Forthcoming publication on Multiplicity

Study of Charged Particle Multiplicities in High Energy Neutrino-Lead Interactions in the OPERA Detector

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Study of Charged Particle Multiplicities in High Energy Neutrino-Lead Interactions in the OPERA Detector

OPERA Collaboration

Abstract

The OPERA experiment has been designed to search for $\nu_\mu \to \nu_\tau$ oscillation in appearance mode through the direct observation of tau neutrinos in the CNGS neutrino beam. In this paper, we report a study of charged particle multiplicities initiated in high energy charged current neutrino interactions in lead in the OPERA detector. We present charged particle average multiplicities, their dispersion and investigate the KNO scaling in different kinematical regions based on event-by-event analysis. The results are presented in detail in the form of tables that can be used in the validation of Monte Carlo generators of neutrino-lead interactions.

CONTENTS

1 Introduction

The multiplicity distribution of charged hadrons is an important characteristics of the final hadron states in hard scattering processes. It reflects the dynamics of the interaction process. Therefore, it has been studied extensively in cosmic rays, fixed target and collider experiments [1–5]. These data are useful to improve models of particle productions which are available as Monte Carlo event generators.

In this paper, we report the results on charged-hadron production initiated in high energy charged-current ν_μ interactions in the OPERA target.

The basic unit that constitutes the target is the Emulsion Cloud Chamber (ECC) detector which is a stack of interleaved nuclear emulsion films acting as high precision trackers and lead plates that provide a massive target. The excellent spatial resolution of nuclear emulsion allows the determination of the event topology and the measurement of charged particle trajectories. Therefore, it is well suited for the investigation of the multiplicity moments of charged particles. However, only few studies of charged-particle multiplicity in neutrino-nucleon interactions were made using the nuclear emulsion technology [5–7].

In the following, a short description of the experimental setup and of the procedure used to locate neutrino interactions in the target is given and the data sample and the analysis procedure are described. Then, multiplicity moments and investigation of KNO scaling in different kinematical regions based on event-by-event measurement are presented in a form suitable for use in the validation of Monte Carlo generators of neutrino−lead interactions.

CONTENTS

2 Experimental Procedure

The OPERA experiment has been designed for the observation of $\nu_\mu \to \nu_\tau$ oscillation in appearance mode in the CNGS neutrino beam. The detector was located at the underground Gran Sasso Laboratory (LNGS) in Italy. It was exposed to the CERN CNGS ν_μ neutrino beam over a baseline of 732 km [8]. The mean energy is 17 GeV, well above the ν_τ-production threshold. OPERA reported the discovery of ν_τ appearance with a significance of 5.1σ [9].

The OPERA detector is a hybrid setup consisting of electronic detectors and a massive lead-emulsion target segmented into ECC units, called brick. The detector, shown in Figure 1 is composed of two identical super-modules (SM). Each super-module has a target section followed by a muon spectrometer which is composed of a dipole magnet instrumented with resistive plate chambers and precision drift tubes Each target section has 31 brick walls interleaved with orthogonal pairs of scintillator strip planes that compose the Target Tracker (TT). A detailed description of the OPERA detector can be found in [10].

A brick consists of 57 emulsion films interleaved with 56 lead plates of 1 mm thickness. The emulsion films are made of 2 emulsion layers, each 44 μm thick coated on both side of the 205 μm transparent plastic base. The brick has transverse dimensions of 128×103 mm, a thickness of 81 mm ($10X_0$ radiation length) and it weighs 8.3 kg. A pair of removable emulsion films (CS) is attached to the downstream face of each brick. They act as interface between the emulsion films in the brick and the TT. There are about 140,000 bricks in total for a target mass of 1.2 ktons.

TT hits pattern are used to identify the bricks possibly containing a neutrino interaction vertex. The most probable brick is then extracted from the target and its CS films scanned. If a signal compatible with the TT predictions is found, the brick is disassembled and its films analysed. Once the vertex has been located a surrounding volume of about 2 cm^3 is scanned to detect short-lived particle decays. Otherwise, the procedure is repeated in the next brick in the probability ranking. Track recognition in an emulsion layer is based on 16 tomographic images, equally spaced through the 44-μ m depth of the layer, taken by the CCD of an automated microscope. A sequence of aligned grains in a layer forms a micro-track and the linking of two matching micro-tracks on each side of the plastic base in a film constitute a base-track. Track positions and slopes are determined by a linear fit through base-tracks in the analysed volume. The details of the event analysis procedure are described in [11].

