Summary of the OPERA analysis

C. Lazzaro on behalf of the OPERA collaboration

E-mail: claudia@lazzaro.ch

Abstract. The OPERA experiment is located in the Gran Sasso underground laboratory and designed to directly detect the appearance of $\nu_\tau$ in a pure $\nu_\mu$ beam by observing the decay of charged $\tau$ leptons produced in $\nu_\tau$ charged current interactions. The OPERA detector is a hybrid detector, containing electronic detectors (ED) and high resolution nuclear emulsions. A short introduction to the detector is presented. The analysis procedures will be described, including the analysis flow chain and the vertex decay search procedure. First results will be presented, including the main kinematic measurements obtained until now and the cross checks made on the background expectation.

1. Introduction
In the past two decades several experiments have provided strong evidence supporting the neutrino oscillation hypothesis. The $\nu$ oscillation was first established by the SuperKamiokande experiment [1] on atmospheric neutrinos and afterwards confirmed by the K2K [2] and MINOS [3] accelerator experiments. These experiments observed the disappearance of $\nu_\mu$ neutrinos; the unambiguous, direct observation of the appearance of a $\nu_\tau$ from an oscillated $\nu_\mu$ neutrino is still missing. The OPERA experiment [4] has been designed to directly observe the $\nu_\tau$ appearance in the CNGS $\nu_\mu$ beam [5] from CERN. The $\nu_\tau$ signature is given by the observation of the decay topology of the charged $\tau$ leptons produced in $\nu_\tau$ Charged Current (CC) interactions.

2. The OPERA experiment
2.1. The CNGS beam
The CNGS beam [5] is a wide band neutrino beam ($\langle E_{\nu_\mu} \rangle = 17$ GeV), which was optimized for the tau production and decay observation at the Gran Sasso laboratory. It is produced by a 400 GeV/c proton beam extracted from the SPS accelerator and that hits a carbon target producing mainly pions and kaons. Positively charged $\pi$ and $K$ are energy selected and focussed with the horn and the reflector into a 1 km long decay tunnel in the direction of the Gran Sasso laboratory. The mesons decay mainly into $\nu_\mu$ and $\mu$. The nominal integrated beam intensity is $4.5 \times 10^{19}$ protons on target ($p.o.t.$), for 200 days of beam operation per year. The time structure of the beam is characterized by a CNGS cycle of 6 s duration with two extraction spills separated by 50 ms and lasting 10.5 $\mu$s each, as shown in Fig. 1.

2.2. The OPERA detector
The decay length of the $\tau$ particles at CNGS energies is below 1 mm on average, thus, to reconstruct the decays, a spatial resolution of the order of about a micron is required. Also, due to the low neutrino cross section, a large mass experiment is mandatory. To fulfill these
requirements, OPERA was built as a hybrid detector consisting of a massive lead/photographic emulsion target to reach the micron resolution at the event vertex, complemented by electronic detectors, see [4] for details.

The detector is made of two identical super-modules (SM), as shown in Fig. 2. Each one contains 31 vertical target walls (perpendicular to the beam), able to hold the basic units of OPERA: the so-called emulsion cloud chamber (ECC) bricks. Each brick is a sandwich of 56 lead plates, 1 mm thick, interleaved by 57 emulsion films; it weighs about 8.3 kg. The transverse dimensions of the brick are $12.5 \times 10$ cm$^2$, the thickness along the beam direction is 7.9 cm, corresponding to about 10 radiation lengths. The two target modules contain in total about 150,000 bricks for a mass of 1.25 kton.

Behind each target wall there are two planes of horizontal and vertical scintillator strips (TargetTracker, TT); the strips are 1 cm thick, 2.6 cm wide and 6.9 m long. The scintillators are mainly used to predict the brick in which a neutrino interaction occurred, to measure the hadronic energy and the precise time of the event. Attached to the downstream side of each brick are two additional films, called Changeable Sheets (CS). They are used to validate the brick, which was predicted to contain the interaction by the electronic detector.

