1 Status of the MINERνA Experiment

MINERνA (Main INjector ExpeRiment ν–A) is a few GeV dedicated neutrino experiment aiming at precise measurements of neutrino and antineutrino – nucleus interactions on a variety of nuclear targets (H, D, He, C, H2O, Fe, Pb) using the NuMI neutrino beam at Fermilab. The MINERνA physics program includes A-dependent neutrino cross section measurements in the 1–20 GeV region, which are expected to improve and further develop neutrino interaction models used in neutrino oscillation experiments and elucidate further nucleon structure modifications in the nuclear medium. Figure 1 shows the schematic layout of the experiment. The MINERνA experiment is described in detail in [1]. The experiment employs a fine-grained, high-resolution fully active detector, consisting of 8 tons of plastic scintillator triangular bars. The nuclear target region is located upstream of the central detector (Figure 1 right) and consists of planes of passive targets of different materials, with tracking planes placed between each plane of passive targets. There is no magnetic field. Neutrino events originating in the central detector are fully contained for neutrino energies below 20 GeV except for the outgoing muon, which is measured (charge and momentum) in the near detector of the MINOS experiment located downstream of MINERνA. That allows for the precise reconstruction of the incoming neutrino as $E_\nu = E_\mu + E_{\mathrm{had}}$, where E_{had} is the energy of the hadronic system produced in the interaction and is reconstructed calorimetrically. The high resolution and fully active elements enable the detection of different interaction topologies. Outgoing particles, mainly hadrons, can be identified via the energy loss $\mathrm{d}E/\mathrm{d}x$ with no charge determination.

The first round of measurements using a *low energy* neutrino beam peaked around 2.5 GeV has been carried out between 2009 and 2012. In this period MINERνA has collected significant statistics: 3.9×10^{20} POT in the neutrino mode and 1.7×10^{20} POT in the anti-neutrino mode. This data set is being analyzed by various groups, including UniGE. The next round of measurements with a *medium energy* neutrino beam peaked around 6.5 GeV and a tail extending up to 20 GeV started in Fall 2013 after the successful upgrade of the beamline for the NOνA experiment. By moving the production target w.r.t. the focusing horn and changing the distance between the horns, the neutrino beam energy can be varied. Neutrino and anti-neutrino beams will be used contingent to the NOvA running plan (2 and 4 years respectively). Thanks to the higher beam intensity and energy, MINERνA has already collected in the ME configuration a data sample almost two times larger compared to the LE data taking.

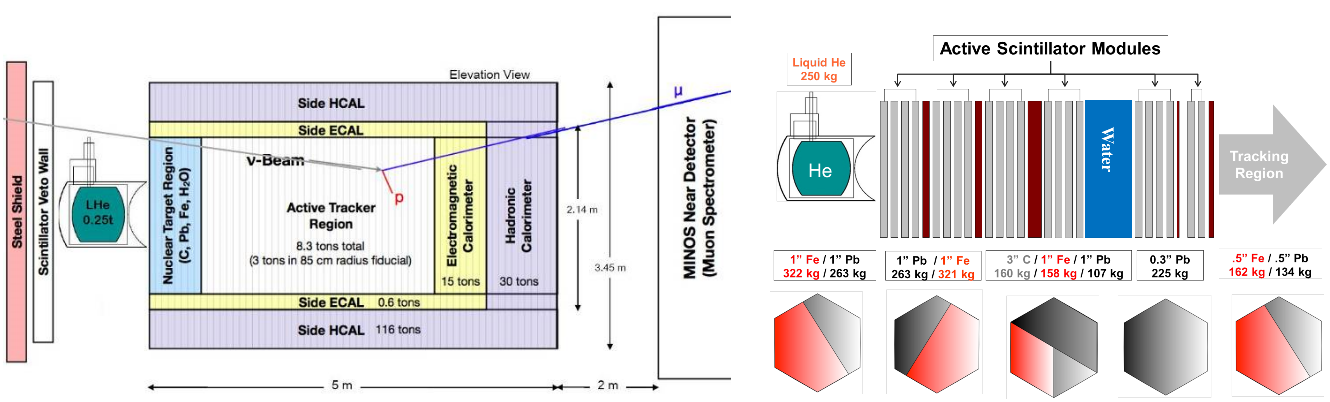

Figure 1: (left) Layout of the MINERνA detector. (right) Nuclear target region located upstream of the fine-grained scintillator tracker.

