Measurement of low-energy neutrino cross-sections with the PEANUT experiment

S Aoki¹, A Ariga², L Arrabito³, D Autiero³, M Besnier⁴,²¹, C Bozza⁵, S Buontempo⁶, E Carrara⁷,⁸,¹², L Consiglio⁹,¹⁰,²³, M Cozzi⁹, N D’Ambrosio¹¹, G De Lellis⁶,¹²,²⁵, Y Déclais³, M De Serio¹³, F Di Capua⁶, A Di Crescenzo⁶,¹², D Di Ferdinando¹⁰, N Di Marco¹⁴, D Duchesneau⁴, A Ereditato², L S Esposito¹¹, T Fukuda¹⁵, G Giacomelli⁹,¹⁰, M Giorgini⁹,¹⁰, G Grella⁵, K Hamada¹⁵, M Ieva¹³, F Juget², N Kitagawa¹⁵, J Knuesel², K Kodama¹⁶, M Komatsu¹⁵, U Kose⁵, I Kreslo², I Laktineh³, A Longhin⁷,⁸,²⁴, B Lundberg¹⁷, G Lutter², G Mandrioli¹⁰, A Marotta⁶, F Meisel², P Migliozzi⁶, K Morishima¹⁵, M T Muciaccia¹³,¹⁸, N Naganawa¹⁵, M Nakamura¹⁵, T Nakano¹⁵, K Niwa¹⁵, Y Nonoyama¹⁵, V Paolone¹⁹, A Pastore¹³,¹⁸, L Patrizii¹⁰, C Pistillo², M Pozzato⁹,¹⁰, F Pupilli¹⁴, R Rameika¹⁷, R Rescigno⁵, G Rosa¹²⁰, A Russo⁶,¹², O Sato¹⁵, L Scotto Lavina⁶, S Simone¹³,¹⁸, M Sioli⁹,¹⁰, C Sirignano⁵, G Sirri¹⁰, P Strolin⁶,¹², M Tenti⁹,¹⁰, V Tioukov⁶, J Yoshida¹⁵ and T Yoshioka¹⁵

¹ Kobe University, 657-8501 Kobe, Japan
² A Einstein Center for Fundamental Physics, Laboratory for High Energy Physics, University of Bern, CH-3012 Bern, Switzerland
³ IPNL, Université Claude Bernard Lyon 1, CNRS/IN2P3, 69622 Villeurbanne, France
⁴ LAPP, Université de Savoie, CNRS/IN2P3, 74941 Annecy-le-Vieux, France
⁵ Dipartimento di Fisica dell’Università di Salerno and INFN, 84084 Fisciano, Salerno, Italy
⁶ INFN Sezione di Napoli, 80126 Napoli, Italy
⁷ Dipartimento di Fisica dell’Università di Padova, 35131 Padova, Italy
⁸ INFN Sezione di Padova, 35131 Padova, Italy
⁹ Dipartimento di Fisica dell’Università di Bologna, 40127 Bologna, Italy
¹⁰ INFN Sezione di Bologna, 40127 Bologna, Italy
¹¹ INFN—Laboratori Nazionali del Gran Sasso, I-67010 Assergi (L’Aquila), Italy
¹² Dipartimento di Scienze Fisiche dell’Università Federico II di Napoli, 80126 Napoli, Italy
¹³ INFN Sezione di Bari, 70126 Bari, Italy
Abstract. The PEANUT experiment was designed to study the NuMi neutrino beam at Fermilab. The detector uses a hybrid technique, being made of nuclear emulsions and scintillator trackers. Emulsion films act as a micrometric tracking device and are interleaved with lead plates used as passive material. The detector is designed to precisely reconstruct the topology of neutrino interactions and hence to measure the different contributions to the cross section. We present here the full reconstruction and analysis of 147 neutrino interactions and the measurement of the quasi-elastic, resonance and deep-inelastic contributions to the total charged current cross section at the energies of the NuMi neutrino beam. This technique could be applied for beam monitoring in future neutrino facilities, and this paper shows its proof-of-principle.
1. Introduction

