Available online at www.sciencedirect.com

Nuclear Physics B (Proc. Suppl.) 145 (2005) 93–97

NUCLEAR PHYSICS B
PROCEEDINGS
SUPPLEMENTS

www.elsevierphysics.com

CNGS neutrino beam systematics for θ_{13}

A. Ferrari [a]* A. Guglielmi [b] P. R. Sala [c]

[a]CERN, 1211 Geneve 23, Switzerland.

[b]Istituto Nazionale di Fisica Nucleare and Dept. of Physics, via Marzolo 8, 35131 Padova, Italy.

[c]Istituto Nazionale di Fisica Nucleare, via Celoria 16, 20133 Milano, Italy.

Energy spectra, intensity and composition of the CERN to Gran Sasso CNGS neutrino beam for $\nu_\mu \to \nu_\tau$ and $\nu_\mu \to \nu_e$ oscillation searches are presented. The associated beam systematics, which is the major ingredient for the $\nu_\mu \to \nu_e$ search sensitivity, are obtained from the study of the previous CERN West Area Neutrino Beam.

1. Introduction

Over the next five years the present generation of oscillation experiments at accelerators with long-baseline ν_μ beams, K2K at KEK [1], MINOS at NUMI beam of FNAL [2] and ICARUS and OPERA [3] at CNGS CERN to Gran Sasso neutrino beams [4] is expected to confirm the $\nu_\mu \to \nu_\tau$ transitions observed in the atmospheric ν and measure $\sin^2 2\theta_{23}$ and $|\Delta m^2_{23}|$ within 10 % of accuracy if $|\Delta m^2_{23}| > 10^{-3}$ eV^2. K2K and MINOS are looking for neutrino disappearance, by measuring the ν_μ survival probability as a function of neutrino energy while ICARUS and OPERA will search for evidence of ν_τ interactions in conventional ν_μ beams.

Even not explicitly optimized for $\nu_\mu \to \nu_e$ searches these experiments can explore $\sin^2 2\theta_{13}$ oscillation parameter beyond the CHOOZ limit [5]. In particular ICARUS and OPERA [3] can reach a combined sensitivity on $\sin^2 2\theta_{13}$ (CP violation and matter effects not accounted for) a factor ~ 5 better than CHOOZ in the allowed parameter region of atmospheric neutrino oscillations for five years exposure to the CNGS beam at nominal intensity [6]. The $\nu_\mu \to \nu_e$ oscillations will be searched for as ν_e charge current events excess over the ν_e contamination of the beam: the key issue will be the knowledge of the neutrino beam composition and spectrum. A strong impact on $\sin^2 2\theta_{13}$ sensitivity is expected from the systematics of the ν_e/ν_μ ratio, and in particular from its normalization error.

The CNGS beam-line design was accomplished on the basis of the previous WANF ν_μ beam experience at CERN SPS [7] for CHORUS and NOMAD experiments [8] which allowed for a powerful study of the neutrino beam providing a strong benchmark for conventional neutrino beams and in particular for the CNGS. In this sense the CNGS beam systematics on ν_e/ν_μ ratio can be derived and predicted from the previous measurements and studies performed with the WANF.

2. The WANF: a case of study

In the WANF ν_μ facility 450 GeV/c protons were extracted by the SPS and sent into a segmented target composed by 11 Be rods, 10 cm of length and 3 mm diameter each. The produced positive (negative) mesons, essentially π and K, were focused (defocused) by two pulsed magnetic lenses (horn and reflector) into a 290 m vacuum decay tunnel were neutrinos were produced. The resulting ν_μ beam in NOMAD at 840 m from the Be target, was characterized by an energy ~ 24.3 GeV and a contamination of $\sim 6.8\%$, $\sim 1\%$ and 0.3% of $\overline{\nu}_\mu$, ν_e and $\overline{\nu}_e$ respectively. Four main processes as sources of neutrinos were recognized:

- 450 GeV/c proton interactions in the Be target which produce $\pi^\pm$, $K^\pm$, K^0,... origi-

---

*On leave of absence from INFN Sez. di Milano.

