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# Opera neutrino oscillation experiment: on the way to $\nu_\tau$ observation

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**Abstract.** The hypothesis of neutrino flavour changing in weak interaction representation via oscillations is confirmed by several experiments, all based on the observation of the disappearance of a given neutrino flavour. The direct appearance of a flavour different from the initial one, was never observed so far. OPERA is the first long baseline neutrino oscillation experiment employing nuclear emulsions for the direct observation of tau neutrinos in the CERN to Gran Sasso muon neutrino beam. At present the experiment is in the data taking phase. The number of detected neutrino interactions have exceeded one thousand. Experiment status and a summary of results from 2007 and 2008 runs is presented in this paper.

## 1. Introduction

After the experimental discovery of neutrino oscillations by Super-Kamiokande many efforts were made to define allowed intervals for neutrino mass differences and mixing. By now from the combination of results of few experiments some of this parameters are measured with reasonable accuracy. Among the best known parameters are the mixing angle  $\Theta_{23}$  and  $\Delta m_{23}$ , which values are given by K2K, SuperK and MINOS experimental data. These parameters govern neutrino oscillations in the so called “atmospheric” mode and in particular define the transition probability  $\nu_\mu \leftrightarrow \nu_\tau$  (1).

$$P(\nu_\mu \rightarrow \nu_\tau) \propto \sin^2(2\Theta_{23})\cos^4(\Theta_{13})\sin^2(\Delta m_{23}^2 L/4E) \quad (1)$$

Mentioned experiments have measured these parameters on the basis of the deficit of observed  $\nu_\mu$  in the neutrino flux originated in Earth atmosphere (Super-K) or accelerator beam (K2K and MINOS). However they were not able to observe appearance of the new neutrinos of the “wrong” flavour ( $\nu_\tau$ ) because of the detector limitations and low neutrino energies. The only way to observe  $\nu_\tau$  is via it’s weak charged current interactions with the matter, in which a  $\tau$  lepton is produced. Hence in order to be able to detect  $\nu_\mu \rightarrow \nu_\tau$  appearance the following requirements must be satisfied:

- The energy of the  $\nu_\mu$  must be over the  $\tau$  production threshold
- The distance from the  $\nu_\mu$  production point to the detector (baseline) must be long enough to allow a reasonable fraction of neutrinos to oscillate to a different flavour

<sup>1</sup> On behalf of the OPERA collaboration.

- The beam intensity must be high enough to provide a reasonable number of events
- The detector must have enough mass to provide a reasonable number of events
- The detector must have a capability to detect short-lived  $\tau$  leptons, that is high spatial resolution.

OPERA is the long (730km) baseline neutrino oscillation experiment, that is the part of CNGS (CERN Neutrino to Gran Sasso) project. The project contains two main parts - the neutrino beam line, located at CERN, (Geneve, Switzerland) and the neutrino detector located at LNGS (Gran Sasso, Italy). The CNGS beam line is designed to provide  $4.5 \times 10^{19}$  protons-on-target (p.o.t.) per year with an average activity of 200 day per year.

The first technical run of CNGS in 2006 has delivered  $0.76 \times 10^{18}$  p.o.t. and was used to commission the electronic detectors of OPERA. A second run in 2007 has delivered  $0.82 \times 10^{18}$  p.o.t. and resulted in 38 neutrino interactions, detected in the OPERA target, which had about 40% of the final mass by that moment. In June 2008 the OPERA detector was complete in mass and fully commissioned. The first OPERA production run has started and by the end of 2008 the CNGS had delivered  $1.8 \times 10^{19}$  p.o.t and about 1700 neutrino events in the target.

