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MINERvA medium-energy physics results

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MINERνA is a neutrino-nucleus interaction experiment in the Neutrino Main Injector beam at Fermilab. With the $\langle E_\nu \rangle \sim 6$ GeV Medium Energy run complete and 12×10^{20} protons on target delivered in neutrino and antineutrino mode, MINERνA combines a high statistics reach and the ability to make precise cross-section measurements in more than one dimensions. Analyses of plastic scintillator and nuclear target data constrain interaction models, providing feedback to neutrino event generators and driving down systematic uncertainties for future oscillation experiments. Specifically, MINERνA probes both the intrinsic neutrino scattering and the extrinsic nuclear effects which complicate the interactions. Generally, nuclear effects can be separated into initial- and final-state interactions, both of which are not known *a priori* to the precision needed for oscillation experiments. By fully exploiting the precisely measured final-state particles out of different target materials in the MINERνA detector, these effects can be accurately probed. In this work, the newest MINERνA analyses since the last ICHEP, which encompass a broad physics range, will be presented: inclusive cross-section measurements in the tracker and *in situ* measurements of the delivered flux, allowing detailed comparisons with generator predictions, and control of systematic flux uncertainties, respectively. Moreover, by exploiting the significant statistics reach offered by the large exposure, MINERνA measures rare processes.

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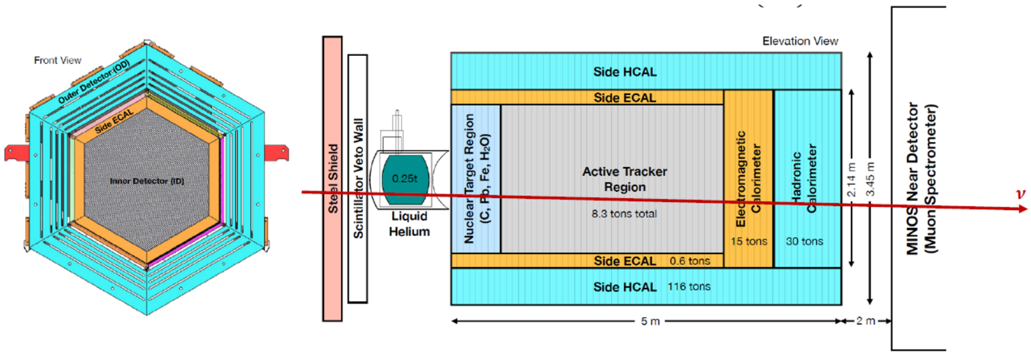

Figure 1: The MINERνA detector.

The MINERνA experiment took data from the Neutrino Main Injector (NuMI) beam at Fermilab for a period of 3 years with $\langle E_\nu \rangle \sim 3.5$ GeV and 7 years with $\langle E_\nu \rangle \sim 6$ GeV, periods known as Low-Energy (LE) and Medium-Energy (ME) respectively. It is a dedicated neutrino-nucleus interaction experiment aimed at reducing neutrino interaction model uncertainties, for use with present and future oscillation experiments. The neutrino interaction model systematic uncertainty majorly contributes to the uncertainty in oscillation parameters [1], motivating precise cross-section measurements to control this systematic. The LE physics programme [2] has produced a range of measurements of incoherent (quasielastic (QE), QE-like, pion production, multi-nucleon correlations, transverse kinematic imbalance) and coherent processes. Likewise, the ME programme, with a large exposure of 12×10^{20} protons-on-target in both neutrino and antineutrino beam modes, has generated analyses which by the time of the last ICHEP had already produced results on charged-current QE-like processes.