0920-5632/$ – see front matter
doi:10.1016/j.nuclphysbps.2005.03.042

nating 96% of the ν_μ flux in NOMAD;

- primary protons non interacting or missing the target which produce in the horn and reflector walls, windows and beam-dump, mesons only weakly or not focused by the beam-optics ($\sim 15\%$ of $\overline{\nu}_\nu + \overline{\nu}_e$);
- "prompt neutrinos" generated in the decay of charmed particles and kaons in the target and dump yielding $\sim 6\%$ of $\overline{\nu}_e$;
- particles reinteractions along the beam-line affecting $\sim 10\%$ of ν_μ and ν_e but $\sim 40\%$ of defocused component $\overline{\nu}_\mu + \overline{\nu}_e$.

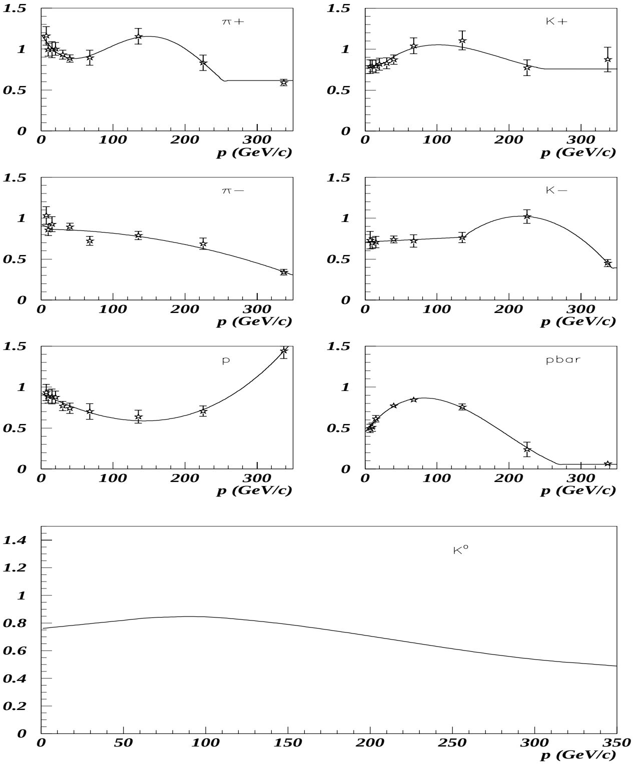

Figure 1. FLUKA to SPY, NA20 meson production corrections as a function of the momentum p. The curves are the results of fitting the weights at fixed p (showed with their uncertainty bars) with combination of polynomial functions [13].

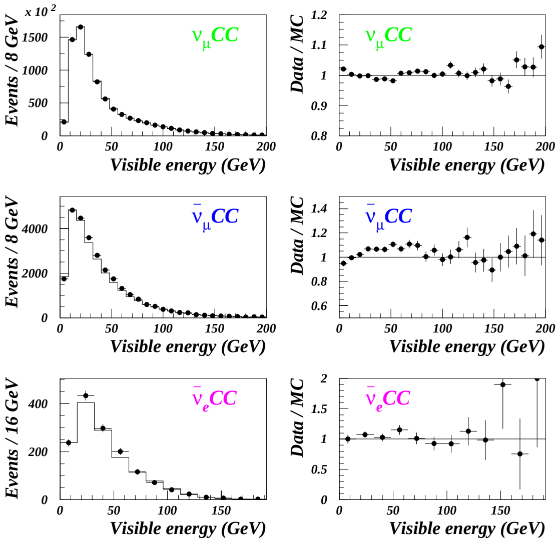

Figure 2. Neutrino energy spectra (left) for the data (points with statistical error bars) and the Monte Carlo (histogram) for ν_μ CC, $\overline{\nu}_\mu$ CC and $\overline{\nu}_e$ CC interactions and their corresponding ratios (right) in NOMAD [13].

In order to predict energy spectra, intensity and composition of the ν beam a sound knowledge of meson production in the target is required. Indeed the accurate description of the K^+ and K^0 relative to the π^+ is essential to calculate the ν_e initial content in the beam.

Direct measurements of π and K production in Be by 400 GeV/c protons were performed by NA20 Collaboration [9] and by the SPY Collaboration

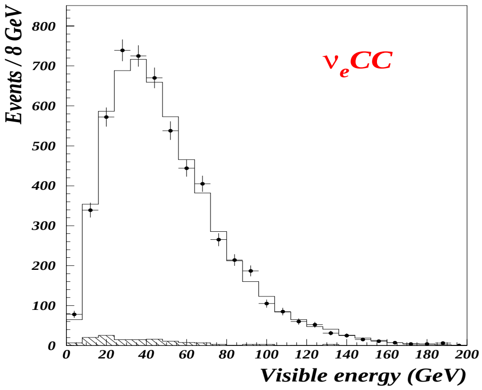

Figure 3. Energy spectrum for the measured ν_e CC interactions (points with statistical error bars) and the Monte Carlo (histogram) in NOMAD [13].

