Neutrino oscillations studies with the OPERA experiment at the CNGS beam

E. Pennacchio (*) on behalf of the OPERA Collaboration

Institut de Physique Nuclaire de Lyon, UCBL-CNRS/IN2P3,
4 rue E.Fermi, F-69622 Villeurbanne, France

Summary. — The OPERA experiment, located in hall C of the Gran Sasso underground laboratory, has been designed to detected the direct appearance of ν_τ in a pure ν_μ beam (CNGS) produced at CERN, travelling over a distance of 730 km. Taus produced in ν_τ charged current interactions are identified by reconstructing their decay path, using the the nuclear emulsion technique. After a short introduction on physical motivations, the OPERA detector will be described. The event analysis chain will be explained, and first physics results presented.

PACS 13.15.+g – Neutrino interactions.
PACS 14.60.Lm – Ordinary neutrinos.
PACS 14.60.Pq – Neutrino mass and mixing.
PACS 29.40.Rg – Nuclear emulsions.

1. – Introduction

The measurements of neutrinos fluxes from all usable sources, the Sun, the Earth atmosphere, accelerator beams and nuclear reactors, form a coherent set of compelling experimental evidences of oscillations between neutrino flavours [1]. Till now it is still missing the observation of the unambiguously appearance of a new flavour in a neutrino flux by identifying the charged lepton produced in its charged current interaction (CC) with matter. The OPERA experiment [2] precisely aims at identifying the τ produced in the CC interactions of ν_τ appearing in a pure ν_μ beam produced at CERN SPS and thus confirming the preferred interpretation of muonic neutrinos disappearance in the atmospheric sector by probing a similar domain of L/E . Having the capability to observe prompt electrons, OPERA will also allow the search for the sub-leading oscillation channel $\nu_\mu \rightarrow \nu_e$.

(*) E-mail:pennacc@ipnl.in2p3.fr

TABLE I. – *Expected number of* τ *and background events for nominal 5 years of data taking, corresponding to* 22.5×10^{19} *p.o.t*

τ decay channel	signal (Δm^2 =2.5 $\times$ 10^{-3} eV^2)	background
$\tau \to \mu$	2.9	0.17
$\tau \to e$	3.5	0.17
$\tau \to h$	3.1	0.24
$\tau \to 3h$	0.9	0.17
ALL	10.4	0.75

2. – The OPERA experiment

2˙1. *The CNGS beam.* – The CNGS beam [3] is a wide band neutrino beam ($< E_{\nu_\mu} > =$ 17 GeV), optimized for ν_τ production and detection. It is produced by a 400 GeV/c proton beam extracted from the SPS accelerator and transported along a 840 m long beam line onto a carbon target producing kaons and pions. The positively charged πs and Ks are energy selected, guided with the horn and the reflector in the Gran Sasso direction. They decay into ν_μ and μ. The muon and all the hadrons which do not interact into the target or not decay are stopped. During a CNGS cycle, which lasts 6 s, there are two SPS extractions, 10.5 μs each, separated by 50 ms. The nominal beam intensity is 4.5×10^{19} proton on target ($p.o.t.$), with 200 days of beam operation per year.

2˙2. *The detection principle.* – The ν_τ is detected through its charged current interaction, followed by τ decay in one ($\tau \to e$, $\tau \to \mu$, $\tau \to h$) or three ($\tau \to 3h$) prongs. The decay lenght is $\approx$ 600 μm ($c\tau$ = 87 μm). In order to identify the decay topologies occurring over so small distances and produce enough τ neutrino interactions, it is mandatory to have a high granularity target with a big mass. These two conflicting requirements are fullfilled in OPERA using the concept of Emulsion Could Chamber (ECC), already employed by the DONUT [4] collaboration to observe the first ν_τ interactions. The OPERA detector basic unit, the brick, is based on the ECC concept. It is a sandwich of 56 lead plates 1 mm thick, interleaved with emulsion plates (2 emulsion layers, 44 μm thick, poured on a 205 μm plastic base). On the downstream face (with respect to beam direction) it is glued a box with a removable pair of nuclear emulsion plates, named Changeable Sheets (CS). The bricks are completely stand-alone detectors, allowing for neutrino interaction vertex and event topology reconstruction, momentum measurement of charged particles by the detection of multiple Coulomb scattering (MCS) in lead plates, identification and measurement of electromagnetic showers and muon-pion separation (using dE/dx). With a target mass of 1.25 $ktons$, assuming nominal 5 years of data taking, the expected number of ν_μ charged and neutral current interactions is $\approx$ 24000, with $\approx$ 170 ν_e and $\overline{\nu}_e$ CC interactions. The number of ν_τ charged current interactions is $\approx$ 115 ν_τ (for Δm^2=2.5 $\times$ 10^{-3} eV^2 and full mixing), leading to the observation of about 10 ν_τ CC events, with less than one background event. The main background sources are the production of charmed particles in charged current events where the primary lepton is unidentified, the events in which the muon undergoes a coulombian scattering at large angle and hadronic interactions mimiking tau decay topologies. The expected number of τ and background events for each channel are summarized in table I.