The study of charged particle multiplicity distributions in $\nu_\mu$ charged current (CC) interactions in the few GeV energy range provides data to validate models of hadron production induced by neutrinos and to measure the interaction cross sections. The description of the dynamics of the interaction is complicated since quasi-elastic (QE), resonance scattering (RES) and deep-inelastic scattering (DIS) types of neutrino scattering show similar contributions. Neutrino interactions above the first resonance production threshold (1238 MeV c$^{-2}$) are classified under DIS. The micrometric resolution of nuclear emulsion detectors makes them well suited to perform detailed studies of $\nu_\mu$ interactions at low energy, since both event topology and angular distributions can be measured with high precision.

The PEANUT (Petit-Exposure At NeUTrino beamline) experiment was designed with a hybrid emulsion–electronic detector configuration to carry out the above-mentioned measurements. The experimental set-up consists of a sequence of target walls interleaved with scintillating fiber trackers (SFT). The target has a modular structure made of units built up using the emulsion cloud chamber (ECC) technique. An ECC is a sequence of nuclear emulsion films used as precision trackers and passive material plates acting as the neutrino target.

The electronic fiber trackers provide the time stamp of $\nu_\mu$ events and predict the position of the $\nu_\mu$ interaction vertex inside the target with an accuracy of better than 1 mm. The track of the muon or of any other reconstructed charged particle is connected in the closest emulsion films and it is followed upstream until the vertex is located.

We have fully reconstructed and measured 147 $\nu_\mu$ interactions and obtained their charged particle multiplicity distribution from which we have estimated the different contributions to the total CC cross section from quasi-elastic, resonant and deep inelastic processes. We have also deconvoluted the experimental detection efficiencies to obtain the expected multiplicity at the primary vertices together with the muon slope. These data are useful for checking models of hadron production in neutrino interactions.

2. The detector

The PEANUT detector is shown in figure 1. It was placed in front of the MINOS near detector in the experimental hall at Fermilab as shown in figure 2, and it was exposed to the $\nu_\mu$ NuMI beam in the low-energy configuration [1].

The emulsion films are about 300 $\mu$m thick and made of two 44 $\mu$m thick emulsion layers deposited on both sides of a transparent 205-$\mu$m-thick plastic support. The emulsions used for the PEANUT experiment belong to the same batch of films used for OPERA [2, 3]. These films were treated with a dedicated procedure called refreshing, erasing most of the unwanted tracks recorded since the production of the films [4].

Emulsion films were packed in ECC modules, called ‘bricks’, similarly to those employed for the OPERA experiment at LNGS [2]. A brick consists of 57 emulsion films, 55 of them interspaced with 1-mm-thick passive material plates and the two most downstream ones, called special sheets (SS), placed in contact. The transverse dimensions of the bricks are $12.5 \times 10.0\, \text{cm}^2$ (the horizontal and vertical directions, respectively), while the longitudinal size along the beam axis is 7.5 cm.

The target consists of four structures called ‘mini-walls,’ each housing a matrix of $3 \times 4$ bricks, for a total of 48 bricks.
Figure 1. Front and side views of the four mini-walls in the PEANUT detector. In the side view, the neutrino beam comes from the left. The $X-Y$ SFT planes are shown in green and the $U$ planes are shown in violet.

Figure 2. Photograph of the PEANUT detector.

The emulsions were sent by plane from their refreshing site in Japan to Fermilab in USA where the ECC were assembled. A facility for emulsion handling and development, equipped with a dark room, was set up in the experimental area at Fermilab.