## 2. The OPERA detector concept

### 2.1. Requirements and solution for the neutrino target - ECC

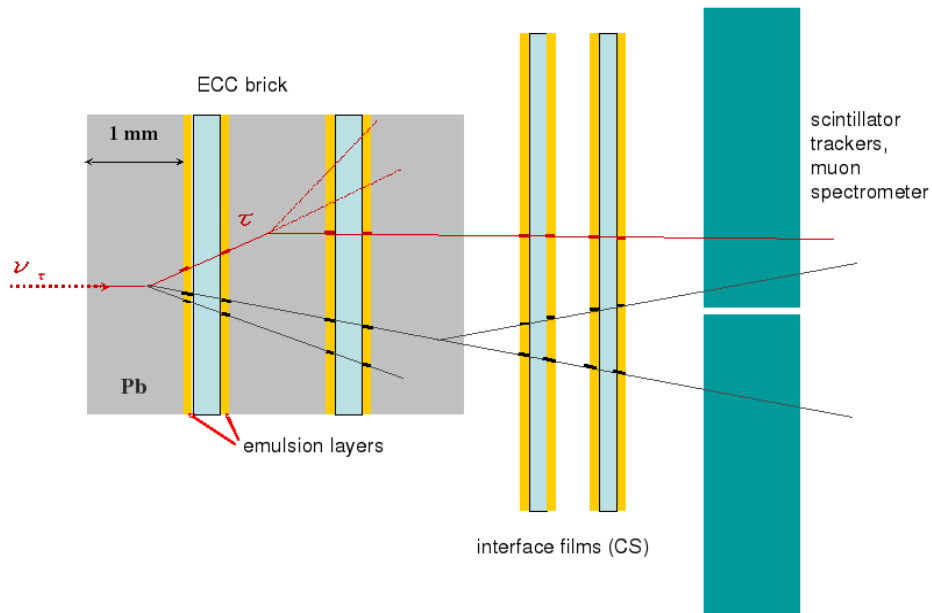
Requirements to the detector are rather conflicting. On one side the mass of the detector must be maximised to have a reasonable event rate. This prompts for the use of heavy materials for the active volume, such as iron or lead. On the other side the event topology must be reconstructed with the micrometric accuracy in order to identify the  $\tau$  lepton, coming from charged current (CC) interaction of a  $\nu_\tau$  with the matter and to separate it from similar topology Charmed mesons, produced in  $\nu_\mu$  interactions. The event volume, needed to perform this job should be optimised in such a way to be able to perform effective zero suppression. The chosen strategy is to make a segmented detector, build of independent blocks with micrometric tracking resolution and a system of targeting the block of interest. A solution for the micrometric accuracy tracking device is a nuclear emulsions. The history of the use of nuclear emulsions for the detection of charged particles falls back to the fifties of 20th century. The method is based on the fact that an ionising particle passing through the gelatin saturated by silver halide layer leaves so called activation centres, just like photons in conventional photography [1, 2].

Recent results of E531, CHORUS, DONUT and other experiments have demonstrated, that the concept of stack of the emulsion films and in particular Emulsion Cloud Chamber (DONUT) fits requirements to the detector building unit [3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16]. The emulsion cloud chamber [17, 18, 19] is the sandwich made of layers of heavy material, where neutrino mostly interact, interleaved by the layers of nuclear emulsion, which provides the necessary tracking accuracy for the interaction products (see Figure 1).