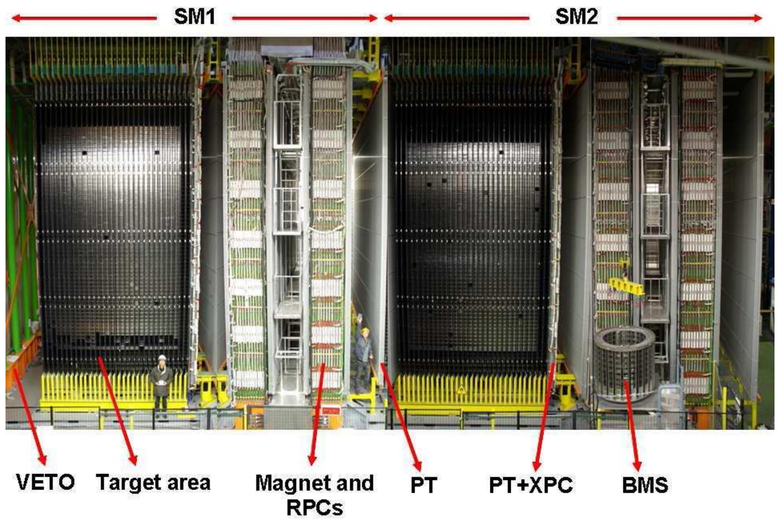

Fig. 1. – View of the OPERA detector. The upper horizontal lines indicate the position of the two identical supermodule (SM1 and SM2). The target area is made of walls filled with the bricks interleaved with planes of plastic scintillators(TT). Arrows show the position of the VETO planes, the drift tubes (PT) pulled alongside the XPC, the magnets and the RPC installed between the magnet iron slabs. The Brick Manipulator System (BMS) is also visible. More details can be found in [5]

.

2˙3. *The OPERA detector*. – The OPERA hybrid detector, shown in picture 1, is divided into two identical supermodule. Each supermodule (SM) has a target part, composed by 31 vertical walls transverse to the beam direction, interleaved with planes of plastic scintillator (TT), for a total of $\approx$ 150000 bricks, and a mass of 1.25 $ktons$ (each brick weights 8.3 kg). The instrumented target is followed by a magnetic spectrometer consisting of a large iron magnet equipped with plastic Resistive Plate Chambers (RPC). The deflection of charged particles inside the magnetized iron is measured by six stations of drift tubes (Precision Trackers, PT). Left-right ambiguities in the reconstruction of particle trajectories inside the PT are removed by means of additional RPC (XPC) with readout strips rotated by 45^0 with respect to the horizontal and positioned near the first two PT stations. Finally, two glass RPC planes mounted in front of the first target (VETO) allow to reject charged particles originating from outside the target fiducial region, coming from neutrino interactions in the surrounding rock material. The electronic detector has the task to provide a neutrino interaction trigger, the event timing, to identify and measure the trajectory of charged particles, to locate the bricks where interactions occur, to perform the muon identification, charge and momentum measurements. The detector is equipped with an automatic machine (the Brick Manipulator System, BMS) that allows the removal of bricks from the detector. A detailed description of the detector and of the data acquisiton system can be find in ref. [5]. Events induced by neutrinos in CNGS are selected on a delayed time coincidence between proton extraction from SPS and the events in OPERA. The syncronization is based on a GPS system, with a precision of $\approx$ 100 ns. In picture 2 the time distribution of events in the neutrino run