During their flight from Japan to USA, the 57 films of a brick were packed together without any spacer in between, in the so-called ‘transportation order’, i.e. from film 1 to 57. On the other hand, when the brick was assembled at Fermilab, the films were packed in the reverse order (from film 57 to 1) and this configuration was named ‘assembly order’. The two different configurations allow discrimination between cosmic-ray tracks integrated during the transportation and neutrino-induced tracks accumulated during the beam exposure. Several tens of bricks were produced, most of them with the same geometry adopted for the OPERA bricks [2]. In this paper, we report on the analysis of 13 bricks exposed to the NuMI beam between October and December 2005.
The three upstream ‘mini-walls’ are followed by two planes of SFTs each, while the most downstream wall is followed by four SFT planes. Each plane has a transverse area of $0.56 \times 0.56$ m, and it is made of horizontal and vertical 500 µm diameter fibers produced by Kururay Co. The SFTs are those previously used in the DONUT experiment [5] and provide the transverse coordinates of the particle tracks. Moreover, behind the second and fourth mini-walls there are two fiber planes called $U$ and rotated by 45° with respect to the other SFT planes. They are used to disentangle ambiguities in the track reconstruction. These fibers are read out by image intensifiers and CCD cameras.

Data-taking with neutrinos started in September 2005. The first exposure period ended in March 2006. Each brick was left on the beam for a period ranging from 2 weeks to about 100 days. After the exposure, the bricks were brought to the surface laboratory, where they integrated cosmic rays for a few hours with the aim of collecting enough passing through tracks for a precise film-to-film alignment. The bricks were then unpacked in the emulsion-handling facility, where they were also marked with reference optical spots or x-ray slits and developed. Emulsions were finally shared for the analysis among various laboratories of the Collaboration.

3. The NuMI neutrino beam

The primary beam for the NuMI facility is given by 120 GeV protons from the main injector to the NuMI target. Protons hitting the target mainly produce mesons; these are focused towards the neutrino experimental areas, travel through a long decay pipe and a fraction of them decay to neutrinos and muons. The target is sufficiently long to enable most of the primary protons from the main injector to interact, but is shaped so that secondary interactions of the π’s and K’s are minimized and energy absorption is low.

Focusing is performed by a set of two magnetic horns. The average meson energy is selected by adjusting the locations of the second horn and target with respect to the first horn. This allows one to select the energy of the meson beam (and therefore of the neutrino beam) during the experiment.

The three configurations of target and horn spacings were defined as the low-energy (LE), medium-energy (ME) and high-energy (HE) beams. The higher-energy beams yield a larger number of neutrino interactions as the cross section is higher, whereas the low energy configuration is especially suitable for neutrino oscillation studies, the main purpose of the MINOS experiment [6].

The particles selected by the focusing horns (mainly pions with a small component of kaons and un-interacting protons) propagate through an evacuated beam pipe (decay tunnel) 1 m in radius and 675 m long, placed in a tunnel pointing downward towards the Soudan mine. While traversing the beam pipe, a fraction of mesons decay, yielding forward-going neutrinos. A hadron absorber consisting of a water-cooled aluminum central core surrounded by steel is placed at the end of the decay pipe to remove the residual protons and mesons. It is followed by a set of beam-monitoring detectors. The 240 m of dolomite rock between the end of the hadron absorber and the MINOS Near Detector are sufficient to stop all muons coming from the decay pipe.

Figure 3 shows the total number of NuMI protons (line) and the protons per week (histogram) delivered since May 2005 until January 2007. The first exposure period of the PEANUT detector is also indicated on the plot. During the PEANUT exposure the NuMI beam...
Figure 3. The total number of NuMI protons (line) and the protons per week (histogram) delivered on the target during the period from May 2005 to January 2007. The first PEANUT exposure is indicated.