The detector is comprised of an inner and an outer sub-detector. The tracking elements are wavelength-shifting strips made from polystyrene, which produce scintillation light that is picked up by photo-multiplier tubes, and provide both spatial and timing information. There is an upstream nuclear target region with passive targets (elemental carbon, iron, and lead) interspersed with tracking modules, and an active tracker region composed entirely of tracking modules. Downstream and around the sides of the hexagonal detector lie electromagnetic (EM) and hadronic calorimeters, designed to detect EM showers and other hadrons. Particle candidates in MINERνA are profiled based on their energy loss inside the detector. The MINOS near detector (ND) [3], which lies downstream of MINERνA, is used to provide charge identification and extra momentum measurement of muons with $E_\mu > 1.5$ GeV. A MINOS track must be matched with a MINERνA muon track by extrapolating the muon track from the MINOS ND back to MINERνA, and comparing timing and location to confirm a coincidence. A detailed description of the detector can be found in [4]. Figure 1 shows the outline of the detector, with the neutrino beam from NuMI superimposed.

The flux at MINERνA is predicted from a GEANT4 beamline simulation [5]. The baseline nominal prediction is reweighted in suitable kinematic variables, to address systematic uncertainties related to hadroproduction (where NA49 measurements [6] are used to cross-check the GEANT4 prediction) and beamline parameters such as the horn magnet current. This procedure provides some control of systematics, producing "universes" of fluxes corresponding to combinations of flux parameters. Each of these universes is further weighted using *in situ* measurements of well-understood electroweak processes. These are neutrino elastic scattering off of atomic electrons

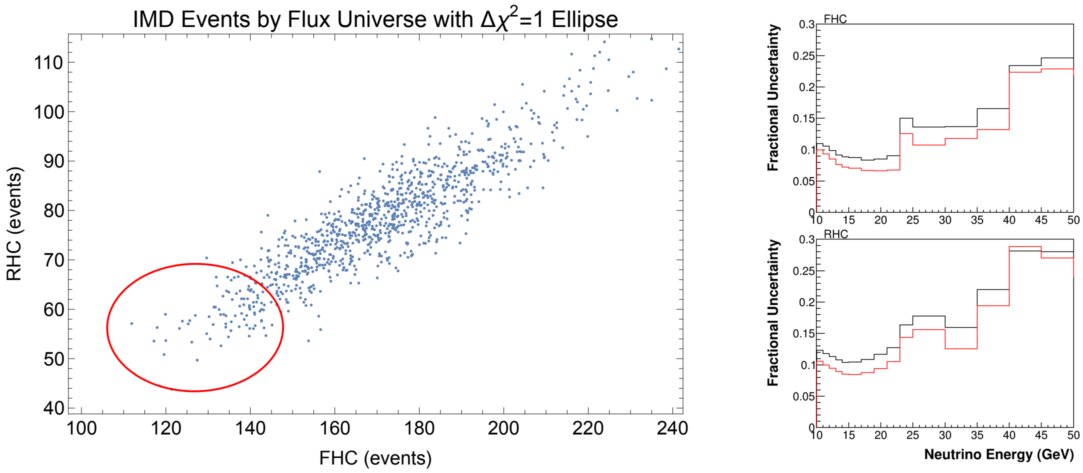

Figure 2: Inverse Muon Decay analysis for ME flux constraint. Left: IMD observed events (1 σ red ellipse) and expected events from each flux universe (points). Neutrino mode N^{ν}_{IMD} (FHC) on the x axis, antineutrino mode $N^{\overline{\nu}}_{\mathrm{IMD}}$ (RHC) on y axis. Top right: Fractional flux uncertainty before (black) and after (red) IMD constraint is applied, neutrino mode. Bottom right: Same as top right, antineutrino mode.

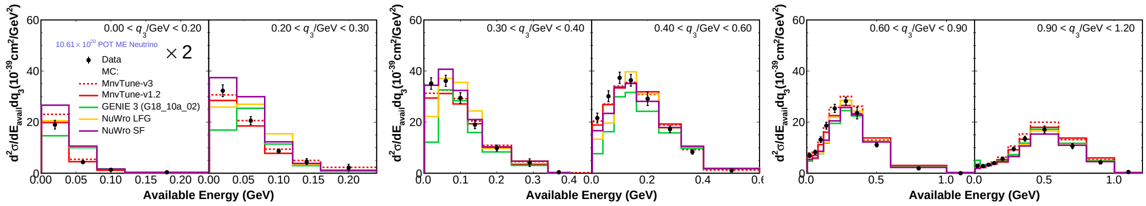

Figure 3: 2D cross section from the inclusive low-momentum transfer analysis, in bins of calorimetrically available energy $E_{\mathrm{avail}} = \Sigma T_p + \Sigma T_\pi + \Sigma E_{\mathrm{others}}$ (x axis) and three-momentum transfer (panels).