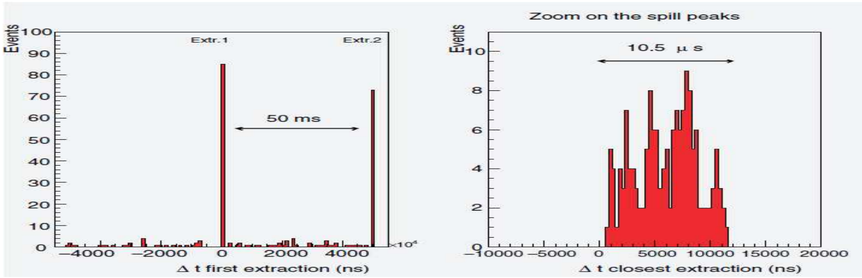

Fig. 2. – Time distribution of the events recorded during the CNGS beam run. Since two extractions are made from the SPS, on the left plot timing is shown with respect to the first one, while on the right plot the more fine distribution on the single extraction is shown.

is shown.

2˙4. *Event analysis chain.* – When a CNGS neutrino interacts in OPERA, the event is recorded and reconstructed by the electronic detectors. If there is a muon in the produced event its trajectory is traced back through the scintillator planes up to the brick where the track originates. When no muons are observed the scintillator signals produced by electrons or hadronic showers are used to predict the location of the brick that contains the primary neutrino interaction vertex. The selected brick is then extracted from the target by the BMS. The overall procedure minimizes the mass loss, allowing a semi-online target analysis. The two CS (cf. section **2**˙2) glued on the downstream face of the brick are removed and the films analysed in order to validate the prediction and measure with micrometric precision the direction of the tracks belonging to the event. The global layout of bricks, CS and TT is schematically shown in fig. 3. If the presence of the event in the predicted brick is confirmed the brick is exposed to X-rays beams and to cosmic rays for sheets alignement. The brick is then disassembled, the films developed and sent to the different scanning laboratories to perform the complete analysis: there are 10 scanning laboratories in Europe and 2 in Japan. LNGS and Nagoya are also CS scanning centers. Emulsion scanning is performed with two different types of automatic microscopes: the

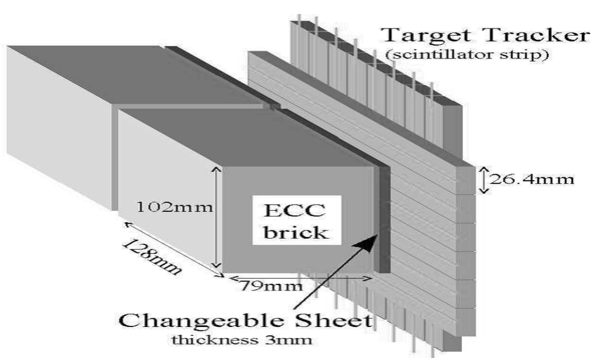

Fig. 3. – Schematic view of two bricks with their Changeable Sheets and target tracker planes.

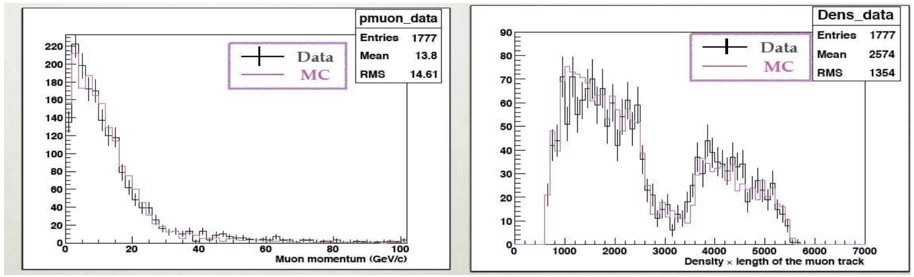

Fig. 4. – Muon momentum distribution (left), product of the muon track lenght times the density of crossed materials (right).

European Scanning System (ESS) [6] and the Japanese S-UTS [7]. The confirmed tracks are followed back in the brick until their stopping point (a track is considered as stopping if not found in 5 consecutive planes). This operation is called "scanback". A volume of $\approx 1\ cm^2$ is then defined around the stopping point, on 5 plates up-stream and 10 down-stream. Track segments are measured within an angular acceptance of 0.6 rad. This region is fully scanned to confirm the presence of the interaction ("volume scan"). Then tracks attached to the vertex can be followed in the forth direction (scan-forth) for kinematical measurement. All the data are then centralized and stored in a Central Database (based on Oracle) existing in two identical master copies at LNGS (Italy) and in the IN2P3 Computing Center in Lyon. The OPERA principle has been fully proved and validated as reported in [8].