CONTENTS

3 Analysis

During the physics runs between 2008 and 2012, OPERA collected data corresponding to 17.9x10^{19} protons on target with 19,505 recorded events [11], out of which 5408 events were fully analyzed. It is observed that 4264 of the located events have an identified muon. For the present measurement a sample of 850 events with a negatively charged muon, identified by the muon spectrometer, randomly selected in order to investigate in detail and to measure the track and vertex parameters in the ECC target. We further require that the square of the invariant mass of the hadronic system, W^2 is larger than 1 GeV^2/c^4 to reduce the quasi-elastic contribution. After this selection the number of $\nu_\mu CC$ interactions is 826. Selected $\nu_\mu CC$ events are inspected carefully and particle tracks are classified as shower, grey and black based on the ionization features. Shower tracks are left by the muon and by highly relativistic charged hadrons resulting from the cascade of interactions generated inside the target nucleus by the primary hadrons emitted with the muon at the neutrino-nucleon interaction. Black tracks are produced by low energy fragments (protons, deuterons, alpha particles and heavier fragments) emitted from the excited target nucleus. The black tracks are classified as backward and forward based on the emission direction. The grey tracks are left by slow particles which are interpreted as being recoil nucleons emitted during the nuclear cascade [12]. The black tracks are easy to recognise visually since they are heavily ionising, they have short pathlengths and stop within one emulsion plate. The separation between shower and grey tracks is based on the Pulse Height Volume (PHV) [13, 14] which is defined as the sum of the number of pixels associated with each track in all sixteen layers of CCD images. PHV indicates the track width and is therefore a measure a measure of the grain density of a track that reflects the energy deposition of a particle in the emulsion film. The PHV distribution of muon tracks is shown in Figure 2. All muon tracks have a PHV value below 85 and we have defined shower tracks by requiring a PHV smaller than 95, one σ above 85. The tacks with PHV $\geq$ 95 are classified as grey. The shower, grey and black track multiplicities are shown in Figures 3, 4 and 5, respectively. The distribution as a function of the emission angle of shower tracks is given in Table 2 and the fraction of track types is displayed in Table 1.

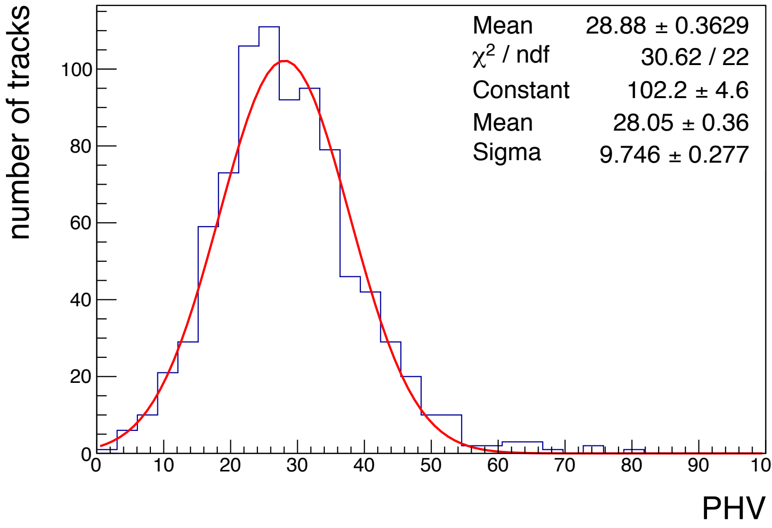

Figure 2: Pulse Height Volume distribution of muon tracks.