2 Scientific motivation

Our interested in MINERνA can be summarized as follows:

1. The extraction of oscillation parameters (mixing angles and Δm^2's) critically depends on the precise knowledge and understanding of neutrino cross sections in order to reduce systematical errors. The existing cross section data is quite old, statistically limited, and measured mainly in bubble chambers filled with hydrogen and deuterium, while modern oscillation experiments use dense nuclear targets. Recent comparisons of neutrino cross section data with different models (Figure 2) have shown that the understanding of neutrino cross sections is far from satisfactory and that nuclear effects can modify significantly the interaction kinematics in a way not yet fully understood.

   Our neutrino group plays an important role in T2K in measuring neutrino cross sections with ND280. At present MINERνA offers the ideal environment for strengthening our activity in the field of neutrino cross section measurements by complementing it with measurements over a broader energy range. The broader neutrino energy range will allow also studying of the Q^2 and W dependence of the cross sections, and thus extracting directly and in a reliable way the protons axial mass M_A, which plays a crucial role in all neutrino quasi-elastic cross section measurements.

   The MINERνA beam energy is close to the one planned for future LBN experiments. This is a great opportunity to measure neutrino and anti-neutrino cross sections on materials that are being considered for the future scintillator based neutrino detectors (carbon, argon, iron). These cross section data will represent an important reference for these future detectors.

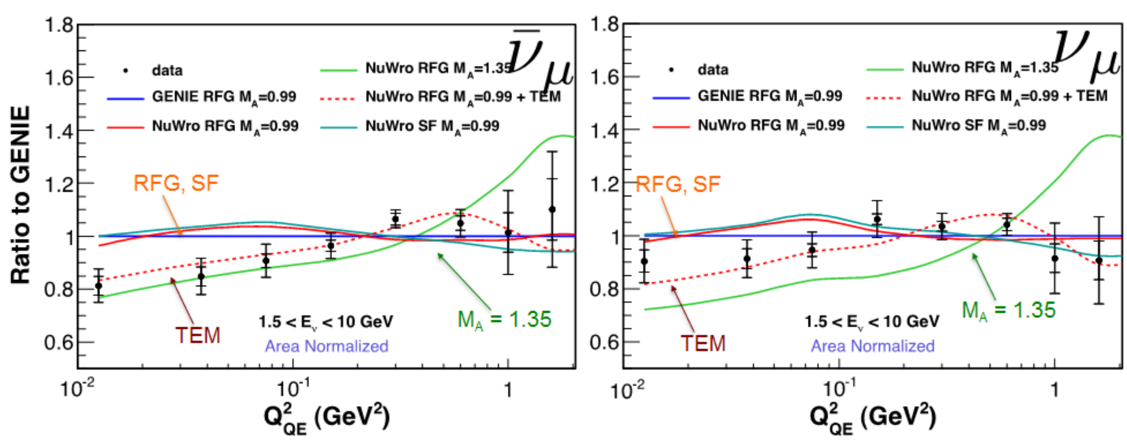

Figure 2: Charged current $\bar{\nu}$ (left) [2] and ν (right) [3] quasi-elastic cross section on CH as a function of Q^2 measured in MINERνA normalized to the RFG model prediction are compared to various models.

2. US groups working on the Fermilab NuMI beam are applying to their funding agencies to join NA61 to perform hadroproduction measurement to characterize the NuMI beam, similar to the ones that we have carried out for T2K. Their proposals will be submitted in Spring 2014. The expertise that we have gained in operating NA61 and analyzing NA61 data for T2K can be efficiently applied to NuMI and MINERνA, when new NA61 data will become available. Collaboration between UniGE and the US groups, in particular University of Pittsburgh and University of Colorado is steadily developing. At present this collaboration focuses on NA61 hardware upgrades.

3. The MINERνA central tracking detector consists of triangular scintillator bars readout with wavelength shifting fibers and MAPMTs. Muons are measured in the MINOS near detector, which is a magnetized iron scintillator detector. We are presently investigate scintillator based neutrino detectors for the future LBN experiments, like the totally active scintillator detector (TASD) and the magnetized iron scintillator detector (MIND). The central detector of MINERνA can be seen as a reduced version of TASD, sufficiently big, however, to understand the functioning and operation of this detector, its performance, track and event reconstruction, background, etc. The combination of the MINERνA detector and MINOS ND, including the matching of the muon track measured in both detectors, offers the possibility to study the performance of a fully active detector followed by a muon detector from real data. These points represent a strong synergy with our R&D projects.

