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Study of KNO scaling in the emulsion based neutrino experiments

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Abstract: KNO scaling was put forward by Koba–Nielsen–Olesen in 1972 and then tested by various experiments up to now. In this paper, the data on charged hadron multiplicity moments with KNO scaling of CHORUS and OPERA, both of them emulsion-based neutrino experiments, are compared. The results are given in detail which is very useful for tuning in MC event generators.

Key words: KNO, neutrino, emulsion, multiplicity

1. Introduction

The charged hadron multiplicity distribution is a very important parameter to understand the characteristics of the final hadronic states and particle production mechanism in neutrino interactions. As it provides the information about the interaction dynamics of charged particles, it has been studied in many experiments with different energies and beams up to now [1–8]. Indeed, such studies are also very useful to improve hadronic multiparticle production models for use in neutrino event generators.

The first study about the behavior of multiplicity distributions was made by Koba, Nielsen, and Olesen (KNO) in 1972 [9]. KNO predicts that multiplicity distribution scaled by the mean value of multiplicity is only function of n / ⟨n⟩. This means that at very high energies, multiplicity distribution comes out as continuous functions as shown in Figure 1a. Here, n is the multiplicity, number of charged hadrons at final state, in an event and P_n is the probability of producing n particles given as,

$$P_n = \frac{\sigma_n}{\sum_0^\infty \sigma_n}$$

where σ_n is the cross section for producing n particles and the mean multiplicity is given as,

$$\langle n \rangle = \sum n P_n$$

If all curves contracted with the mean multiplicity ⟨n⟩ and extended along vertical direction with the same weight, the area under curves remain unchanged. The KNO scaling predicts that all curves coincide and eventually give a single curve as shown in Figure 1c, that is,

$$\langle n \rangle \, P_n = \Psi \left(\frac{n}{\langle n \rangle} \right) \quad z = \frac{n}{\langle n \rangle}$$

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where $\Psi(z)$ is independent of primary energy [10]. One of the consequences of KNO scaling is that dispersion over mean multiplicity is independent of kinematic quantities.

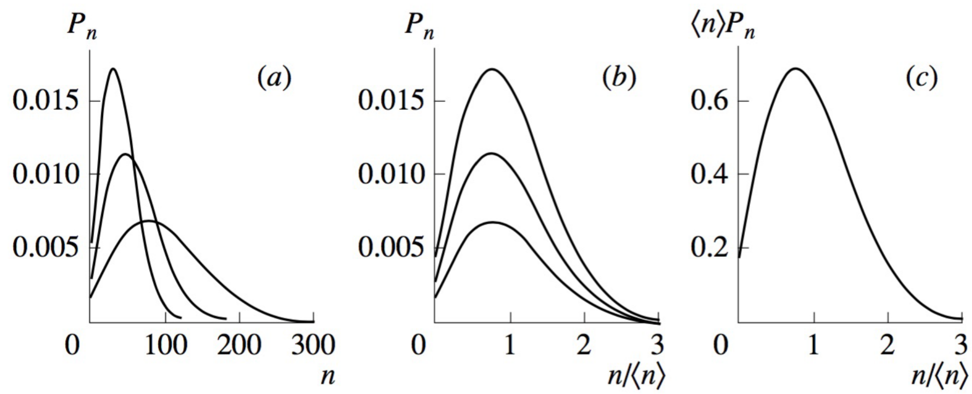

Figure 1. If the normalized functions (a) are scaled with $\langle n\rangle$ along horizontal and vertical directions they coincide at each point (c).

Although most of the data are agree with KNO behavior, some of them showed a violation of KNO scaling. For example, E735 Collaboration observed a strong violation above Intersecting Storage Rings (ISR) energies as shown in Figure 2 [11]. According to their data, KNO scaling is not satisfied over 200 GeV center of mass energy range.

The KNO scaling is also tested in many neutrino-nucleon interactions and most of them are based on old bubble chamber experiments [1–6,12,13]. Although their multiplicity distributions are consistent with KNO scaling, a quantitative criteria is not applied for the hadron track selection. Therefore, their data cannot be compared with theoretical models in a consistent way.