Figure 4. Energy spectrum of the NuMI beam in the LE configuration [1] (top). Neutrino CC cross sections as a function of the neutrino energy [7] (bottom).

was in its LE configuration. The energy spectrum reported in the top plot of figure 4 [1] shows an energy peak between 3 and 4 GeV. The bottom plot shows the contributions to the total neutrino cross section as a function of the neutrino energy as expected from the data and theoretical models [7].
4. Neutrino event reconstruction

Data acquisition of the SFT detector is triggered by a signal of the proton kicker extraction magnet of the NuMI beam. Each beam spill lasts about 11 $\mu$s with a cycle of 1.87 s. The readout gate of the CCD camera is 100 $\mu$s wide. The number of expected neutrino interactions in the PEANUT target is $3 \times 10^{-3}$ per spill.

CCD data are processed after each beam spill by a local PC. Hits in the $X$ and $Y$ projections are reconstructed and used as input for the tracking algorithm. Two-dimensional (2D) tracks are reconstructed in the $XZ$ and $YZ$ planes separately. Hit pairs are used as seeds to initiate the tracking, but only tracks with at least six hits are used for the analysis, thus reducing the combinatorial background. 2D tracks sharing at least one hit in either the $U$- or $V$-plane are then merged into three-dimensional (3D) tracks.

After three weeks of data-taking, bricks are extracted from the target and depacked and their films are chemically developed for analysis.

The brick analysis starts selecting all the 3D tracks with hits recorded during its exposure time and with an impact point on the downstream surface within 5 mm from the edge. Given the absence of any veto system in front of the PEANUT target, penetrating muons originating from neutrino interactions in the surrounding rock are tagged by the presence of hits in the planes upstream of the brick. These tracks are then discarded from the original sample. Nevertheless, given the relatively low efficiency of the SFT planes (ranging from 50 to 70%), in the starting sample there is a residual contamination of rock muons, which is eliminated in later stages of the analysis.

3D tracks selected with the above-mentioned procedure are used for tagging neutrino interactions. At least one track coming out of the neutrino interaction vertex in the brick has to match with a 3D track reconstructed with SFT hits. The matched emulsion track is termed the reference track. The Monte Carlo (MC) simulation has shown that reconstructed 3D tracks are associated with muons in about 98% of the cases. Moreover, the MC simulation predicts that the 3D requirement reduces the neutral current interaction fraction to about 1%, thus making the $\nu$ event sample essentially made of CC neutrino interactions with a purity of about 99%. This matching criterion produces a bias on the average muon momentum estimated to be less than 5%.

Analysis of the emulsion films provided a sample of tracks originating inside the brick. A neutrino interaction is defined by one or more tracks originating from the same emulsion film and making a vertex with impact parameters within 10 microns. The measured residuals between 3D SFT tracks and those reconstructed in the emulsions are 500 $\mu$m in position and 6 mrad in angle, as shown in figure 5.

The topology of the neutrino interaction is defined after the analysis of a volume of about 0.33 cm$^3$ around the point where the tracks originate. The tracking algorithm reconstructs all the charged particles with trajectories inclined by no more than 400 mrad with respect to the perpendicular to the emulsion films, in both angular projections, thus providing a bias in the multiplicity reconstruction.

No momentum cut is applied in the analysis. Nevertheless, the angular tolerance in the track reconstruction prevents the tracking of particles with a momentum below 380 MeV c$^{-1}$.

The vertexing algorithm looks for any possible association of tracks reconstructed in the fiducial volume to the reference track. If no other particle is connected to the reference track, the neutrino interaction is classified as single prong. In this case, the longitudinal position of the neutrino interactions vertex is known with an uncertainty of 500 $\mu$m within the 1 mm...
lead plate, whereas this uncertainty decreases to a few microns when more charged tracks are reconstructed. Since most of the neutrino interactions occur in the lead plates, the reconstructed charged multiplicity does not include nuclear fragments produced at the neutrino vertex, which are mostly absorbed in the lead plate itself.
Figure 7. Display of a five-prong vertex. The reconstruction in the SFT (top figures) and in the emulsions (bottom figures) is shown. The front view is also shown for the emulsion reconstruction. The arrow indicates the emulsion track with a corresponding SFT 3D track. This track is followed back with the scan-back procedure up to the interaction point.