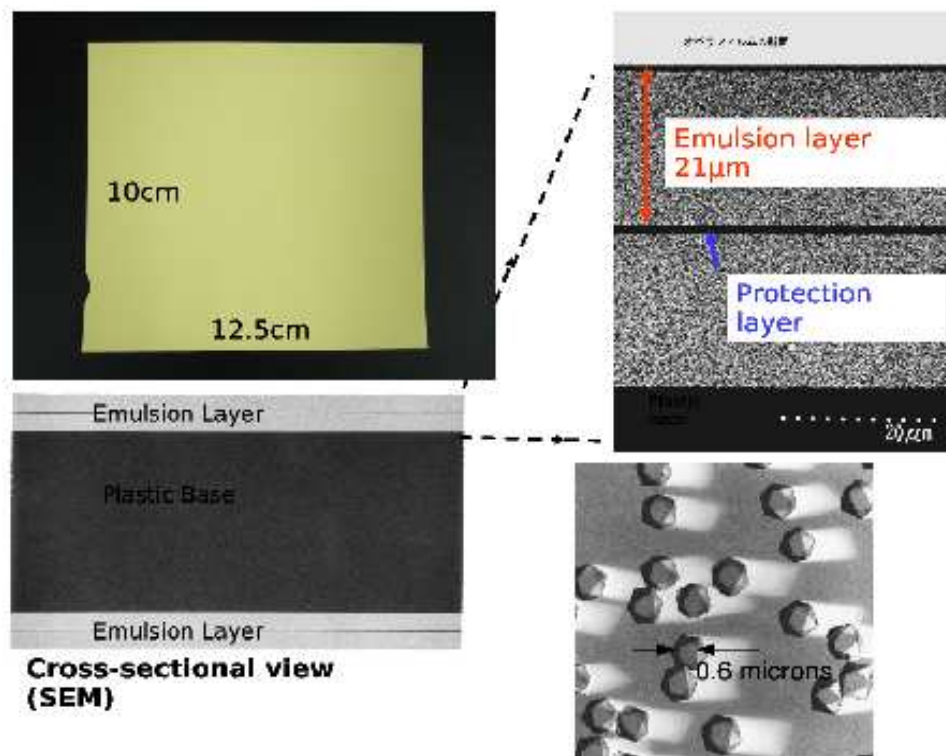
The optimisation of the geometry was done by the DONUT experiment, which aim was to detect prompt  $\nu_\tau$  interactions. In case of OPERA however the lead was chosen as the material for the target, instead of iron, in order to further decrease the detector volume. The OPERA ECC consists of 57 emulsion sheets 300 microns thick each and 56 lead sheets 1mm thick [20]. The area is  $128 \times 102mm^2$  and the thickness is 79mm with a weight of about 8 kg each. The nuclear emulsion sheets used in OPERA were commercially produced by the Fuji Film<sup>2</sup> company. They are made of a transparent plastic base film for mechanical support (200  $\mu m$  thick) on which are deposited two 200  $\mu m$  thick layers of photosensitive gel (see Figure 2). The intrinsic emulsion coordinate resolution is 0.2  $\mu m$ .

The ECC of interest, containing the neutrino interaction vertex is pointed to by the external tracking device (see the next chapter). At the downstream surface of each ECC a special doublet

<sup>2</sup> Fuji Film, Minamiashigara, 250-0193, Japan



**Figure 1.** Tracks in the ECC with CSD are indicated by the external electronic detectors.



**Figure 2.** The structure of the nuclear emulsion films, used in OPERA detector.



**Figure 3.** Emulsion Cloud Chamber brick with attached Changeable Sheet Doublet used in OPERA detector.

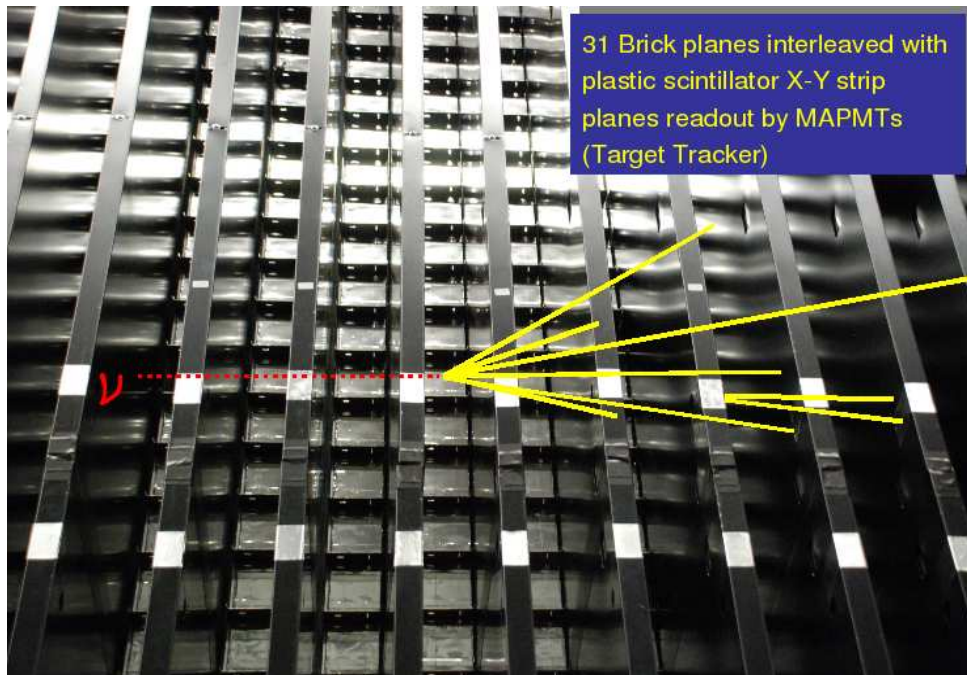
(Changeable Sheet Doublet or CSD) of emulsions is attached in a separate package (see Figure 3). When the ECC is extracted these two emulsion sheets are developed first and tracks related to the interaction are reconstructed there. If at least one track is found in the CSD then the brick is disassembled and sent for further processing, otherwise it is equipped with a new CSD and returned back to the detector. Processing includes the deposition of fiducial marks on the emulsions by X-ray exposure, exposure to cosmic muons in order to improve the film to film alignment, development of emulsions and analysis with the aid of optical high-magnification microscope system.