In this work, multiplicity distributions and KNO scaling behavior of CHORUS and OPERA experiments, which have similar beam energies and based on the same technique, are compared. Such combined data are very useful for hadronic multiparticle production models for MC event generators.

2. Overview of experiments

The CHORUS and OPERA experiments were designed to search for neutrino oscillations in the appearance mode. Both detectors were hybrid setup that combines the nuclear emulsion technology and electronic detectors.

The CHORUS experiment was designed to search for $\nu_\mu \rightarrow \nu_\tau$ oscillations in the SPS Wide Band Neutrino Beam [14]. As CHORUS is based on nuclear emulsion technique, it provides event by event analysis with submicron spatial resolution. In total about 100k charged-current (CC) neutrino interactions with at least one muon were located in the emulsion target, using fully automated scanning systems. However, the multiplicity analysis was based on a subsample of located CC events. A randomly selected 627 events visually inspected and measured in detail. In their analysis, particle classification was not based on ionization features but particles were classified by using the pseudo-rapidity variable $\eta = -\ln\tan(\theta/2)$, where θ is emission angle of shower particles with respect to beam axis as shown in Figure 3 [7].

This allows the track classification to be independent of any variation in the microscope optics and scanner. Therefore, the multiplicity distributions can be compared with theoretical models in a straightforward manner. All prongs with pseudo-rapidity greater than 1 are selected as shower particles.

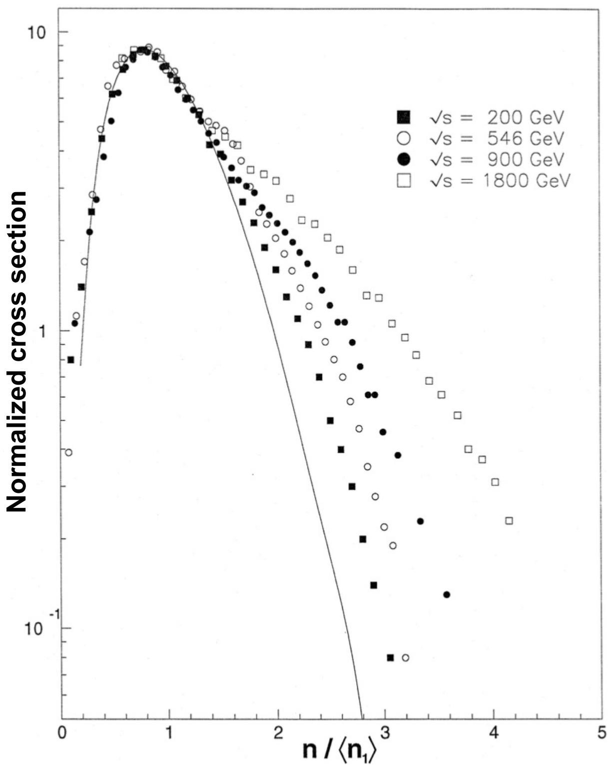

Figure 2. Violation of KNO scaling at high energies [11].

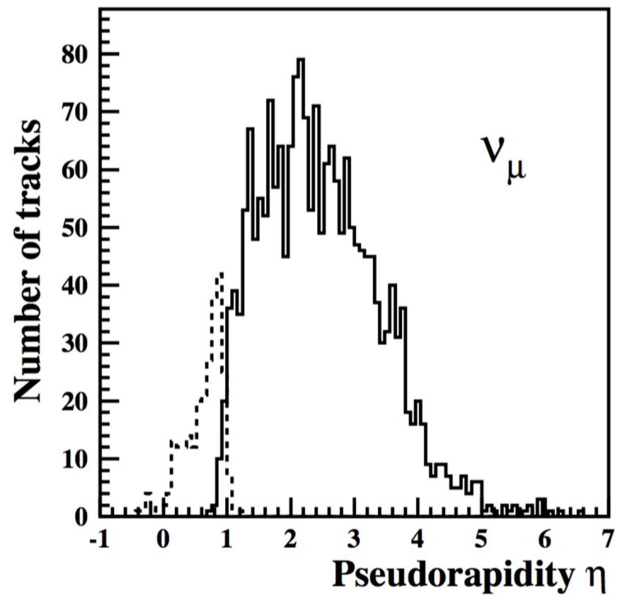

Figure 3. Pseudo-rapidity distributions for tracks classified as shower of the CHORUS experiment.