For the scanning of the emulsion we used new generation scanning systems [8–11]. We followed two different analysis methods: the scan-back procedure and a general scan method, both applied in the OPERA experiment [2, 12, 13]. See [14]–[17] for details of these scanning procedures.

The scan-back method, schematically shown in figure 6, is based on the scanning of a small area around a predicted point with a narrow angular acceptance. 3D tracks are matched with emulsion tracks recorded in the two most downstream films of the brick, the SS doublet. They are the starting point of the scan-back method and are followed until they stop.

Unlike prediction scanning, the scanning of the large surface where all the tracks within a wide angular acceptance are collected is called a ‘general’ scan. In the general scan approach all of the emulsion film surface is analyzed. The tracking procedures described above are then applied. Candidate multi-prong vertices and single-prong interactions are searched for.

Figure 7 shows as an example a five-prong event vertex detected in the ECC. The event reconstruction with the electronic trackers is shown in the top part. The solid line indicates the
Figure 8. Comparison of NOMAD data and MC after the tuning of the event generator. Left: multiplicity distribution of charged hadrons; right: hadron momentum distribution [20].

3D track reconstructed by the SFT. We use vertical lines to show the position of fiber trackers. Dashed lines are used for the \(U\)- and \(V\)-planes and solid lines for the \(X\)- and \(Y\)-planes. In the bottom figure, we show the vertex reconstruction in the emulsions also for the front view. The small arrow in both figures indicates the reference track matched with the SFT prediction. This track is followed upstream up to the interaction plate. The remaining four tracks were reconstructed with the analysis of the volume surrounding the stopping point of the scan-back track.

5. Detection efficiencies

An MC simulation was developed in the GEANT3 framework [18]. The geometry of the detector with four walls and SFT planes was also fully simulated. The response of the detector is simulated according to the performance obtained with real data at different levels. The position and slopes of emulsion tracks are smeared according to the measured resolution, and some of them are rejected according to tracking inefficiencies. For the SFT detectors the simulation includes the efficiency of the fibers and their resolution, accounting for the measured differences in the various planes. The average efficiency of the SFT planes was about 60%, as measured with rock muons. Both the emulsion and the SFT simulated data are reconstructed with the same software used for the data analysis.

Neutrino events were generated according to the energy spectrum of the NuMI beam [1] in the LE configuration shown in figure 4 with an average energy of 4 GeV. We neglected the effect on the energy spectrum due to the angular tilt of the beam impinging on the PEANUT surface with respect to the MINOS one. The neutrino event generator was tuned on data from the NOMAD experiment [19, 20] and is at present used by the OPERA Collaboration. Figure 8 shows good agreement between the prediction of the event generator and NOMAD data. In the left plot the charged particle multiplicity distribution is shown. On the right plot, the charged hadron momentum distribution is reported.

In our MC simulation, the event vertices are placed randomly in the bricks and then propagated in the detector by GEANT3. A comparison between data and MC events was performed after the implementation of all the steps of \(\nu_\mu\) event reconstruction, from tracking in the electronic detector down to the vertex reconstruction in the ECC bricks.
The ratios of deep inelastic, quasi-elastic and resonance production cross sections to the total CC cross section used to build the MC sample are taken from [21]–[23] and are
\[
\frac{\sigma_{\text{DIS}}}{\sigma_{\text{CC}}} = 0.70 \pm 0.04, \quad \frac{\sigma_{\text{QE}}}{\sigma_{\text{CC}}} = 0.19 \pm 0.04, \quad \frac{\sigma_{\text{RES}}}{\sigma_{\text{CC}}} = 0.11 \pm 0.02.
\]
(1)

Figure 9 shows the multiplicity distribution of 3D tracks reconstructed by the SFT tracker in $\nu_\mu$ events, which shows good agreement between data and MC. A second step in the $\nu_\mu$ event reconstruction is the matching of SFT tracks with emulsion tracks. Residuals in the simulation are compatible with those obtained in the data analysis, as shown in figure 5.

