied.

Figure 7 shows the reconstructed neutrino energy and Q^2 compared to our current MC prediction. Absolute predictions are provided by our flux simulation. Note that the event deficit is flat in Q^2, but not in neutrino energy. However as one can easily see the error bars in the simulation show a significant neutrino flux uncertainty. In addition the error envelope will have significant bin-to-bin correlations but are not presented in this preliminary result.

6. Summary

MINERνA is a fully functioning detector running at FNAL exploiting the high flux NuMI beam-line. It will precisely study neutrino interactions in the 1-20 GeV range employing a fine-grained, high-resolution, detector. MINERνA will improve our knowledge of Neutrino cross sections at low energy, low Q^2, and A-Dependence in neutrino interactions (Targets He, C, Fe, Pb and H_2O). These data will be interesting in there own right but will also be important for minimizing systematic errors in oscillation experiments.

7. Acknowledgments

Funding support from the Department of Energy (U.S.A.) was greatly appreciated.