The development of automated emulsion scanning systems during the last twenty years resulted in the possibility to scan about  $20\text{cm}^2/\text{hour}$  of emulsion surface in fully automated mode [21, 22] with a tracking resolution of 2 microns and 2 mrad for relativistic particles. The realisation of such systems for OPERA was performed by two different groups in Europe and Japan, demonstrating similar performance. Some important advances were made, in particular a scanning approach without immersion oil [23], and an automatic emulsion changing system, which allows computer-controlled emulsion placement and removal at the microscope table [24].

As soon as all tracks in the volume of interest are scanned and reconstructed [25], the primary interaction vertex location and the search for secondary interaction or decay vertices can be performed, as well as particle identification, electromagnetic shower reconstruction, measurement of particle momentum with the aid of Coulomb multiple scattering. On the basis of this information a decision about the nature of interaction is then made.

## *2.2. Brick triggering - Target Tracker*

In order to point out the ECC unit, where the interaction has happened a scintillating tracking detector is utilised (further Target Tracker). The OPERA detector is composed of two identical units, called supermodules. Each supermodule consists of 31 walls. Each wall in turn is composed of an ECC wall and a Target Tracker (TT) wall. A TT wall is made of two planes of orthogonal plastic scintillator strips (680 cm x 2.6cm x 1cm). The strips are extruded from polystyrene, doped with 2% of p-terphenyl and 0.02% of POPOP. Each strip is coated by the reflective white paint based on  $TiO_2$ . Each strip has a groove along its length, in which a wavelength



**Figure 4.** Target tracker of the OPERA detector

shifting fibre is glued. The particle crossing the strip produces scintillation in the blue spectral region, which is absorbed by the fibre and converted to the green spectral region. The strips are grouped by 64 and each group is read out by an Hamamatsu 64-channels multianode PMTs (see Figure 4).

### 2.3. Muon Spectrometers

In each super-module, the target is followed by a magnetic muon spectrometer. This is an important tool to reject the background of  $\nu_\mu$  interactions, which in some cases may mimic the topology of the  $\nu_\tau$  interactions. The spectrometer is designed to measure the muon momentum in the range up to about 50 GeV with a resolution  $\Delta p/p$  better than 0.25, and the muon sign.

The magnet of each spectrometer is made of two vertical iron walls and horizontal magnetic flux return yokes. The nominal field in the iron walls is 1.46 T. Each of iron walls is made of 12 iron slabs 5cm thick each, interleaved with 2 cm wide gaps for the inner tracking detector made of X-Y planes of bakelite Resistive Plate Chambers (RPC). The read-out is performed by means of 2.6 cm pitch and 8 m long vertical strips, which measure the coordinate in the bending plane, and 3.5 cm pitch and 8.7 m long horizontal strips. In order to resolve left-right ambiguity two RPC planes with inclined by  $\pm 42.6$  deg readout strips are placed in front of each spectrometer.