A magnetic spectrometer is placed behind the target section in each super module: each arm of the dipole magnet is composed of 12 iron slabs, interleaved by 11 Resistive Plate Chambers (RPC). Before, after and between each arm a station of vertical drift tubes (Precision Trackers, PT) permit an accurate measurement of the curvature of the charged particles in the magnetic field region, yielding a measurement of the charge and momentum of particles leaving the target, mainly muons. Two additional glass RPC planes (VETO) are mounted in front of the detector to select the charged particles originating from outside the target, due to neutrino interactions in the surrounding rock material.

Events generated by the CNGS neutrino beam are selected using a delayed coincidence between the proton extraction spill from the SPS and events in the detector. The synchronization between the SPS at CERN and the OPERA detector at LNGS is based on a GPS system, with a precision of 100 ns.

2.3. The $\tau$ detection principle

The $\tau$ events are identified selecting the decay topology of the short-lived $\tau$ leptons produced in the $\nu_\tau$ Charged Current (CC) interactions, decaying to one prong (electron, muon or hadron) or three prongs (hadrons). The one-prong events are characterized by a kink at the tau decay
Figure 2. The OPERA detector at the Gran Sasso laboratory.

Table 1. Expected number of $\tau$ and background events in OPERA for 5 nominal years of data taking.

| decay channel | signal ($\Delta m^2 = 2.5 \times 10^{-3} eV^2$) | 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       |

vertex or by a track with a large impact parameter with respect to the primary vertex. The reconstruction of the event topology is possible due to the high resolution of the emulsions in the brick.

The brick analysis and the event reconstruction in the brick include the momentum measurement of charged particles by the multiple Coulomb scattering (MCS) in the lead plates, a measurement of electromagnetic showers and muon-pion separation.

Assuming 5 years of data taking with nominal beam intensity, the total number of $\nu_\mu$ interactions expected in the detector is about 24,000, and about 170 $\nu_e$ and $\pi_e$ CC interactions. The number of $\nu_\tau$ charged current interactions is about 115 (for $\Delta m^2 = 2.5 \times 10^{-3} eV^2$ and full mixing); including decay branching ratios and experimental efficiencies, about 10 tau decays from $\nu_\tau$ CC events are expected to be observed, with tight selection conditions keeping the background below one event. The main background sources are:

- events with hadronic re-interactions mimicking tau decay topologies,
- the production of (short-lived) charmed particles in charged current $\nu_\mu$ interactions where the primary lepton is not identified,

The expected number of $\tau$ and background events for each channel are summarized in Table 1.
3. The analysis chain

The selection of neutrino events is performed off-line. Every time a trigger of the electronic detectors is compatible with an interaction inside the target and in time with the beam, an algorithm is applied to the electronic detector data to select the most probable brick in which the interaction occurred. The analysis of the electronic detector includes the reconstruction of the event, that permits first of all a selection between NC-like (Neutral Current) and CC-like events. In the case of a CC event, the muon track is reconstructed with PT, RPC and TT data. Different procedures, including a Hough transformation and a Kalman filter, are applied to estimate the position of the muon on the CS of a brick, to select in this way the brick containing the interaction. A measurement of the muon momentum is obtained using the information of the drift tubes (PT) in the spectrometer with a resolution of 20% up to a momentum of 30 GeV/c [6]. If no muon track is reconstructed, the TT data of the hadronic shower are used to estimate the position of the interaction vertex. In both cases an estimation of the hadronic energy of the event is obtained by the analysis of electronic detector data.

For each event a probability map for the closest bricks to contain the neutrino interaction is calculated, and the brick with the highest probability is extracted from the target, the CS films are developed and analyzed to validate the brick prediction. If the event is found in the CS, the brick will be exposed to X-rays and cosmic rays for the alignment of the emulsion films. The brick is then disassembled, the films developed and sent to the different scanning laboratories to perform the complete analysis; there are ten scanning laboratories in Europe and two in Japan.