[7], as well as the Inverse Muon Decay (IMD) $\nu_\mu + e^- \rightarrow \mu^- + \nu_e$. MINERνA recently completed an analysis of 127(56) IMD events in neutrino(antineutrino) beam modes, comparing the expected number of IMD events for each universe against the observed number of events [8]. By applying Bayes' formula, each flux universe is further constrained, driving down the fractional flux uncertainty. Combining the neutrino-electron and IMD constraints yields the current most stringent constraint on the integrated $\nu_\mu(\overline{\nu}_\mu)$ flux of 3.3%(4.7%) [9].

Furthering MINERνA's objective of clarifying nuclear effects on neutrino cross sections, a measurement of the inclusive ν_μ charged-current scattering at low three-momentum transfer on the tracker was performed [10]. It was shown in the LE era [11] that multi-nucleon effects are needed to describe the cross section at low three-momentum transfer, which is sensitive to initial-state correlations such as two-particle-two-hole (2p2h) effects. MINERνA compared new models of nuclear effects implemented in event generators, as well as MINERνA specific tunes based on modifications to `GENIE` [12] based on prior measurements (MnvTune-v1.2) and on theory-driven grounds (MnvTune-v3); these latter tunes have by far the better agreement with data. This confirms the necessity for empirical modification to the kinematic "dip region" between QE and $\Delta(1232)$ resonance production previously identified by MINERνA. MnvTune-v3 changes the Valencia 2p2h model and the tune [13] by SuSAv2 2p2h and the QE high-momentum struck nucleons compared to MnvTune-v1.2, and implements a 25 MeV resonant removal energy for outgoing hadronic systems.

The need for an empirical modification of the interaction Monte Carlo can also be seen in the MINERνA muon analysis [14], where the large sample of over 4×10^6 candidate events with only