Each spectrometer magnet is also equipped by a High Precision Tracker system (HPT) consisting of vertical gas drift tubes 8 m long and 38 mm in diameter each. These tubes are arranged in walls, allowing precise measurement of muon track coordinate and angle before and after deflection inside the magnets. The muon deflection happens only in horizontal plane, so HPT measures coordinates and angles in the same plane.

### 2.4. Ancillary facilities

ECC assembling was performed by a dedicated mini-factory (Brick Assembling Machine, BAM), located in the LNGS underground laboratory. ECC bricks were piled by 5 anthropomorphic robots in automatic mode and packed by a specially designed line. The changeable sheet dublet

was packed separately in a polystyrene box and glued at the downstream surface of each ECC brick.

The insertion and extraction of the ECC bricks into and from the detector supermodules is done by the Brick Manipulating System (BMS). The BMS consists of two independent units, serving both supermodules from the two sides of the detector. Each BMS unit is composed of an instrumented movable platform positioned inside a cradle. The cradle is placed within a 10 m high structure called “portico” acting like an elevator. The BMS system provides automatic brick insertion, extraction and bookkeeping of the whole target history in the database.

After the extraction of the brick four X-ray marks for alignment are deposited on the two CSD and the most downstream ECC films. These spots are then used to align CSD to the ECC last emulsion sheet. The brick is then exposed to X-rays to print lateral marks used for quick alignment of the films. In order to further improve the alignment bricks are exposed to cosmic muons in a dedicated exposure pit, where the low energy and the electromagnetic components of the cosmic flux are filtered out by an iron slab at the ceiling of the pit.

Next steps in the ECC processing are disassembling the brick and developing its 57 emulsion sheets. The development procedure is done by six automated chains containing a series of tanks with the corresponding chemical solutions. The facility is build with the goal to automatically develop up to 3000 emulsion sheets per day.

### *2.5. Emulsion scanning*

When the development is completed, the emulsion sheets are dried and distributed over the OPERA scanning laboratories in Europe and Japan. Presently OPERA is in possession of about 40 scanning microscope systems. In the scanning laboratory a step from the meters scale of the OPERA detector target to the micrometers scale of the neutrino interaction topology is accomplished (Figure 5). Each emulsion layer is read out by the microscope in 15-16 levels of depth. Combination of silver grain images in these levels allows to reconstruct track segments on each of two sides of the emulsion sheet. These segments are called microtracks. Combination of microtracks allows to build straight track segments through the emulsion films base. These segments are called base tracks. Combination of the base tracks of all the emulsion sheets in the ECC in turn allows to fully reconstruct tracks, the interaction vertex, the interaction products and their kinematical parameters (see at the bottom of Figure 5).