The first scanning procedure in the brick (Scan Back phase) is focused on the neutrino interaction vertex location: the tracks found in the CS are followed from the most downstream film of the bricks to their stopping point (a track is considered as stopped, if it is not found in three consecutive films along its upstream extrapolation). Next, a volume around the stopping point is scanned (Total Scan): an area of 1 cm$^2$ is analysed around the stopping point in 10 films downstream and 5 upstream of the stopping plate. With the tracks found in the volume, the vertex is constructed, using the impact parameter (IP) of the tracks to the vertex; the IP of a track is defined as the shortest distance between the reconstructed candidate vertex and the track. As can be seen in Fig. 6, a precise measurement of the IP is fundamental to have a good $\tau$ decay detection capability. In addition, tracks attached to the vertex can be followed in the downstream direction (Scan-Forth) for kinematical measurements.

In order to detect all possible decay topologies near the primary vertex, a systematic decay search procedure is applied to the events; this includes three main steps:

- analysis of the impact parameter distribution,
- detection of possible decay topologies on tracks attached to the primary vertex,
- search for extra tracks from neutral decays or gamma conversion not attached to the primary vertex.

The measurement of a charged particle’s momentum in a brick is possible due to the precise measurements of the angular deviations produced by multiple Coulomb scattering in the lead plates; for charged particles up to 6 GeV/c a resolution better than 22% [7] is obtained. For higher momentum particles (passing through an entire brick), the measurement is based on position deviations and the resolution is better than 33% up to 12 GeV/c.

For the detection of the decay topology it is especially important to reconstruct the gamma rays in the bricks, since 70% of 1-prong hadronic $\tau$ decays include one or more $\pi^0$. The $\gamma$ reconstruction is performed by the analysis of the electromagnetic shower; its energy is determined with a Neural Network algorithm that uses as input mainly the number of tracks found in the shower and its shape and size.

With the decay search procedure neutrino induced charm events are also found. Charmed particles are produced in about 4% of CC $\nu_\mu$ interactions at the CNGS energies, and they have
similar lifetime and decay topologies as the $\tau$ particle; this also means that they can mimic a $\tau$ decay in case the primary muon is not identified. Hence, the study of charmed particle decays in the OPERA experiment is necessary to validate the procedures used for the selection and identification of short-lived particles and their efficiencies estimated by the Monte-Carlo, and to measure the background from charm decays.

4. Physics results
The results presented here were obtained from electronic detector data collected in 2008-2009, and the decay search analysis applied to about 35% of the 2008/-009 emulsion data sample, this corresponds to an integrated beam intensity of $1.89 \times 10^{19} p.o.t$ and 1088 $\nu$ events of which 901 were classified as CC interactions. The analysis of this sample was reported together with the first $\tau$ decay candidate in [8]¹. In this section the data-MC comparison of some kinematical variables and the background estimation used to validate the analysis and to cross-check the MC is presented.

4.1. Eletronic detector data analysis
Many kinematical variables were studied, mostly related to the muon track, such as the reconstructed muon momentum in the CC events and the length of the muon track times the density of the crossed material, which is the main variable used for the muon identification. These are shown in Fig. 3.

An important cross check is the comparison of the measured and expected ratio between neutral current and charged current interactions. The measured (visible) $NC/CC$ ratio is taking into account the true $NC/CC$ ratio ($= 0.3$), the muon identification efficiency, the fraction of the CC misidentified as NC events, and the fiducial volume selection efficiency. The fiducial volume selection is necessary to reduce the background accumulation at target borders due to particles produced in beam-neutrino interactions outside the target in the rock and surrounding material. Very good agreement is found for this ratio between the MC-expectation and the measurement in the preliminary analysis of 2008 and 2009 data, not including systematic errors under study, as shown in Table 2.

A good agreement between electronic detector data and MC expectation for the other investigated variables was observed.

¹ The tau decay candidate is not described here, since it is covered in the contribution of Bjoern Wonsak [9].
Table 2. Measured (visible) and expected MC ration NC/CC.

| MC NC/CC | 0.236 ± 0.005(stat) |
|-----------|---------------------|
| Data 2008-2009 NC/CC | 0.230 ± 0.008(stat) |

Figure 4. Distribution of muon slopes for $\nu_\mu$ CC events measured at the primary vertex and comparison with the MC expectation.