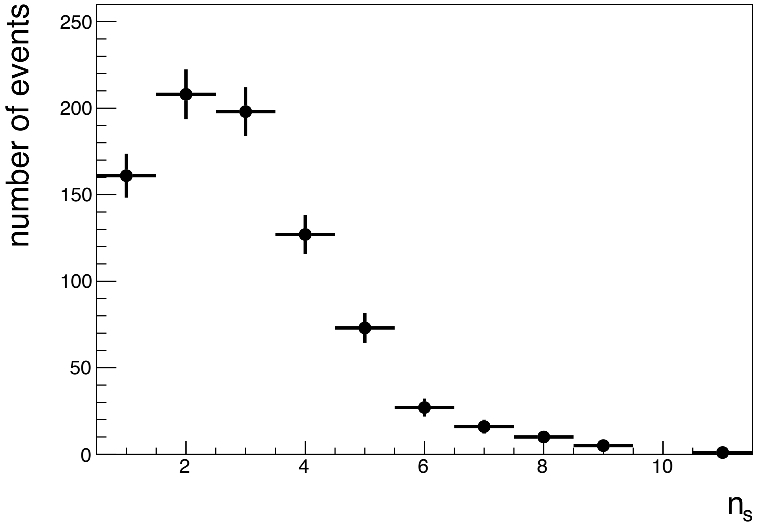

Figure 3: Multiplicity distribution of shower tracks.

CONTENTS

Efficiency Estimation

3.1 Efficiency Estimation

Reconstruction and location efficiencies are computed using the standard OPERA simulation framework. The neutrino fluxes and spectra are based on a FLUKA simulation [15] of the CNGS beam-line. The neutrino interactions in the detector are generated using the NEGN generator [16]. MC-generated $\nu_\mu CC$ events are processed through the full OPERA simulation chain, from the event classification and brick finding provided by the electronics detectors to the CS analysis and event location and analysis in the brick, up to the decay search.
The location efficiency, shown in Table 3, of the $\nu_\mu CC$ events is estimated as a function of the square of the invariant mass of the hadronic system W_ν^2 and of the charged hadrons multiplicity in the shower, referred to as charged particles multiplicity in what follows, equal to $n_{ch} = n_s$ -1, the number of shower tracks minus the muon track. Since the event location is done using shower tracks, the location efficiency does not depend on the black and grey track multiplicity at the neutrino interaction vertex. Figure 6 shows the good agreement between the charged particles multiplicities obtained for observed and MC simulated data. The location efficiency correction is hereafter applied to the measured data distributions.

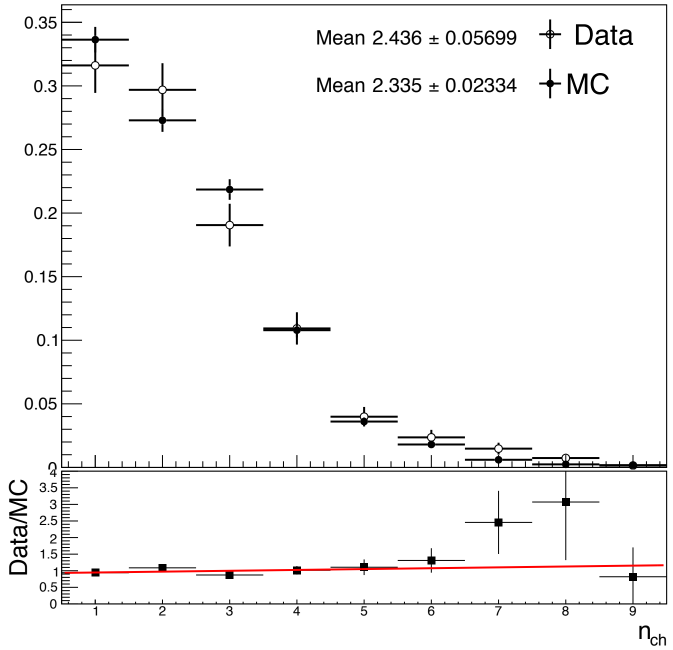

Figure 6: Data-MC comparison of the charged particles multiplicity.

Table 3: Location efficiency as a function of W^2 and the charged particles multiplicity.