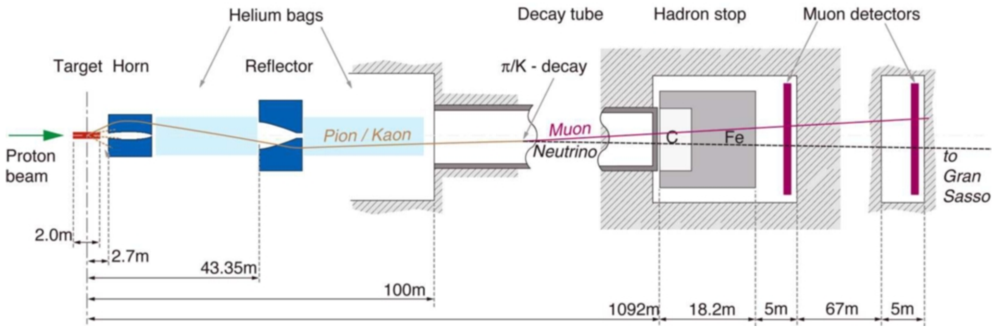

Figure 4. Schematic layout of the future CNGS neutrino beam line.

[10] at 450 GeV/c. Accuracy of Monte Carlo generators of hadronic interactions for the meson production could limit the sensitivity to neutrino oscillation searches. The best agreement between predictions and data was found with FLUKA standalone code [11] which reproduces the measured π and K yields at the level of $\sim$ 20% in the momentum region $30 \div 100$ GeV/c which is expected to contribute most to ν flux [12]. Furthermore an accurate description of the primary proton beam spot, focusing system as well as of the materials inserted in the beam line from the target to the dump (hadronic reinteraction processes) is also mandatory especially for the neutrino beam minor components.

A complete analysis of this ν beam was performed by a beam line simulation from the Be target up to the NOMAD detector including the FLUKA generator with further corrections to the meson production based on the residual differences between the predicted and measured meson yield in Be. These reweighting functions were calculated as a function of the meson momentum by integrating the particle production over 10 mrad of angular acceptance and including also the transport efficiency as a function of production angle along the beam-line. The K_0 reweighting was obtained from the corresponding for $K^{\pm}$ using a "quark-counting model" with 15 % of uncertainty [13].

The agreement with the measured ν interactions in NOMAD was at the few percent level (fig. 2) with a systematic normalization error of $\sim$ 7% on ν_μCC/p.o.t. essentially determined by the accuracy on the π^+ and K^+ production in the Be target (3.4%) and on the proton beam spot position on the Be target. The corresponding energy dependent error ranged between 2 and 5% in the $2 < E_\nu < 100$ GeV neutrino energy. Due to correlations between the sources of the ν_μ and ν_e fluxes, the normalization uncertainties on ν_e/ν_μ ratio was smaller the the uncertainties on the individual ν_μ and ν_e fluxes: 4.2% [13]. The corresponding energy-dependent uncertainty ranged from 4 to 6 %.

3. The CNGS neutrino beam

In the CNGS neutrino beam facility (Fig. 4) the primary protons at 400 GeV/c of momentum with nominal intensity of $4.5 \cdot 10^{19}$ pot/year (proton beam shared operations), will be extracted from the CERN SPS and sent to a carbon target, 13 graphite rods of 10 cm length, 5 and 4 mm of diameter, the first eight spaced by 9 cm. Similarly to previous WANF neutrino beam a magnetic horn and a reflector will allow the focusing (defocusing) of positive (negative)charged secondaries into a $\sim$ 1 km long decay tunnel where an intense ν_μ neutrino beam is produced. A large graphite and iron dump will absorb the residual hadrons at the end on the beam-line. A particular attention was devoted to have the full containment of the proton beam spot in the target and to reduce as well as possible the quantity of material in the beam line in order to maximize