The OPERA experiment was designed to search for $\nu_\mu \to \nu_\tau$ oscillations in appearance mode in the CNGS neutrino beam [15]. The detector had 2 identical Super-Modules and each of them had a target section followed by a muon spectrometer. The target was made of walls filled with lead/emulsion bricks interleaved with 31 planes that compose the Target Tracker.

A brick is a mechanical unit which consist of 57 emulsion films interleaved with 56, 1 mm thick lead plates and total weighs 8.3 kg. Like CHORUS, OPERA is an emulsion-based experiment. This allows event by event analysis of each located neutrino interactions. OPERA has located about 5603 neutrino interactions in their bricks [16]. For the multiplicity measurement, a subsample of 817 neutrino events with an identified negative muon was selected. The charged particle classification at neutrino interaction vertex is based on Pulse Height Volume (PHV) of CCD camera. It corresponds to track width and defined as a sum of the number of pixels associated with each track in all sixteen layers of images. Therefore, this parameter reflects ionization features of the particles. Figure 4 shows the PHV distribution of muon tracks. Based on this distribution track with PHV <85 is classified as shower particle. The multiplicity distribution of shower particles of both experiments is shown in Figure 5. Some important parameters of CHORUS and OPERA experiments are given in Table 1 for a comparison.

3. Multiplicity distributions and KNO scaling

One of observable in neutrino interactions is the charged multiplicity which can be measured easily and its distribution is a very helpful tool for studying fragmentation models. To date many experiments with electrons,

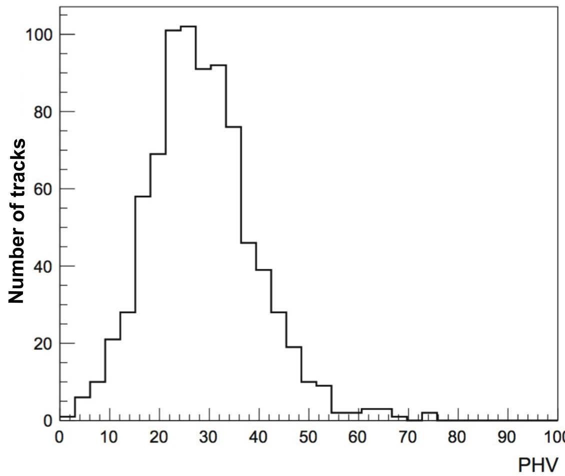

Figure 4. Pulse height volume distribution for muon tracks of the OPERA experiments.

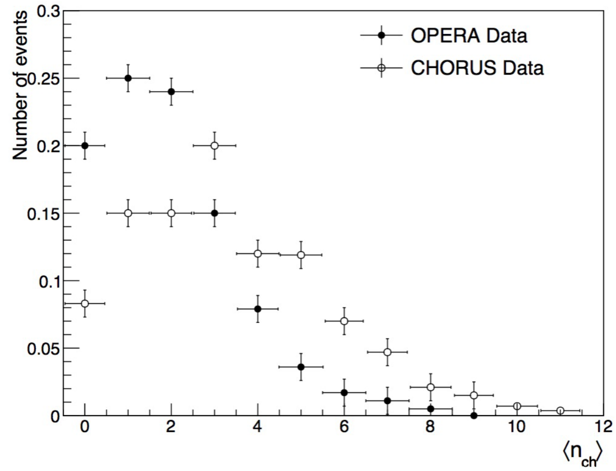

Figure 5. Charged hadron multiplicity distributions of CHORUS and OPERA experiments.

Table 1. Summary table of CHORUS and OPERA experiments.