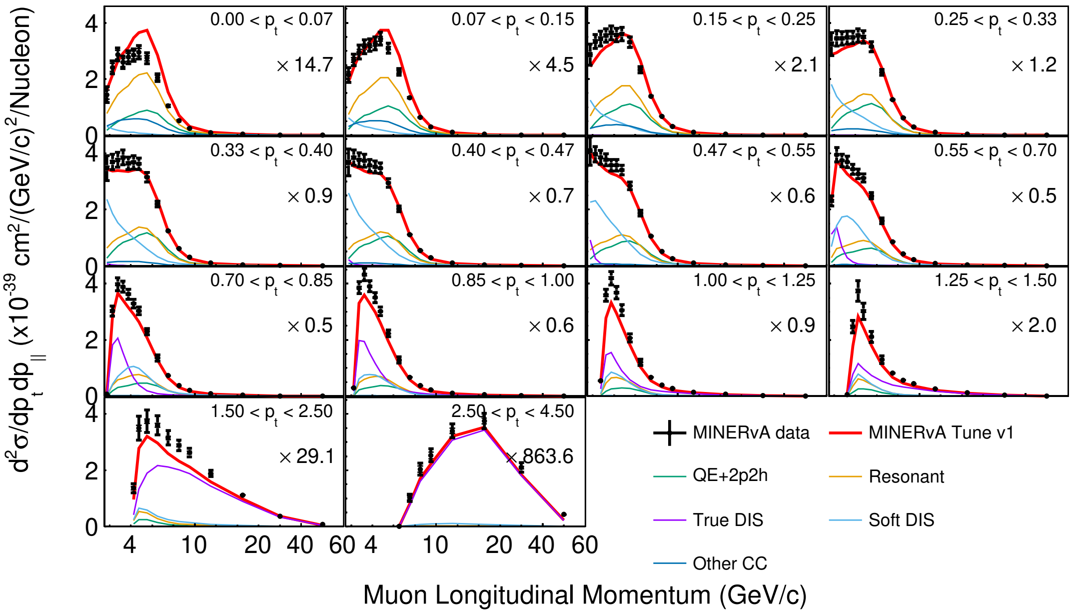

Figure 4: Inclusive muon 2D cross section, with MnvTune-v1 in red. Coloured curves: QE, resonant, "true" (hadronic invariant mass $W > 2\ \mathrm{GeV}/c^2$ and $Q^2 > 1\ \mathrm{GeV}^2/c^4$) deep-inelastic, "soft" (not "true") deep-inelastic, 2p2h. Note the significant overprediction in the first p_t bin (top left panel)

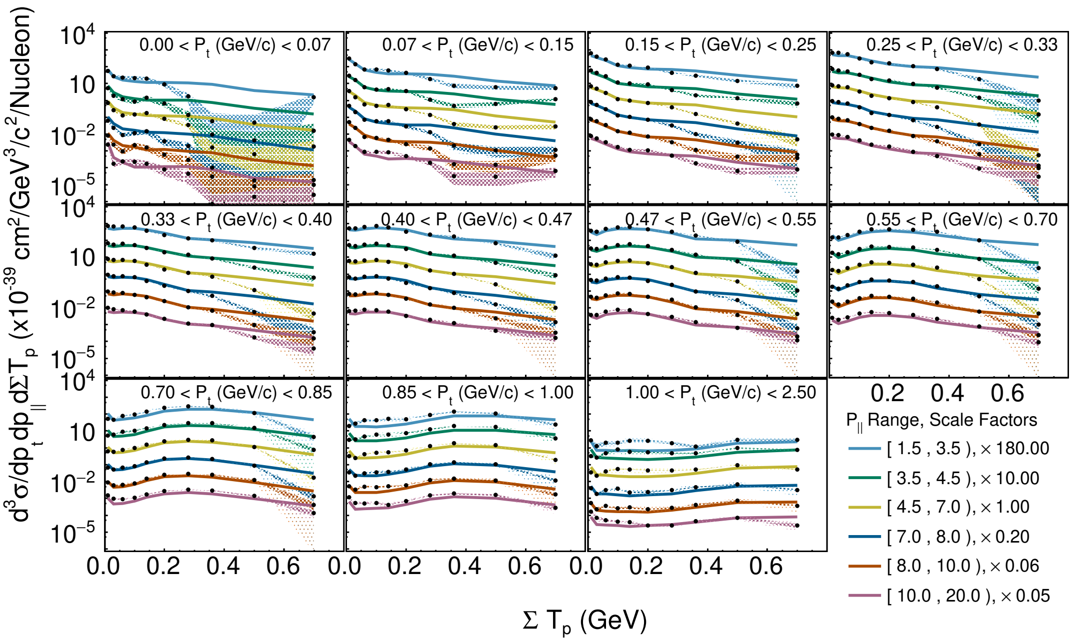

Figure 5: Muon QE-like 3D cross section. Coloured curves are MnvTune-v4.4.1 prediction. Data error bands shown. Each colour is one $p_{\|}$ bin. Note the significant overprediction in all bins of $p_{\|}$ for low p_t (top left) and high ΣT_p.

8655 predicted bakcground events shows an overprediction by the baseline Monte Carlo of the cross section in the region of $p_{\|} \in [3, 15]\ \mathrm{GeV}/c$ and low p_t. Here, p_t is the muon momentum transverse to the beam direction, and $p_{\|}$ is along the beam. The baseline MnvTune-v1 used here, developed in the LE era, included Random-Phase Approximation (RPA) screening of QE scattering at low four-momentum transfer Q^2, an enhanced 2p2h Valencia model, and suppression of resonant pion production as suggested by bubble chamber data [15]. This overprediction illustrated the need for additional suppression of the resonant pion production at low Q^2, which here is low p_t; this is shown in Fig. 4, in the first panel. Additionally, none of the model combinations or generators completely described data, which motivated an analysis of QE-like interactions $\nu_\mu + A \rightarrow \mu^- + \text{nucleons} + A'$ [16].