$\mathbf{W^2}$	$\mathbf{n_{ch} = n_s - 1}$						
$(GeV)^2/c^4$	0	1	2	3	4	$\geqslant 5$	*All*
1-3	0.41 ± 0.03	0.44 ± 0.03	0.50 ± 0.04	0.47 ± 0.06	0.47 ± 0.09	0.57 ± 0.18	0.50 ± 0.01
3-6	0.39 ± 0.02	0.42 ± 0.02	0.48 ± 0.03	0.48 ± 0.04	0.43 ± 0.06	0.61 ± 0.11	0.56 ± 0.01
6-9	0.38 ± 0.03	0.51 ± 0.03	0.61 ± 0.03	0.70 ± 0.04	0.75 ± 0.08	0.50 ± 0.12	0.59 ± 0.01
9-12	0.34 ± 0.03	0.56 ± 0.02	0.64 ± 0.02	0.65 ± 0.04	0.76 ± 0.07	0.71 ± 0.08	0.63 ± 0.01
12-15	0.31 ± 0.03	0.51 ± 0.02	0.63 ± 0.02	0.64 ± 0.03	0.68 ± 0.05	0.59 ± 0.09	0.60 ± 0.01
15-19	0.34 ± 0.03	0.55 ± 0.02	0.62 ± 0.02	0.70 ± 0.03	0.70 ± 0.04	0.76 ± 0.06	0.64 ± 0.01
19-25	0.30 ± 0.04	0.56 ± 0.02	0.66 ± 0.02	0.69 ± 0.02	0.69 ± 0.03	0.67 ± 0.05	0.66 ± 0.01
25-35	0.33 ± 0.04	0.59 ± 0.02	0.46 ± 0.02	0.55 ± 0.02	0.64 ± 0.03	0.73 ± 0.04	0.67 ± 0.01
>35	0.44 ± 0.04	0.41 ± 0.02	0.45 ± 0.02	0.49 ± 0.02	0.56 ± 0.03	0.49 ± 0.04	0.48 ± 0.01
All	0.35 ± 0.01	0.52 ± 0.01	0.60 ± 0.01	0.66 ± 0.01	0.68 ± 0.01	0.63 ± 0.01	0.63 ± 0.01

CONTENTS

Multiplicity Distribution

3.2 Multiplicity Distributions

The average charged particles multiplicity as a function of W^2 is presented in Figure 7. The data is well described by a linear function in lnW^2:

$$\langle n_{ch} \rangle = a + b\ lnW^2 \tag{1}$$

The values for the fitted parameters a and b are

$$\langle n_{ch} \rangle = (-0.12 \pm 0.19) + (0.87 \pm 0.07) lnW^2 \tag{2}$$

The average charged particles multiplicity increases with W^2. The values for different W^2 bin intervals are in given in Table 4. A comparison with other experiments is given Table 5.

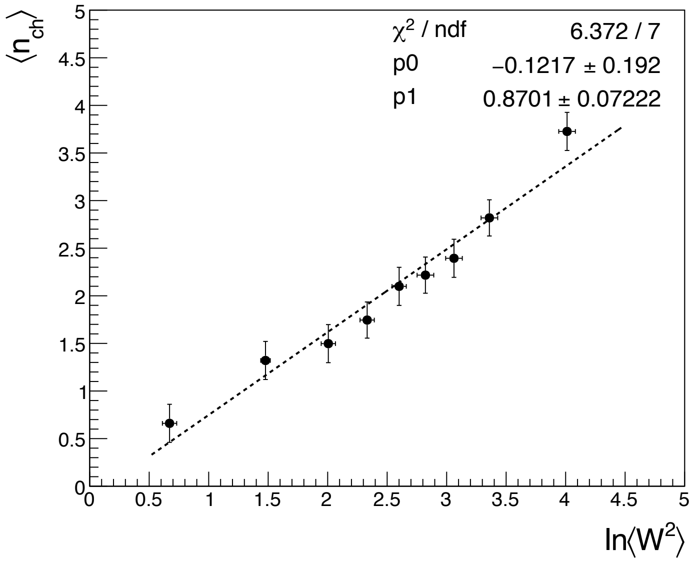

Figure 7: The average charged particles multiplicity distributions as a function of lnW^2.

Table 4: The charged particles multiplicity distribution as function of W^2(errors shown are statistical only).

		$\mathbf{n_{ch} = n_s - 1}$												
$W^2 (GeV)^2/c^4$	$\langle W^2 (GeV)^2/c^4 \rangle$	0	1	2	3	4	5	6	7	8	9	10	$\geqslant 11$	Events
1-3	1.99 ± 0.05	59	22	8	2	0	1	0	0	0	0	0	0	92
3-6	4.40 ± 0.08	29	41	25	4	2	0	1	0	0	0	0	0	102
6-9	7.47 ± 0.08	28	37	17	12	6	1	1	0	0	0	0	0	102
9-12	10.39 ± 0.09	9	27	27	13	9	2	1	0	0	0	0	0	88
12-15	13.70 ± 0.08	10	26	30	26	7	2	3	1	0	0	0	0	105
15-19	17.03 ± 0.11	11	14	37	15	8	4	1	0	1	0	0	0	91
19-25	21.75 ± 0.19	8	19	23	20	11	3	2	3	0	0	0	0	89
25-35	28.86 ± 0.30	4	16	16	20	13	7	3	1	1	0	0	0	81
>35	56.81 ± 3.00	3	6	15	15	17	7	4	5	3	0	1	0	76

Table 5: Values of the parameters of the linear fit to the average charged hadrons multiplicity dependence on lnW^2. The results from other experiments are also shown for the comparison.

