The OPERA experiment

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Abstract

After setting-up and target filling, OPERA is about to start its full-scale data taking. Good performance in previous short runs is reported, showing a rich physics output, event by event, based on high-resolution tracking, prompt/non prompt lepton identification and kinematical analysis. Observation of ν_τ interactions, tagged by τ decay, as a direct signal of ν oscillation in appearance mode, could be within reach already this year, as the long-baseline CERN facility, CNGS, is scheduled to send soon again neutrinos toward the Gran Sasso Lab.

1 Introduction

Increasing experimental evidence of neutrino oscillation has been collected in the last decade, by exploiting both the natural neutrino sources and the available artificial sources like reactors and dedicated accelerator lines. However, leaving aside major unanswered questions about the neutrino properties (eigenstate masses and their hierarchy, Majorana behavior, CP violation, etc.), the direct observation of flavor appearance, complementary to the widely reported flavor disappearance, yet remains among the missing elements of the picture. OPERA [b] was designed to provide a direct evidence of the "atmospheric" oscillation $\nu_\mu \rightarrow \nu_\tau$ by looking for the ν_τ appearance in a "pure ν_μ" beam. The status and short-term perspectives of OPERA are the subject of the present contribution to the Quarks 2008 Conference held in Sergiev Posad, Russia. The design and actual implementation of the OPERA detector will be briefly reviewed in the next Section. Performance with the dedicated CERN neutrino beam to Gran Sasso (*CNGS*), at its first exploitation, will be reported in Sec. 3. Details of the event-by-event "hybrid" analysis stream will be examined in Sec. 4. The expected physics output, with short-term plans and an outlook to the future, is considered in the last Section.

2 The OPERA detector

OPERA is conceived as a modular, hybrid apparatus, as it combines electronic tracking devices and nuclear emulsion films interspersed with lead sheets as target elements (featuring the so-called Emulsion Cloud Chamber, ECC, technique). A recent picture of the OPERA detector, as built in Hall C of the Gran Sasso underground Laboratory in Italy (LNGS), is shown in Fig. 1.

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[b] **O**scillation **P**roject with an **E**mulsion t**R**acking **A**pparatus

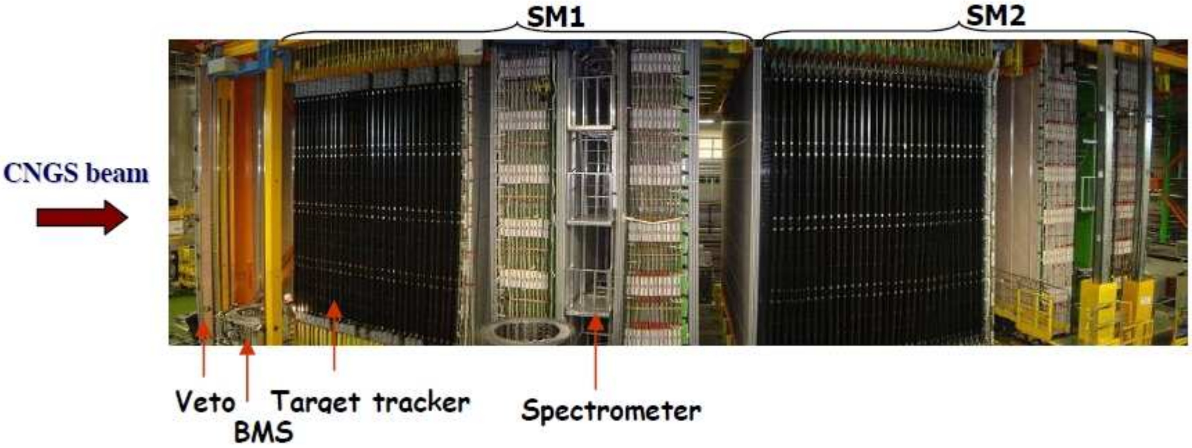

Figure 1: The OPERA detector at Gran Sasso Underground Lab, Italy

Figure 2: The ECC brick, with its CS doublet (see text) shown open.