The reconstructed multiplicity at the primary vertices is shown in figure 10 together with the MC expectations assuming the cross sections given in equation (1). The track multiplicity does not include nuclear fragments produced at the neutrino vertex, which are mostly absorbed in the lead plates and cannot be detected in emulsion. The fragments emerging from the lead are erased by the condition of forming a track with at least two segments.

The distribution of muon slopes in $\nu_\mu$ reconstructed interactions is shown in figure 11. The slope is measured with respect to the direction of the incoming neutrino beam. The muon is defined as the emulsion track matching the 3D SFT track. The purity of this selection is about 98%.

6. Experimental results

We analyzed the reconstructed events aiming at disentangling the contributions from deep inelastic, quasi-elastic and resonance production within the total CC cross section. The measured data yield in the $j$th bin of the multiplicity distribution is given by
\[
N_{\text{Data}}(j) = A \times (a_{\text{dis}} \epsilon_{\text{dis}} N_{\text{dis}}(j) + a_{\text{res}} \epsilon_{\text{res}} N_{\text{res}}(j) + a_{\text{qe}} \epsilon_{\text{qe}} N_{\text{qe}}(j)),
\]
(2)
where $\epsilon_i$ ($i = \text{dis, res, qe}$) denotes the reconstruction efficiency estimated by the MC simulation, $a_i$ the different fractions of the scattering processes and $N_i(j)$ the yield of the corresponding
processes in the $j$th bin. The factor $A$ provides the same normalization for the distributions in the left and right sides of the equation.

The applied condition of a 3D track reconstructed in the SFT reduces the expected contribution of neutral current events from 17 to less than 4%. Moreover, the emulsion-to-SFT matching procedure produces an additional bias in favor of CC interactions, so that the neutral current fraction is reduced to about 1%. We thus disregard the neutral current component.

The different fractions are defined as

$$a_j = \frac{\int \sigma_j(E)\phi(E) \, dE}{\sum_i \int \sigma_i(E)\phi(E) \, dE},$$

(3)
Table 1. Unfolded muon slope (left) and multiplicity (right) distributions bin by bin. The distributions are normalized to one.

| Muon slope bin (mrad) | Yield       | Multiplicity bin | Yield       |
|----------------------|-------------|------------------|-------------|
| 0–67                 | 0.225 ± 0.033 | 1                | 0.352 ± 0.052 |
| 67–134               | 0.126 ± 0.025 | 2                | 0.210 ± 0.043 |
| 134–200              | 0.162 ± 0.040 | 3                | 0.156 ± 0.065 |
| 200–267              | 0.119 ± 0.052 | 4                | 0.033 ± 0.036 |
| 267–334              | 0.081 ± 0.048 | ≥ 5              | 0.249 ± 0.145 |
| 334–400              | 0.054 ± 0.054 |                 |             |
| ≥ 400                | 0.233 ± 0.118 |                 |             |

where $\phi(E)$ is the spectrum of the NuMI beam. The fractions $a_i$ are estimated by minimizing the difference in the shapes of the data and MC multiplicity distributions. The MC distribution depends on six parameters: $a_i$ and $\varepsilon_i$. The $\varepsilon_i$ are evaluated from MC with the constraints $\sum_i a_i = 1$ and $a_{\text{res}}/a_{\text{qe}} = 0.58 ± 0.16$, so that the fit depends only on one free parameter. The best fit values are

$$a_{\text{dis}} = 0.68^{+0.09}_{-0.11} \text{(stat)} ± 0.02 \text{(syst)}$$ (4)

$$a_{\text{qe}} = 0.20^{+0.06}_{-0.07} \text{(stat)} ± 0.02 \text{(syst)}$$ (5)

$$a_{\text{res}} = 0.12 ± 0.04 \text{(stat)} ± 0.02 \text{(syst)}.$$ (6)

The uncertainty in the ratio $a_{\text{res}}/a_{\text{qe}}$ is the main source of systematic uncertainty in the measurement. By varying this ratio within its experimental error, we have estimated the systematic uncertainty of our measurement. It is worth stressing that the fit of the multiplicity distribution provides the same value for the deep inelastic fraction even if the constraint on the $a_{\text{res}}/a_{\text{qe}}$ ratio is removed.