## **3. Expectations and results from 2008 physics run**

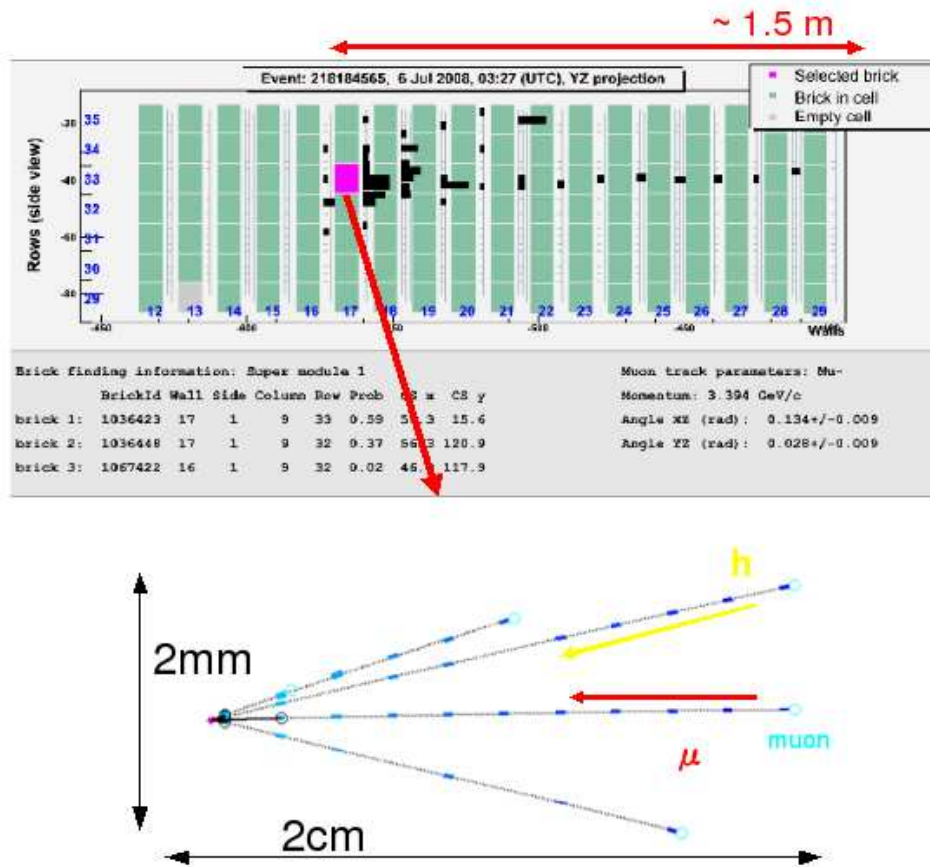
By June 2008 OPERA detector was fully commissioned with about 146000 ECC bricks in its target section for a total of about 1.25 kton. At the end of the run in November 2008 the total delivered luminosity constituted  $1.8 \times 10^{19}$  protons on target. This corresponds to the expected number of identified  $\nu_\tau$  interactions about 0.6 and about 26 of identified interactions of short-lived charmed products. The total number of neutrino interactions registered in the OPERA detector is about 1700, which is in agreement with the expectation.

On the basis of these events the detection efficiency is being estimated. Preliminary numbers based on low statistics analysis are very close to those expected from the Monte-Carlo simulation.

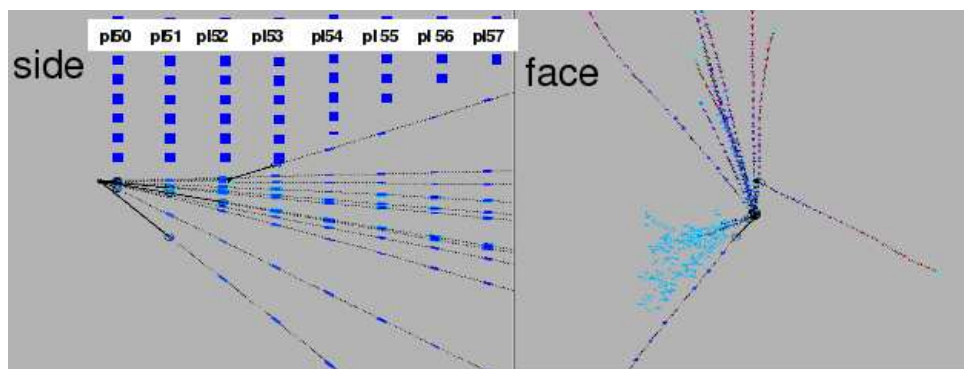
By December 2008 about 20% of all extracted emulsions were processed, so the expected number of  $\nu_\tau$  interactions is about 0.12 which is compatible to the fact of no such events observed so far. Two decay candidates with short-lived charmed products have been observed. (for instance see Figure 6).

Figure 7 shows the distribution of the reconstructed momentum of the muons emitted in on-time  $\nu_\mu$  CC interactions occurring in the OPERA target, in the spectrometers and the structure and also in the Borexino detector and in the rock situated upstream of OPERA in hall C of the LNGS. The expectation from a Monte-Carlo simulation are also shown.