Reaction	**E_ν(GeV)**	**a**	**b**	**Ref.**
ν_μ-emulsion	40	0.45± 0.24	0.94± 0.08	[5]
ν_μ-emulsion	50	1.92 ± 0.68	1.19± 0.23	[6]
ν_μ-emulsion	8.7	1.07 ± 0.05	1.32± 0.11	[7]
ν_μ-Lead	20	-0.12 ± 0.19	0.87± 0.07	OPERA

CONTENTS

Dispersion

3.3 Dispersion

One of the characteristics of the multiplicity distribution which is of considerable theoretical interest is its dispersion. In this section we investigate its dependence on the average multiplicity. The dispersion D_{ch} is defined as

$$D_{ch} = \sqrt{\langle n_{ch}^2 \rangle - \langle n_{ch} \rangle^2} \tag{3}$$

For independent particle production it follows Poisson distribution:

$$D_{ch} = \sqrt{\langle n_{ch} \rangle} \tag{4}$$

However, it was observed that charged particles production in hadronic interactions satisfies an empirical parameterization [17]:

$$D_{ch} = A + B\langle n_{ch} \rangle \tag{5}$$

Figure 8 shows the dependence of the dispersion on the average multiplicity $\langle n_{ch} \rangle$ with a linear fit superimposed. The values of the fit parameters are

$$D_{\langle n_{ch} \rangle} = (0.53 \pm 0.10) + (0.42 \pm 0.05)\langle n_{ch} \rangle \tag{6}$$

In Table 6, parameters A and B obtained in other experiments are shown for a comparison.

Table 6: Parameters A and B obtained by a linear fit on the distribution of D_{ch} versus $\langle n_{ch} \rangle$. The results obtained in other neutrino experiments are also shown.

Reaction	**A**	**B**	**Ref.**
ν_μ-Emulsion	1.18± 0.17	0.20± 0.05	[5]
ν_μ-p	0.36 ± 0.03	0.36± 0.03	[4]
ν_μ-Lead	0.53 ± 0.10	0.42± 0.05	OPERA

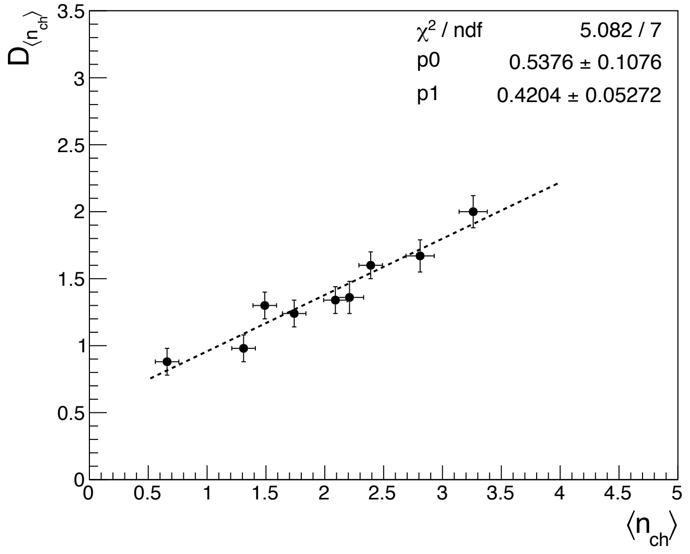

Figure 8: The charged particles multiplicity dispersion as a function of $\langle n_{ch} \rangle$.