3. – Physics results

In this section some distribution for ν_μ charged current events obtained with electronic detector, are compared to Monte Carlo simulation. The results show a reasonable agreement. In the left part of fig. 4 the muon momentum distribution is shown, in the right part the product of the muon track length times the density of crossed materials, i.e. the measured range of the particle, the main variable used for muon identification. Continous line is used for Monte Carlo distribution. The visible ratio between neutral current and charged current has also been measured after the removal of the background from beam neutrino interactions occurring outside the target region and projecting neutral particles which reinteract with the OPERA target. The values NC/CC obtained for 2008 and 2009 data, respectively equal to 0.23±0.014(stat.) and 0.23±0.009(stat.), are in good agreement with the predicted Monte Carlo value NC/CC=0.23±0.014(stat.). The event track multiplicity distribution and the muon slopes measured at primary vertex (in the bricks), compared to Monte Carlo predictions, are shown in fig. 5. Soft muon momenta (p $< 6\ GeV$) are measured in the bricks using the coulombian multiple scattering (MCS). In order to crosscheck the method of momenta measurements in the bricks the momenta for this sample of muons are also measured using the electronic detector, and the comparison between the results obtained with two methods is shown in fig. 6. The correlation is good.

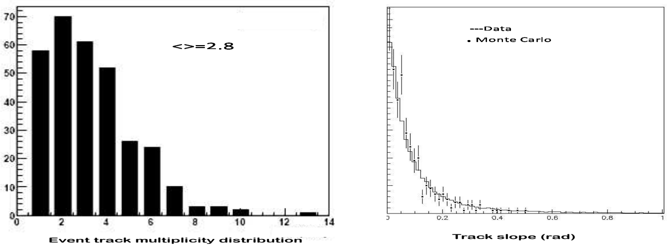

Fig. 5. – Event track multiplicity distribution (left), muon slopes measured at primary vertex (right).

3˙1. *Decay search.* – All the scanning activities till fall 2009 have been focused on vertex location. A systematic decay search (DS) was started on 2008 and 2009 data in order to find all possible decay topologies. This new procedure has the aim to improve the vertex definition and the impact parameter (IP) distribution, to detect all possible kink topologies on tracks attached to the primary vertex and to search for extra tracks from decays not attached to primary vertex. This procedure has already been applied on a large part of 2008 data, and allowed to identify 20 charm candidates, in part already found with the scanback and vertex location procedure. The IP distribution obtained from real data with the application of the DS is shown in picture 7. For comparison also the IP distribution for τ obtained with Monte Carlo data is shown. To complete charm candidates search the decay search procedure will be applied to the full 2008 and 2009 statistic. An examples of charm candidate is shown in fig. 8: 3 tracks have been reconstructed at the primary vertex, and 4 to the decay one. All the impact parameters (of the order of the micron) have been measured. The minimum invariant mass was estimated to be 1.74 GeV strengthening the charm hypothesis. Topological details of the event are summarized in the table in fig. 8: the ϕ angle is found to be close to 180° which corresponds to a back to back emission of the charm with respect to the muon.

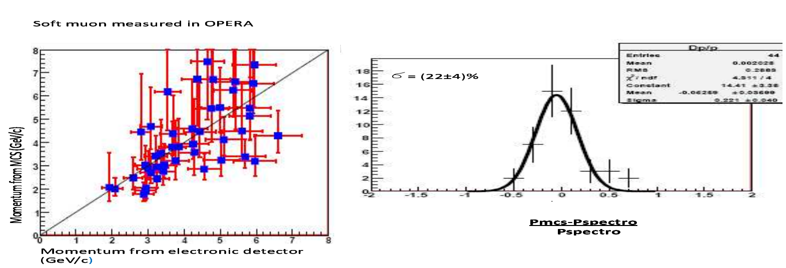

Fig. 6. – Correlation between muon momentum measure in the brick (using MCS) and the electronic detector.

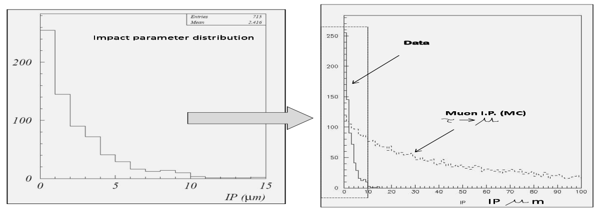

Fig. 7. – IP distribution.