This analysis produced a three-dimensional cross section over the same two muon variables as well as the calorimetrically available energy $E_{\text{avail}} \simeq \Sigma T_p$, the RHS being the sum of kinetic energy of all protons. ΣT_p is uniquely sensitive to nuclear effects such as nucleon binding energy. The reference model was MnvTune-v4.4.1, which incorporates low-Q^2 nonresonant pion suppression, RPA screening, enhanced 2p2h. In the low-p_t region, for high ΣT_p, the Monte Carlo significantly overpredicts data, once again pointing to modelling shortfalls. This region is dominated by 2p2h and low-invariant-mass pion production, where the pion is reabsorbed in the nucleus. It is possible that this final-state interaction (FSI) is overpredicted. In Fig. 5, the different coloured lines correspond to different bins of $p_\parallel$. Coloured bands indicate the errors for data in each $p_\parallel$ bin.

Finally, MINERνA has completed a measurement of coherent pion production $\nu_\ell + A \rightarrow \ell^- + \pi^+ + A$, first observed in [17], for the ME beam and, for the first time, in the passive nuclear targets [18]. The analysis is crucial for differentiating between different models of the coherent cross section, which generally predict different dependences on nuclear mass number. The cross section ratios $(\mathrm{d}\sigma_{\mathrm{A}}/\mathrm{d}E_\nu)/(\mathrm{d}\sigma_{\mathrm{CH}}/\mathrm{d}E_\nu)$ (where σ_{CH} for the cross section in the tracker) are shown in Fig. 6. The ratios on Fe and Pb are not consistent with an energy-independent mass-number scaling; at low E_ν the scaling appears to be as $A^{1/3}$, and at $E_\nu \gtrsim 10$ GeV to be $A^{2/3}$.

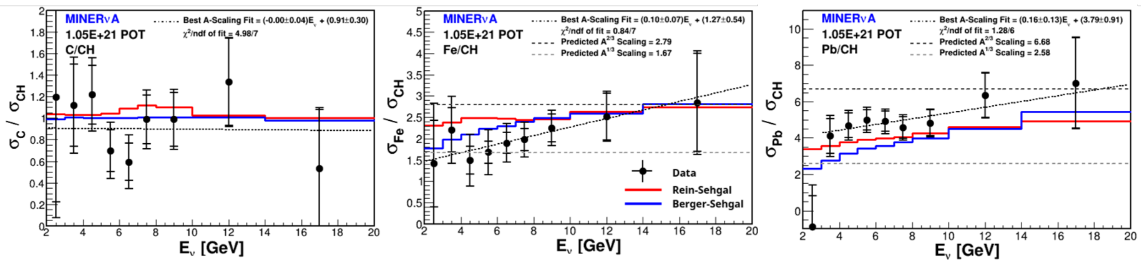

Figure 6: Ratios $(\mathrm{d}\sigma_A/\mathrm{d}E_\nu)/(\mathrm{d}\sigma_{CH}/\mathrm{d}E_\nu)$ as a function of E_ν for the passive nuclear targets (C, Fe, Pb). Dashed lines indicate $A^{2/3}$ (upper), $A^{1/3}$ (lower), and E_ν-dependent (sloped) scalings. Rein-Sehgal (red) and Berger-Sehgal (blue) cross section models shown.

References

[1] M.A. Acero *et al* (NOvA), *Improved measurement of neutrino oscillation parameters by the NOvA experiment*, *Phys. Rev. D* **106** (2022) 032004 [hep-ex/2108.08219].

[2] X.-G. Lu *et al* (MINERνA), *Exploring neutrino-nucleus interactions in the GeV regime using MINERνA*, *EPJ Special Topics* **230** (2021) 4243 [hep-ex/2107.02064].

[3] D.G. Michael *et al* (MINOS), *The magnetized steel and scintillator calorimeters of the MINOS experiment*, *Nucl. Instrum. Meth. A* **596** (2008) 190 [physics.ins-det/0805.3170].