	CHORUS	**OPERA**
Purpose	observation of $\nu_\mu \rightarrow \nu_\tau$ oscillation short baseline	observation of $\nu_\mu \rightarrow \nu_\tau$ oscillation long baseline
Beam	SPS wide band ν_μ beam	CNGS ν_μ beam
Detector	Hybrid	Hybrid
Target	Emulsion	Lead
Av. beam energy	27 GeV	17 GeV

nuclei and protons have measured multiplicity. However, the multiplicity data in neutrino interactions are very rare. Only recently two emulsion based neutrino experiments CHORUS and OPERA published multiplicity distributions and also tested KNO scaling with a reliable statistics [7,8]. Their multiplicity distributions follow a negative binomial distribution exhibiting approximate KNO scaling.

In order to compare dependency of multiplicity on square of invariant hadronic energy, CHORUS and OPERA data are scaled to the origin as shown in Figure 6. Here W^2 is the invariant hadronic energy and expressed as follows:

$$Q_\nu^2 = 2E_\nu \left(E_\mu - p_\mu cos\theta_\mu\right) - m_\mu^2$$

$$W^2 = 2m_N E_{had} + m_N^2 - Q_\nu^2$$

The Q_ν^2 is the squared four-momentum transfer, E_ν and E_μ are the energy of the neutrino and the muon, m_N and m_μ are the mass of the nucleon and muon. Momentum of muon is p_μ and θ_μ angle of muon with respect to the beam axis [8]. As can be seen both data sets are very consistent with linear dependence on lnW^2. Therefore, a line $\langle n_{ch} \rangle = a + blnW^2$ is superimposed on both data sets. The values of the fitted parameters are given in Table 2 separately.

Similarly, the linear dependence of dispersion on average multiplicity distribution was first observed for ν-Em interaction and then confirmed with ν-Pb interaction. Their distributions are shown in Figure 7 with the combined fit. As seen, both data are consistent with the empirical parameterization $D_{ch} = A + B \langle n_{ch} \rangle$ and the parameters of the linear fit to the distributions are given in Table 3.

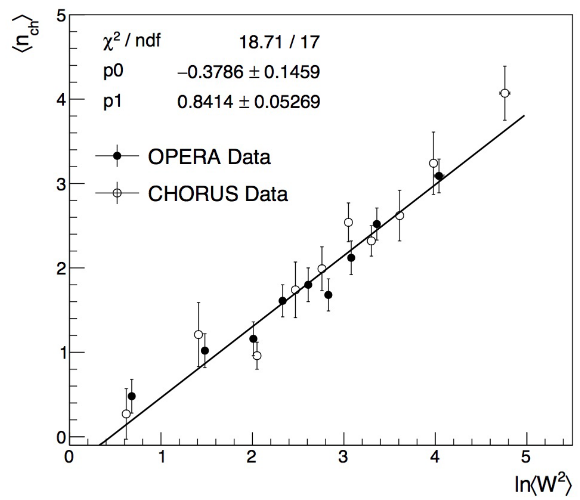

Figure 6. The average charged hadron multiplicity distributions of CHORUS and OPERA experiment.

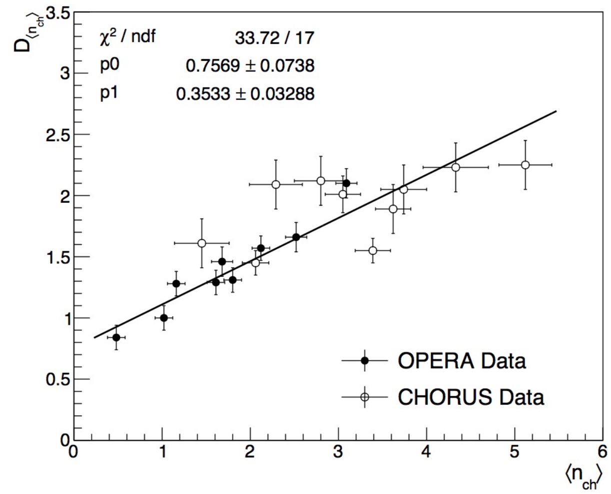

Figure 7. The charged hadrons multiplicity dispersion distributions of CHORUS and OPERA experiments.

Table 2. Fit parameter values of the average charged multiplicity dependence on lnW^2.