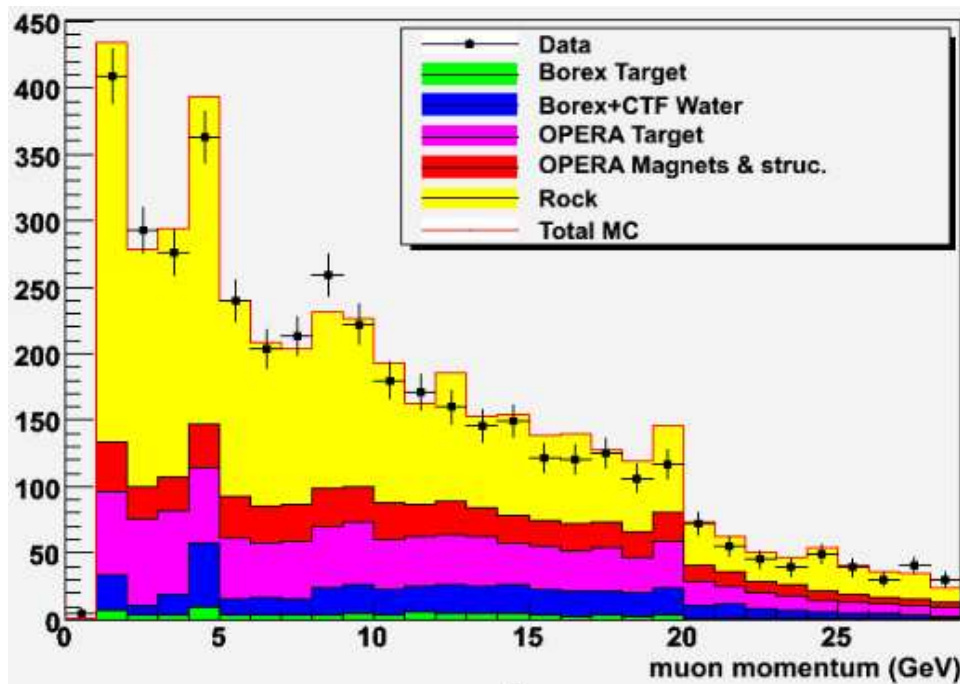


**Figure 5.** In the scanning laboratory a step from the meters scale of the OPERA detector target to the micrometers scale of the neutrino interaction topology is made. At the top of the figure the supermodule display is presented with hits registered by the Target Tracker. At the bottom the neutrino interaction is shown as it is reconstructed in the ECC (coloured segments are basetracks, reconstructed in emulsion sheets).



**Figure 6.** Reconstructed neutrino interaction event with charmed secondary decayed in the OPERA ECC.





**Figure 7.** Reconstructed momentum distribution of the muons related to neutrino interactions upstream of OPERA detector.

#### 4. Results summary and future prospects

The OPERA experiment has started full data taking in the CNGS neutrino beam with the total luminosity of  $1.8 \times 10^{19}$  p.o.t. accumulated during the 2008 first physics run. About 1700 interactions were registered by the OPERA detector. Assuming mass square difference given by Super-Kamiokande and MINOS  $\Delta m_{23} = 2.5 \times 10^{-3} eV^2$  the expected number of identified  $\nu_\tau$  interactions about 0.6 and about 26 decays of short-lived charmed particles.

The Detector and all the ancillary facilities performed very well, the event analysis chain successfully proceeds “quasi-on-line”. Detector efficiencies and background were estimated with the use of real data and are in a good agreement with the Monte-Carlo simulation estimates. A number of interesting event topologies have been analysed (Charmed decays, prompt  $\nu_e$  interaction).

For the year 2009 we expect a run with 173 days of the beam, providing  $3.5 \times 10^{19}$  protons on target (requested  $4.5 \times 10^{19}$ ). Together with 2008 a nominal number of about 2  $\nu_\tau$  candidate events, reconstructed and identified are expected. This data will allow also a more precise evaluation of all the partial efficiencies, of the level of background interactions and of the final sensitivity of the experiment to  $\nu_\tau$  appearance in the CNGS  $\nu_\mu$  beam.

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