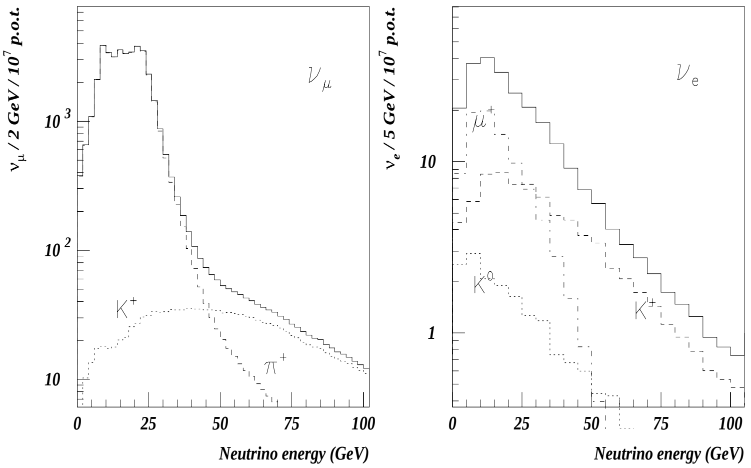

Figure 5. Muon and electron neutrino spectra with parent particles at the Gran Sasso site.

the neutrino flux in the Gran Sasso site.

A full detailed simulation of the CNGS beam line was performed within FLUKA framework. At the nominal proton beam intensity $4.5 \cdot 10^{19}$ pot/year (proton beam shared operations) roughly 2900 ν_μCC/kt/year are expected at the Gran Sasso site. The increase the proton beam intensity has been studied, resulting in a possible upgrade bigger than 40% [14].

The muon neutrino flux will be characterized by an average energy of 17.4 GeV and $\sim 0.6\%$ ν_e to ν_μ contamination for $E_\nu < 40$ GeV (Fig. 5). The $\overline{\nu}_\mu$ and $\overline{\nu}_e$ component are below 2% and 0.2% respectively. The ν_τ intrinsic level in the beam will be below 10^{-6} allowing for clean $\nu_\mu \rightarrow \nu_\tau$ appearance experiments with both ICARUS and OPERA detectors. Due to the 732 Km of base-line the contribution to neutrino beam from the $K^\pm$, K^0 is reduced by a factor $1.5 \div 2$ with respect to the WANF, while those from high energy proton interactions downstream of the graphite target and from prompt charmed particles and kaons decay in the target and dump are negligible. The ν_e component will be mainly produced in the μ^+ decay instead from K^+ and K^0 as in the WANF.

4. CNGS beam systematics

The previous scheme used for the WANF neutrino beam calculation based on FLUKA and SPY, NA20 hadroproduction data in Be is well suitable for the CNGS neutrino neutrino beam. The Be-C scaling due to the different target material is expected to be almost independent on the secondary meson type, to depend only weakly on the transverse momentum of the meson, so contributing less than 2% to the uncertainty on neutrino flux and less than 0.5% to ν_e/ν_μ ratio.

The systematics of neutrino flux at Gran Sasso can be evaluated from the WANF by properly rescaling the contribution of each meson to neutrino flux according to the different production processes. A total normalization error of $\sim 4\%$ can be predicted for both ν_μ and ν_e where $\sim 3.8\%$ of uncertainty is the secondary production at the target and $\sim 1.1\%$ error is due to particle reinteractions along the beam-line. Owing to the target configuration and the 732 km base-line, the position of proton beam on the target section, the beam-line optics such as horn and reflector currents and the amount of material included in the simulation are not critical but contribute only 0.8% to normalization error of ν_μ and ν_e flux. Due to correlations between the sources of the ν_μ and ν_e fluxes, where both neutrinos are essentially produced from π^+ of different momenta, the ν_μ by pion decay and ν_e from the subsequent muon decay, a large cancellation occurs in the ν_e/ν_μ error evaluation. Therefore the normalization uncertainty on ν_e/ν_μ is expected to be only $\sim 3.1\%$. The corresponding bin-to-bin energy dependent error is estimated to be $2.5 \div 4\%$ in the relevant part of the spectrum for ν_μ, ν_e and ν_e/ν_μ ratio.