4. MINERνA plans to resume this Fall test beam studies of the prototype scintillator tracker (about 1 m^3 of scintillator bar planes interleaved with Pb and Fe planes) to calibrate the MINRνA scintillator response to pions and electrons. Several studies of the TASD and MIND prototypes can be carried out at this facility. Moreover, the MICE calorimeter (see below) is very similar to the MINERνA central tracker (except for its smaller size of $\sim$ 1 ton). The measurements of stopped muons and pions will be a precious input to MINERνA.

3 UniGE contributions and involvement in MINERνA

We submitted an application to join the experiment in Spring 2012 and admitted to the collaboration in Summer 2012. Since then our participation in MINERνA has been slowly building up with the full time involvement of C. Martin-Mari (candoc) since January 2013. This project will involve A. Bravar (MER, etat) Y. Karadhzov (MA, etat) and C. Martin-Mari (assistant, FNS).

From the start we got involved in the analysis of inclusive charged current neutrino cross section. In particular we focused on the study of the A-dependence of the cross section by taking cross section ratios between various materials and the scintillator tracker. Since all targets are exposed to the same neutrino beam, the neutrino flux cancels in these ratios and the effect of different acceptances and reconstruction

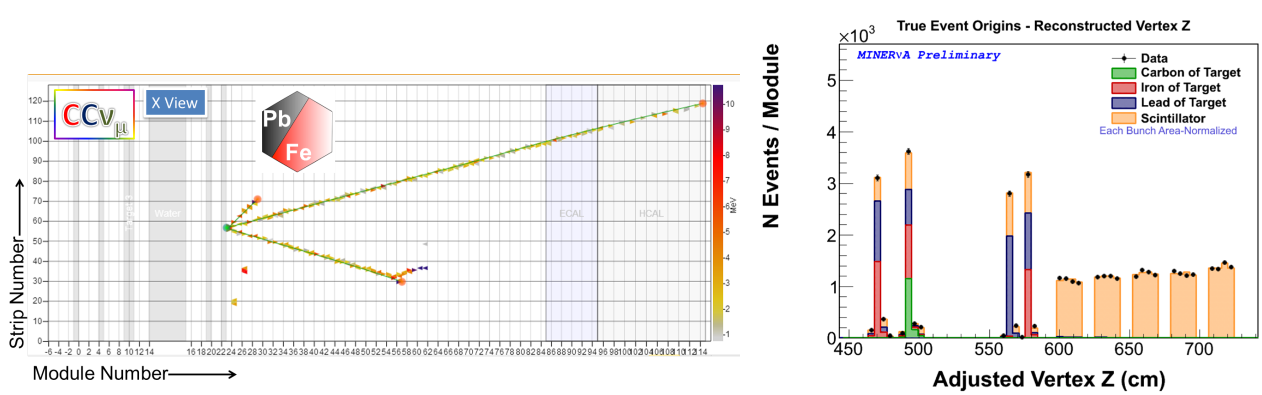

Figure 3: Typical CC neutrino scattering event (left) on the most downstream nuclear target. Visible are the outgoing muon (long track) and two hadrons produced in the interaction. Breakdown of inclusive scattering events (right) from different nuclear targets w.r.t. various target materials including events from the scintillator tracker (plastic background).

efficiencies is reduced in these ratios. UniGE (C. Martin-Mari) contributed to the validation of the analysis procedure performing cross checks at various analysis steps, help validate the background subtraction procedures (Figure 3 right), and unfolding of the cross section ratios. We studied the reconstruction efficiencies in the nuclear target region for different inelastic event selection criteria. We also developed automatic procedures to track all changes in the reconstruction and analysis software, by applying importance threshold levels on each one of the base histograms in the source code, to assure the consistency of the software tools. This analysis has been completed very recently. The cross section ratios are shown in Figure 4 and have been submitted for publication to Phys. Rev. Lett. [4]. As can be noticed in Figure 4 the agreement between the data and the event generator is not always satisfactory, indicating a lack of full understanding of the underlying neutrino interaction mechanisms on nuclei. A. Bravar served as chair of the internal MINERνA review committee.

Our focus has then moved to the study of the same ratios using the antineutrino sample. Up to this point our work has been related with the characterization of the event sample, data – Monte Carlo comparisons, and the validation of event selection procedures.