These results are obtained with a different experimental technique than those available in the literature. The measured fractions are consistent with the measurements performed with conventional detection techniques [21]–[23]. By using the quasi-elastic cross section measured with NOMAD data [19] and normalizing it to the inclusive CC cross section measured with the MINOS Near Detector data [24], we have obtained a value of $(22.8 ± 1.5)\%$ that is consistent with our estimate of $(20.5^{+2}_{-1})\% ± 2\text{(syst)}\%$.

The muon scattering angle and the charged particle multiplicity in neutrino interactions carry most of the kinematical information on the interaction dynamics. The reconstruction efficiency affects the measured variables modifying the shape of their distributions. Therefore, after the unfolding of the reconstruction efficiencies, the data can be used to study the true distribution of physical variables and tune neutrino event generators.

We report in table 1 the distributions of muon scattering angle (on the left) and charged particle multiplicity (on the right) after the unfolding of the detection efficiencies. The distributions are normalized to one. Note that the track multiplicity includes the muon. The average true multiplicity is 2.6, while the reconstructed one is 1.5.

As mentioned in section 4, the angular acceptance in the scanning of the emulsion films was limited to slopes inclined by at most 400 mrad with respect to the perpendicular direction; moreover, the tolerances used in the tracking algorithm prevent the reconstruction of tracks with
momentum below 380 MeV c\(^{-1}\). These facts mainly contribute to the discrepancy between the average true and the reconstructed track multiplicity.

7. Conclusions

The PEANUT experiment was designed to study the neutrino interactions in the few GeV energy range using the ECC technique. The analysis of the nuclear emulsions has been carried out using last generation fully automated microscope systems, operating at a scanning speed one order of magnitude larger than in the past.

The main goal of the experiment was to measure the contribution of the different scattering processes to the total CC neutrino cross section. This measurement is important for future neutrino oscillation experiments, which will use high-intensity neutrino sources in the few GeV energy range. A better knowledge of neutrino cross sections at this energy is needed in order to optimize the performances of next-generation neutrino experiments. Unlike all the measurements available in the literature, the measurement reported here has used the ECC technique.

The emulsion technique provides a topological reconstruction of neutrino interactions with micrometric accuracy and negligible systematic uncertainties. Therefore, the cross-section measurements reported here were based on the study of charged-particle multiplicity, particularly sensitive to the quasi-elastic and resonant processes.

A sample of 147 \(\nu_\mu\) CC interactions was fully reconstructed. The topology of these events was studied aiming at the measurement of multiplicity distributions of charged particles produced in neutrino interactions and of the scattering angle distribution of the emitted muons. The detector performances were evaluated with a full MC simulation. The deep inelastic fractional contribution to the total CC neutrino cross section was found to be

\[
adis = 0.68^{+0.09}_{-0.11} \text{ (stat)} \pm 0.02 \text{ (syst).} \tag{7}
\]

This measurement is consistent with data reported by previous experiments using different experimental techniques. We have also unfolded the neutrino detection efficiencies from the charged particle multiplicity and the muon scattering angle distributions. The results of the unfolding can be used to tune neutrino event generators in experiments operating on the NuMI neutrino beamline. The uncertainty of the reported measurements is dominated by the limited statistics of the analyzed data sample. The emulsion technique has proven to be particularly suited to the detection of low-energy neutrino interactions and the measurement of their topologies.

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