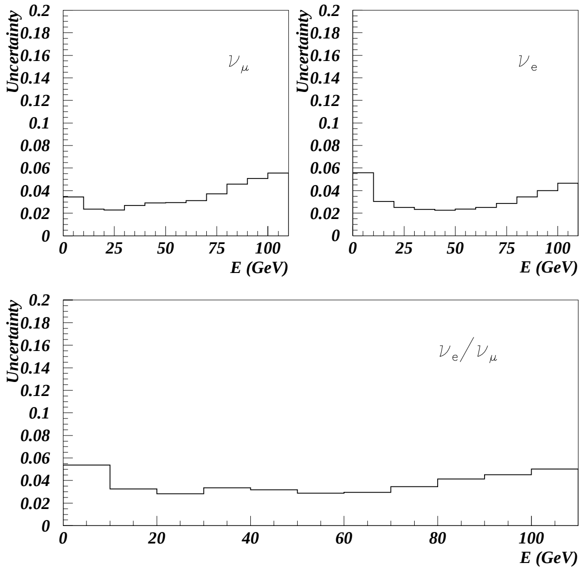

Figure 6. Energy dependent uncertainty for ν_μ and ν_e neutrino flux and for their ratio ν_e/ν_μ.

5. Conclusions

The CERN to Gran Sasso CNGS neutrino beam project for $\nu_\mu \rightarrow \nu_\tau$ oscillation search with ICARUS and OPERA detectors largely benefits of the WANF experience with CHORUS and NOMAD experiments.

The neutrino flux can be predicted at Gran Sasso within a systematic uncertainty $\sim 5\%$, the ν_e/ν_μ ratio will be known with $\sim 3.1\%$ normalization error and $3 \div 4\%$ energy dependent error, better than quoted by ICARUS and OPERA, opening the possibility to search for $\nu_\mu \rightarrow \nu_e$ oscillation exploring $\sin^2 2\theta_{13}$ beyond the CHOOZ limit.

However the sensitivity on both $\nu_\mu \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_e$ oscillation channels are completely dominated by the statistics. In 5 years of CNGS standard operations, $4.5 \cdot 10^{19}$ pot/year, 12 ν_τ CC events can be recognized in ICARUS and similarly in OPERA if $\Delta m^2_{23} = 2.6 \cdot 10^{-3}$ eV^2. In the same time an excess of only 21 $\nu_\mu \rightarrow \nu_e$ CC events over 120 ν_eCC from beam contamination and $\nu_\mu \rightarrow \nu_\tau$ is expected in ICARUS (2.35 kton fiducial mass) for $E < 20$ GeV if $\sin^2 2\theta_{13} \sim 0.04$ ($\theta_{13} \sim 6^0$). The foreseen increase of proton beam intensity is mandatory.

REFERENCES

1. M.H. Ahn et al.,Phys. Rev. Lett. 90 (2003) 021802.
2. The Fermilab NuMI Group, FNAL NuMI-346, 1998; E. Ables et al., FNAL P-875, 1995; Nucl. Instrum. and Meth. A503 (2001) 122.
3. The ICARUS Coll., Nucl. Instrum. and Meth. A461 (2001) 324; CERN-SPSC/2002-27, SPSC-P-323,(2002).
   The OPERA Coll., CERN-SPSC-P-318, LNGS-P25-00; M. Komatsu and al., hep-ph/0210043 (2002).
4. G. Acquistapace et al., CERN-98-02, INFN/AE-98/05 (1998); CERN-SL/99-034(DI), INFN/AE-99/05 Addendum.
5. M. Apollonio et al., Eur. Phys. J. C27 (2003), 331.
6. M. Komatsu et al., J. Phys. G 29 (2003) 443.
7. L. Casagrande et al., CERN 96-06, 1996.
8. The CHORUS Coll., Phys. Lett. B 497 (2001) 8, and references therein
   The NOMAD Coll., Nucl. Instr. and Meth. A 404 (1998) 96.
9. H.W. Atherton et al., CERN-80-07, 1980.
10. G. Ambrosini et al., Eur. Phys. J. C 10 (1999) 605.
11. A. Fasso' et al., in A. Kling, F. Barao, M. Nakagawa, L. Tavora, P. Vaz, eds., *Proceedings of the Monte Carlo 2000 Conference* (Springer-Verlag, Berlin, 2001) 955.
12. G. Collazuol et al., Nucl. Instr. and Meth. A 449 (2000) 609.
13. P. Astier *et al.*, Nucl. Instr. and Meth. A 515 (2003) 800.
    A. Guglielmi and G. Collazuol, INFN/AE-03/05 (2003).
14. M. Benedikt et al., CERN-AB-2004-022 OP/RF.