1. We will continue to participate actively in the operation, maintenance, and data taking (shifts) of the experiment.

2. We will continue the analysis work on inclusive cross sections and cross section ratio measurements, in particular for the anti-neutrino LE data sample and the neutrino ME data sample, which will become available for analysis starting this Summer. The ME neutrino data are being currently

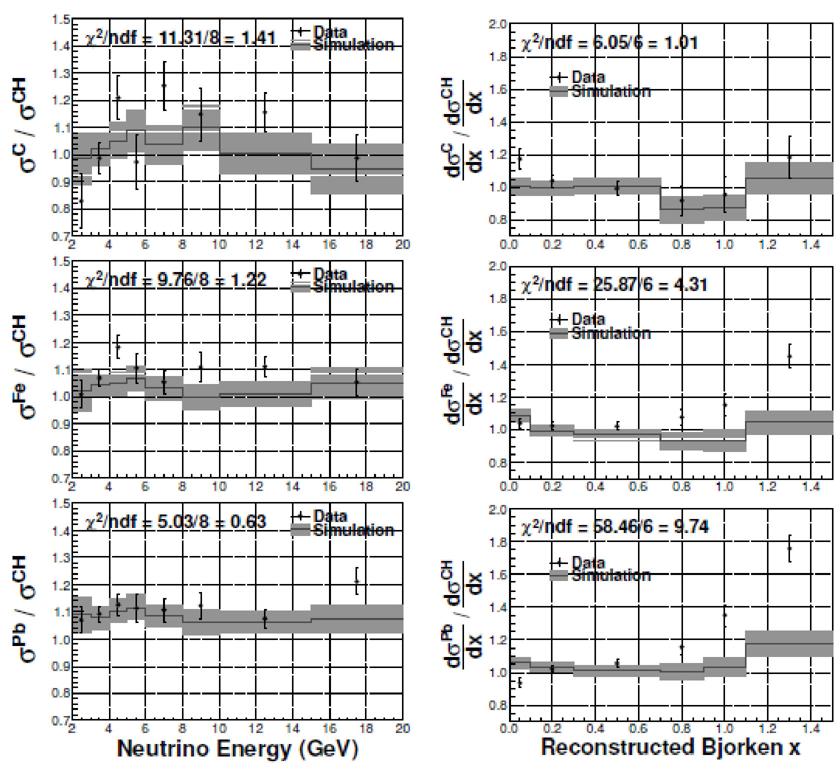

Figure 4: Ratios of the charged-current inclusive ν_μ cross section as a function of $E\nu$ (left) and as a function of reconstructed x (right) for C/CH (top), Fe/CH (middle), and Pb/CH (bottom). Error bars on the data (simulation) show the statistical (systematic) uncertainties.

calibrated and validated. We already took responsibility for the analysis of the inclusive anti-neutrino cross sections using LE data. We plan also to take responsibilities in the analysis of inclusive neutrino cross sections at higher energies (ME data), concentrating in particular in the DIS region. We will also focus on the study of the hadronic system and its energy determination, since the determinations of the event kinematics and variables, including the incoming neutrino energy, depends crucially on the ability to correctly reconstruct this energy.

We plan to explore the possibility of using additional target materials can be used in MINERνA, like a $^{4}0$Ca based target which would be very similar to an argon target. We plan also to explore water based scintillators to replace the existing water target in MINERνA with an active one.

3. We plan to participate in the test beam measurements using the prototype of the MINERνA detector. A beam request to the FNAL directorate (T-977) has been submitted in March 2014. The test beam activity might start already this Fall or early 2015 and will involve the collaboration of UniGE, Fermilab, University of Rochester, and College of William and Marry. These measurements will last several months. We plan to take important responsibilities in the operation of the test beam and later in the analysis of collected data.

   MINERνA primary need is to calibrate the scintillator response (reconstructed energy) to pions and electrons, to measure the resolution in the response, and to reduce and then estimate the bias on the calorimetric shower energy reconstruction for these particles. The detector itself consists of 40 planes of scintillator that are arranged in different configurations, and instrumented with 40 multi-anode phototubes. The detector schematic is shown in Figure 5. The run plan involves taking data in four detector configurations: (i) HCAL heavy configuration with 32 planes of steel (MINERνA has 20 planes in its HCAL), which will provide for a more uniform measurement of the calorimetric response for pions at the highest momenta (ii) ECAL + HCAL configuration with 20 planes of lead and 20 planes of steel, the same as the MINERνA detector installed in the NUMI hall. This is also the ideal configuration for calorimetry with the electron sample. (iii) Tracker + ECAL with 20 Tracker + 20 ECAL planes, which is also MINERνA-like, which can be used for tracking studies and possibly some interaction rate tests. (iv) Tracker only (TASD), which will provide the stopping properties of lower energy protons and pions in the MINERνA tracker.