CONTENTS

KNO Scaling

3.4 KNO Scaling

Koba, Nielsen, and Olesen have shown that the shape of the multiplicity distribution $P(n_{ch})$ scaled by the average multiplicity $\langle n_{ch}\rangle$ is asymptotically independent of the primary energy at high energies except through $z = \frac{n_{ch}}{\langle n_{ch}\rangle}$ [18]:

$$\langle n_{ch}\rangle \,.\, P(n_{ch}) \xrightarrow{E\to\infty} \Psi\Big(z = \frac{n_{ch}}{\langle n_{ch}\rangle}\Big) \tag{7}$$

KNO scaling is derived from Feynman scaling, i.e., based on the assumption that the rapidity density $\frac{dn_{ch}}{dy}$ reaches a limiting value at $y = 0$ above a certain energy which corresponds to an asymptotic scaling of the total multiplicity as $\langle n_{ch}\rangle \propto ln\sqrt{s}$. To be exact KNO scaling implies that the intercept A in the linear fit to the dependence of the dispersion on the average multiplicity be compatible with 0, which is not the case at low to medium energies for all kinds of interactions. Buras et al. [19] have introduced a new variable z' defined as

$$z' = \frac{n_{ch} - \alpha}{\langle n_{ch} - \alpha\rangle} \tag{8}$$

where the energy independent parameter alpha is chosen in order to provide an extension of the KNO scaling to low energies.

$$\Psi(z') = (n_{ch} - \alpha)\frac{\sigma_{n_{ch}}}{\sigma_{inel}} \tag{9}$$

A tentative explanation to a non-zero value for alpha has been proposed in terms of a leading particle effect in interactions of hadrons [20] and of neutrinos [21] as well as resulting from the heavy nuclear targets in neutrinos experiments using emulsion [5]. Alpha is equal to minus the extrapolated point of intercept of the fitted dispersion line with the average multiplicity axis in Figure 8 and found to be 1.27.

Figure 9 shows the distributions obtained for Ψ as a function of z' for three different intervals of W^2 for ν_μ-lead CC interactions. The curve superimposed on the data yields the following function:

$$\Psi(z') = (-3.3z' + 38.8(z')^3 - 12.3(z')^5 + 1.15(z')^7)e^{-3.22z'} \tag{10}$$

The data shows good agreement with KNO scaling. Similar results have been obtained in other experiments [5], [21–24] with different α.

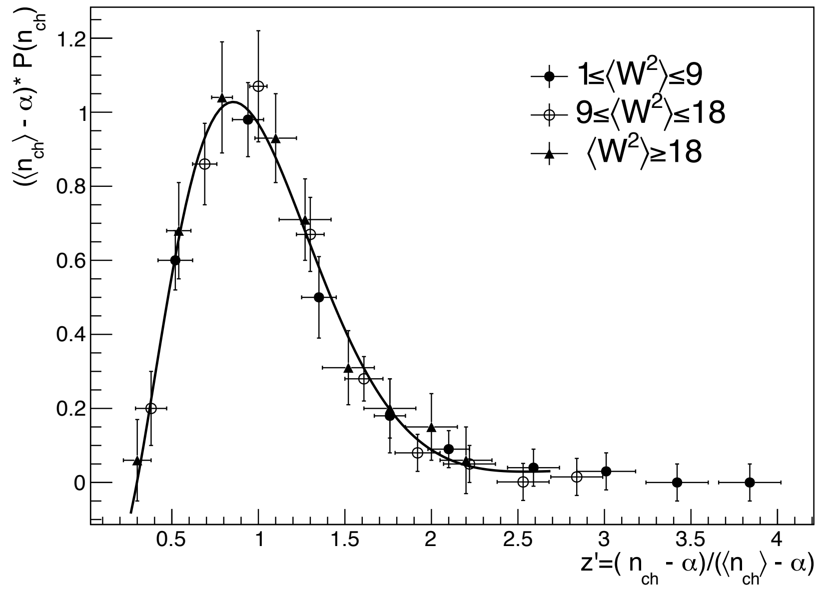

Figure 9: KNO scaling distribution. A curve represents a fit to pp data [20].

CONTENTS

Conclusion

4 Conclusion

In the this article, we studied the characteristics of the multiplicity distribution of charged hadron particles in neutrino-lead interactions in the OPERA detector. The results presented in this paper have been obtained with the main objective to aid in tuning neutrino-lead interaction models of the Monte Carlo event generators. To ease the use of these results, the numbers are presented in detail in the form of tables. The results can be summarized as follows.

i The dependence of the average multiplicity $\langle n_{ch} \rangle$ on lnW^2 is approximately linear.

ii The dependence on the charged charged particles multiplicity n_{ch} of its dispersion D_{ch} is approximately linear. The same result is obtained in other neutrino experiments.

iii KNO scaling is valid in the given energy ranges for the charged particles multiplicity.

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