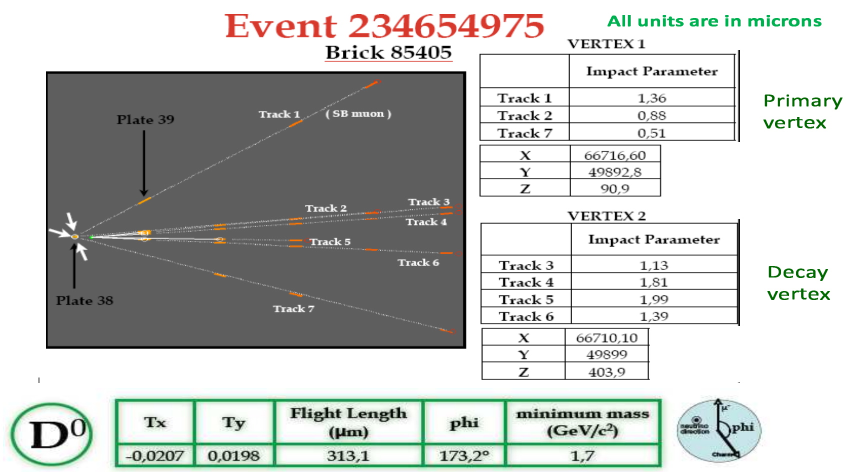

Fig. 8. – Charm candidate: the primary and secondary vertex are clearly visible. Impact parameter are shown in the tables, and kinematical reconstruction results are also shown.

4. – Performances

OPERA has already taken data during two physics run in 2008 and 2009. The CNGS beam performances are summarized in table II.

TABLE II. – *Run Statistics*

CNGS performances	1.782 $\times 10^{19}$ *p.o.t*	3.522 $\times 10^{19}$ *p.o.t*
On-time events	10122	21428
Candidates in the target	1698	3693

Till now (March 2010) almost 1500 events have been located, 943 for 2008 data and 438 for 2009. The analysis for 2008 data is completed. A detailed summary of events locations can be found in table III and table IV for 2008 and 2009 run respectevly.

Table III. – *Events location summary for 2008 run (March 2010).*

	0mu	1mu	All
Events predicted ny the electronic detector	406	1292	1698
Found in CS	271	1045	1316
Vertices located in bricks	151	792	943
Vertice located in dead materials	6	38	44
Interactions in the upstream brick	6	33	39

Table IV. – *Events location summary for 2009 run (March 2010).*

	0mu	1mu	All
Events predicted ny the electronic detector	865	2297	3162
Extracted CS	829	2211	3040
CS Scanned	666	1802	2468
Found in CS	376	1139	1515
Vertices located in bricks	67	371	438
Vertice located in dead materials	2	11	13
Interactions in the upstream brick	3	36	39

5. – Conclusions

OPERA has taken data in 2008 and 2009 corresponding to a total luminosity of 5.3×10^{19} *p.o.t.*, proving the full chain of the handling and analysis of the events. The performances of the electronic detector are reliable and well understood. A systematic decay search has been started on 2008 and 2009 events in order to find all possible decay topologies. Several charm events has been found as expected. A new run will start by the end of April 2010 allowing to increase the event statistics.

* * *

It is a pleasure to thank the organizer of this conference for the interest to OPERA physics, all the colleagues from the OPERA Collaboration, the founding agencies of the different countires participating to the experiment and the Computing Centre in Lyon (CCIN2P3) supporting the OPERA data analysis infrastructures.

REFERENCES

[1] Strumia A., and Vissani F., arXiv:hep-ph/0606054v3
[2] Guler st al.,(OPERA collaboration), *An appearance experiment to search for* ν_τ *oscillations in the CNGS beam* in *experimental proposal, CERN-SPSC-2000-028*
[3] *C*NGS project : on line at *http://proj-cngs.web.cern.ch/proj-cngs/*
[4] Kodama K et al.(DONUT Collaboration), *Phys,Rev.Lett*, **93** (2004) 101801;
[5] Acquafredda R et al.(OPERA Collaboration), *JINST*, **4** (2009) P04018;
[6] Arrabito L et al.,, *Track reconstruction in the emulsion-lead target of the OPERA experiment using the ESS microscope JINST*, **2** (2007) P05004;
[7] Aoki S et al.,, *The fully automated emulsion analysis system NIM*, **B51** (1990) 466;
[8] A.Agafonova et al.(OPERA Coll.), *The detection of neutrino interactions in the emulsion/lead target of the OPERA experiment JINST*, **4** (2009) P06020 arXiv:0903.2973