Interaction	a	b
$\nu-$Em (CHORUS)	0.45 ±0.24	0.94 ±0.08
$\nu-$Pb (OPERA)	-0.19 ±0.18	0.76 ±0.07
Combined fit	-0.37 ±0.14	0.84 ±0.05

Table 3. Fit parameter values of D_{ch} versus $\langle n_{ch} \rangle$.

Interaction	A	B
$\nu-$Em (CHORUS)	1.18 ±0.17	0.20 ±0.05
$\nu-$Pb (OPERA)	0.59 ±0.12	0.46 ±0.06
Combined fit	0.75 ±0.07	0.35 ±0.03

After the KNO scaling has been experimentally tested in many experiments at high energies, in 1973, Buras et al. [17] have introduced a new variable the alpha parameter (α) which provides an extension of the KNO scaling to low energies. Then, z' definition with a new variable α as follows,

$$\langle n_{ch} \rangle . P \langle n_{ch} \rangle \xrightarrow{E \to \infty} \Psi(z) \quad z' = \frac{n_{ch} - \alpha}{\langle n_{ch} - \alpha \rangle}$$

This modified formula is used in both CHORUS and OPERA data to test the KNO scaling and the obtained alpha parameter, which depends on the reaction, is given in Table 4. The Figure 8 shows KNO scaling data belong to the CHORUS and OPERA charged current (CC) interactions which is valid in their energy region. In order to compare and test KNO scaling, the W^2 bins of both experiments are tuned to be thesame W^2 intervals, namely $1 \leqslant W^2 < 18$ and $W^2 \geqslant 18$. Then, a fit is superimposed on the both data sets. The parameterisation of the fitted curve is,

$$\Psi(z) = \left(Az^3 + Bz^4\right) e^{-Cz}$$

which was put forward first by Slattery [18] at pp data.

According to the fit parameters given in Table 5, the superimposed fit line shows a good agreement with both data sets. Therefore, CHORUS and OPERA multiplicity distributions satisfy to good accuracy the KNO scaling.

Table 4. Alpha parameters.

Interaction	**Alpha parameters**
$\nu-$Em (CHORUS)	-5.82
$\nu-$Pb (OPERA)	-1.28
Combined fit	-2.14

Table 5. Fit parameters.

A	**B**	**C**	$\mathbf{x^2/ndf}$
30.23	-9.8	3.25	0.65

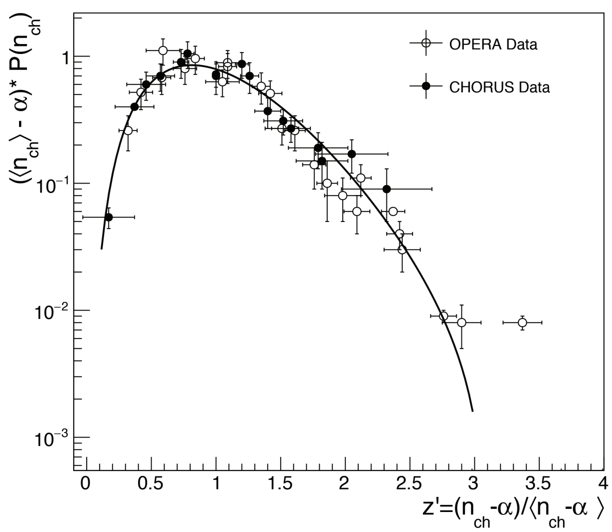

Figure 8. KNO scaling ν-Em and ν-Pb interactions.

4. Conclusion

In this article, CHORUS and OPERA data on charged hadron multiplicity moments and KNO scaling are compared. Both experiments are based on the same technique and used neutrino beam. Although they have different average beam energies and target, the multiplicity moments have similar behavior. New fits are superimposed on the combined data sets. The dependence of the average shower multiplicity on lnW^2 and on dispersion is consistent with a linear model. In particular, their multiplicity distributions exhibit KNO scaling as a function of an appropriate variable z'. The multiplicity distributions and fit parameters of the combined data can used for tuning MC event generators.

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