[4] L. Aliaga *et al*, *Design, calibration, and performance of the MINERνA detector*, *Nucl. Instrum. Meth.* ***A*** **743** (2014) 130 [physics.ins-det/1305.5199].

[5] L. Aliaga *et al* (MINERνA), *Neutrino flux predictions for the NuMI beam*, *Phys. Rev.* ***D*** **94** (2016) 092005 [Publisher's note: *Phys. Rev.* ***D*** **95** (2017) 039903] [hep-ex/1607.00704].

[6] C. Alt *et al* (NA49), *Inclusive production of charged pions in p + C collisions at 158 GeV/c beam momentum*, *EPJ* ***C*** **49** (2007) 897 [hep-ex/0606028].

[7] E. Valencia *et al* (MINERνA), *Constraint of the MINERνA medium energy neutrino flux using neutrino-electron elastic scattering*, *Phys. Rev.* ***D*** **100** (2019) 092001 [hep-ex/1906.00111].

[8] D. Ruterbories *et al* (MINERνA), *Constraining the NuMI neutrino flux using inverse muon decay reactions in MINERνA*, *Phys. Rev.* ***D*** **104** (2021) 092010 [hep-ex/2107.01059].

[9] L. Zazueta *et al* (MINERνA), *Improved constraint on the MINERνA medium energy neutrino flux using* $\overline{\nu}e^- \to \overline{\nu}e^-$ *data*, hep-ex/2209.05540.

[10] M.V. Ascencio *et al* (MINERνA), *Measurement of inclusive charged-current* ν_μ *scattering on hydrocarbon at* $\langle E_\nu \rangle \sim 6$ *GeV with low three-momentum transfer*, *Phys. Rev.* ***D*** **106** (2022) 032001 [hep-ex/2110.13372].

[11] P.A. Rodrigues *et al* (MINERνA), *Identification of Nuclear Effects in Neutrino-Carbon Interactions at Low Three-Momentum Transfer*, *Phys. Rev. Lett.* **116** (2016) 071802 (Erratum: *Phys. Rev. Lett.* **121** (2018) 209902) [hep-ex/1511.05944].

[12] C. Andreopoulos *et al*, *The GENIE neutrino Monte Carlo generator*, *Nucl. Instrum. Meth.* ***A*** **614** (2010) 87 [hep-ph/0905.2517].

[13] R. Gran *et al* (MINERνA), *Antineutrino Charged-Current Reactions on Hydrocarbon with Low Momentum Transfer*, *Phys. Rev. Lett.* **120** (2018) 221805 [hep-ex/1803.09377].

[14] D. Ruterbories *et al* (MINERνA), *Measurement of inclusive charged-current* ν_μ *cross sections as a function of muon kinematics at* $\langle E_\nu \rangle \sim 6$ *GeV on hydrocarbon*, *Phys. Rev.* ***D*** **104** (2021) 092007 [hep-ex/2106.16210].

[15] C. Wilkinson *et al*, *Reanalysis of bubble chamber measurements of muon-neutrino induced single pion production*, *Phys. Rev.* ***D*** **90** (2014) 112017 [hep-ex/1411.4482].

[16] D. Ruterbories *et al* (MINERνA), *Simultaneous measurement of proton and lepton kinematics in quasielastic-like* ν_μ*-hydrocarbon interactions from* 2 *to* 20 *GeV*, hep-ex/2203.08022.

[17] A. Higuera *et al* (MINERνA), *Measurement of Coherent Production of* $\pi^\pm$ *in Neutrino and Antineutrino Beams on Carbon from* E_ν *of* 1.5 *to* 20 *GeV*, *Phys. Rev. Lett.* **113** (2014) 261802 [hep-ex/1409.3835].

[18] M.A. Ramírez *et al* (MINERνA), *Neutrino-induced coherent* π^+ *production in C, CH, Fe and Pb at* $\langle E_\nu \rangle \sim 6$ *GeV*, hep-ex/2210.01285.

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