   This activity is highly synergetic with other test beam activities that we are planning at CERN and RAL, thus a mutual benefit is expected. This activity aims at characterizing the response of a

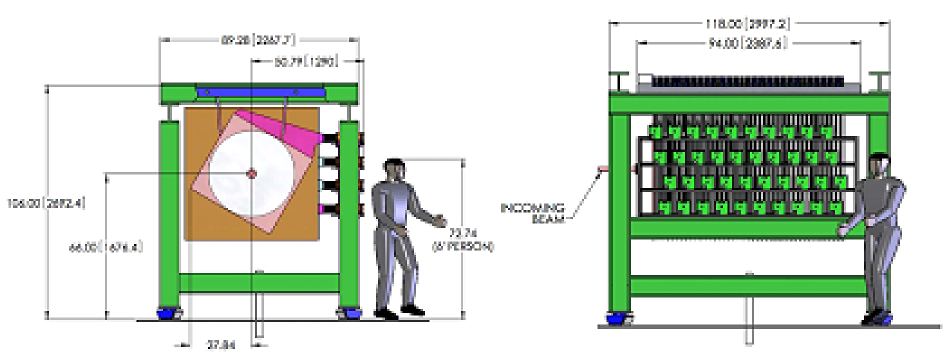

Figure 5: Front and side view of the MINERνA detectpr prototype.

totally active scintillator detector with a beam of well defined energy and composition. We plan to contribute also to the upgrade of the MINERνA prototype readout, which consists in replacing the MAPMTs with Si-PMs and new readout electronics similar to the one being developed for NA61.

4. While the study of cross section ratios does not depend on the neutrino flux normalization and the study of the shapes of differential distributions (like Q^2) depends only mildly on the neutrino flux, the extraction of absolute cross sections requires a precise knowledge of the neutrino flux. MINERνA uses different techniques to reduce the uncertainties associated with the neutrino flux: $\nu_\mu e^- \to \nu_\mu e^-$ elastic scattering, the so called *low*$-\nu$ method, and simulations of the NuMI beamline using different hadroproduction models and data samples. Presently, the error on the neutrino flux is around 15%, which limits significantly the precision on absolute cross section measurements that can be achieved. When new NA61 hadroproduction data at the nominal Fermilab beam energy of 120 GeV will become available, they will be used to improve the neutrino flux predictions with uncertainties below 5%.

   Recently we got involved in the simulations of the NuMI beam, taking responsibilities for the GEANT4 based beam Monte Carlo. Our aim is to improve on the neutrino flux predictions using all available hadroproduction data and existing hadroproduction models before new NA61 hadroproduction data become available. We plan to exploit the muon monitors downstream of the decay tunnel to tune the simulations of the neutrino flux. MINERνA also took and is planning to take additional data with special settings of the focusing horn currents. We plan to use these data as well to validate and further improve the neutrino flux predictions.

4 Conferences

- A. Bravar *et al.* (for the MINERνA Collaboration), The MINERνA Neutrino Experiment at Fermilab, 25$^{\text{th}}$ International Nuclear Physics Conference, INPC2013, Firenze, Italy, 2 – 7 June 2013.

- A. Bravar *et al.* (for the MINERνA Collaboration), Charged-Current Inclusive Scattering in MINERνA, 15$^{\text{th}}$ International Workshop on Neutrino Factories, Superbeams and Beta Beams, NuFACT13, Beijing, China, 19 – 24 August 2013.

- A. Bravar, Neutrinos & Nucleons & Nuclei, 10$^{\text{th}}$ Eutropean Reserch Conference on Electromagnetic Interactions with Nucleons and Nuclei, EINN2013, Paphos, Cyprus, 28 October – 2 November 2013.

5 Financial Request

References

[1] L. Aliaga *et al.* (MINERνA Collaboration), submitted to *Nucl. Instrum. Meth.*, arXiv:1305.5199 [ins-det].

[2] G.A. Fiorentini *et al.* (MINERνA Collaboration), *Phys. Rev. Lett.* **111**, 022502 (2013).

Si-PMs and DRS electronics for test beam	80'000
Water based scintillator explorations	20'000
Travel (collaboration meetings and shifts)	50'000
Conferences	25'000
Total	175'000

Table 1: Financial request related to UniGE participation in MINERνA in 2014 - 2016.

[3] L. Fields *et al.* (MINERνA Collaboration), *Phys. Rev. Lett.* **111**, 022501 (2013).

[4] B.G. Tice *et al.* (MINERνA Collaboration), submitted to *Phys. Rev. Lett.*, arXiv:1403.2103 [hep-ex].