Figure 5. Correlation between muon momentum measurements in the brick (using MCS) and by the electronic detector.

4.2. Analysis of emulsions
The vertex position in the plane transverse to the beam (x-y coordinate distribution) is observed to be uniform, indicating that the transverse vertex location procedure is not biased. In Fig. 4 the measured muon slopes are compared with the MC expectation.

The muon momentum measured in the emulsions (by multiple Coulomb scattering) for the soft muons is compared with the measurement obtained with the ED to validate the procedure. They are in good agreement, as shown in Fig. 5, with a resolution of about 20%.

The IP distribution at the $\nu_\mu$ vertex is shown in Fig. 6; it is well contained within 10 microns; the IP distribution for the daughter tracks from $\tau$ decays form a Monte Carlo simulation is also shown, typical $\tau$ decay IP values are well beyond the region dominated by the experimental resolution.
4.3. Background

As discussed in the previous section, the two most important background sources for the OPERA experiment are hadron re-interactions and charm decays.

4.3.1. Hadronic re-interaction

To study the hadronic re-interaction background, first of all a MC analysis has been done, after simulation of a very large number of hadron interactions in lead. The kink probabilities are evaluated by applying the same cuts as for the tau decay analysis; integration over the $\nu_\mu$ NC hadronic spectrum yields a background probability of $(1.9\pm0.1)\times10^{-4}$ kinks/NC. This probability decreases to $(3.8\pm0.2)\times10^{-5}$ per NC event when taking into account the cuts on the event global kinematics. With the collection of a sufficient number of events, a search for hadronic re-interactions in the data was also started. So far, a total of 9 m of hadrons tracks have been followed for the presence of re-interactions far from the vertex region. No events were found that satisfy the selection criteria for $\nu_\tau$ candidates, corresponding to an upper limit of $1.54\times10^{-3}$ kinks/NC event (90\% C.L.). This search will be extended to about 100 m of tracks in order to validate and eventually replace the MC estimation.

4.3.2. Charm decay events

To limit this source of background it is extremely important to have a good identification of the primary muon; in OPERA the muon identification reaches $\sim 95\%$. The charm background expectation for the 1-prong hadronic tau decay channel (the found tau candidate is in this channel) for the statistics collected until now is $0.007\pm0.004$ (syst) events.

An example of a neutral charm candidate decaying in 4 prongs is shown in Fig. 7: 3 tracks have been reconstructed at the primary vertex. All the measured impact parameters at the two vertices are of the order of a micron. The minimum value of the invariant mass was estimated to be $1.74 \text{ GeV}/c^2$; the angle $\phi$ between the directions of the parent track and of the primary hadron shower momentum in the transverse plane, is found to be close to 180$^\circ$ which corresponds to a back-to-back emission of the decaying particle with respect to the muon, strengthening the charm hypothesis.

Improvement of the charm background reduction is under evaluation by implementing the systematic follow-down of low energy tracks in the bricks and the inspection of their end-range for a better hadron-muon separation.

For the statistics collected in 2008-2009, the charm decays found and expected from MC
Figure 7. Charm events: charged charm with a clear kink shown by the red dot on the left and $D^0$ decay into 4 prongs on the right.

Simulations are shown in Table 3.

Table 3. Charm decays found for the statistics collected in 2008-2009, and MC expectation.

|          |                      |
|----------|----------------------|
| 20 charm candidates | Expected: 16 ± 2.9 |

5. Conclusions

OPERA is collecting neutrino interactions in its lead-emulsion targets since 2008. Up to now, 1921 neutrino vertices have been precisely located and the decay search analysis has been completed for a sub-sample of 1088 events. One tau decay candidate was found [8], and the full analysis chain was tested. The electronic detectors are running reliably and the performance is well understood. A systematic decay search was started in 2008 and 2009 located neutrino interactions in order to find all possible decay topologies. The good agreement between the observed number of charm decays and the MC expectation confirms the capability to find and reconstruct decays of short-lived particles with the OPERA detector. The background sources are under control, and the data analysis of the 2009-2010 run is in progress. The experiment is expected to continue data taking for two more years in CNGS beam.

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