Overall, the apparatus is 20 m long, with a cross-section of 9×10 m^2. VETO planes, made of glass RPC detectors, are placed upstream of two supermodules, SM1 and SM2, each consisting of a massive instrumented target section and a magnetic spectrometer. Each target section is a sequence of 31 vertical steel containers (walls), hosting ECC target elements, interleaved with double-layered plastic scintillator planes as Target Trackers (TT). Each spectrometer is made of a 990 ton Fe dipole magnet, instrumented with RPC planes (22 planes of inner trackers, and outer crossed trackers, XPC) and drift tube walls (Precision Trackers, PT). A large number of ECC target units, called bricks, have been assembled and inserted into the target walls. As this is the core element of OPERA, some details about its structure are given here below. An ECC brick (Fig. 2) is a light-tight, regular array of 57 emulsion films interleaved with 56 Pb plates, 1 mm thick, accounting for most of its 8.3 kg mass. The transverse size of a brick is 128×102 mm^2; the longitudinal size is 79 mm, with 10 X_0 along the beam direction. Each film is double-coated, on both sides of a 205 μm thick plastic base, with two thin (44 μm) sensitive emulsion layers. For the inter-calibration purposes explained in Sec. 4, a doublet of emulsion films, inserted in close contact in a light-tight aluminized paper envelope and then secured in a plastic box (both shown open in Fig. 2), are attached to each brick. Since they can be independently checked and substituted, they are called Changeable Sheet (CS).

A dedicated Brick Assembly Machine (BAM), with state-of-art automation and robotics, accomplished the challenging task of careful and precise handling of millions of Pb plates and emulsion films, mass-

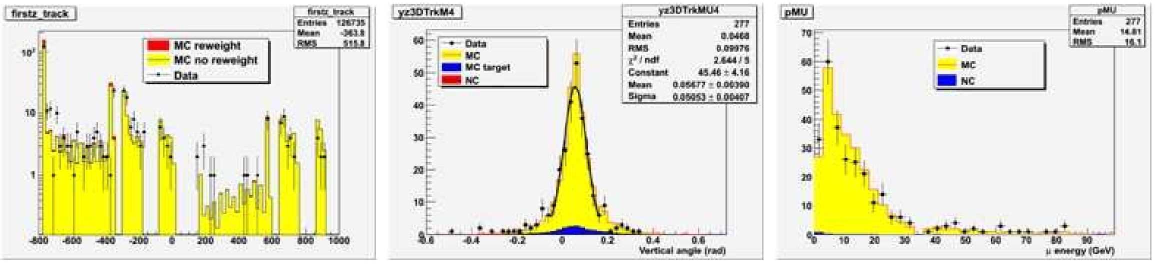

Figure 3: Preliminary data-MC comparison for beam-related events. Left to right: 1) longitudinal distribution of outside-target events; 2) muon angle 3) muon energy

producing suitable ECC bricks since March 2007. Brick ready for exposure are inserted in the target walls by another dedicated system, called Brick Manipulator System (BMS), installed on both sides of the OPERA detector. At the time of Quarks 2008 Conference, 134,000 ECC bricks were already produced and inserted into their target walls, corresponding to 87% of the expected final mass of 1.35 *kton*. The first supermodule was completed, and the filling of the second one was expected to be over soon. Full details about the OPERA detector, its components and its related experimental infrastructure at LNGS can be found in Ref. [1].

3 Performance with the CNGS beam

The CNGS [2] is an almost pure ν_μ beam (4% $\bar{\nu}_\mu$ contamination, less than 1% ν_e and $\bar{\nu}_e$ contamination, negligible content of ν_τ) with a wide-band energy spectrum optimized to maximize, under the oscillation hypothesis, the number of CC ν_τ interactions at the LNGS location (baseline: 732 *km*), were the average neutrino energy is 17 GeV. A first short run of CNGS took place in August 2006, delivering an integrated intensity of 7.6×10^{17} protons on target (p.o.t.). Correspondingly, 319 "beam-related events" were reported by OPERA [3], at that time in empty target configuration. A second run was performed in October 2007, with 8.24×10^{17} p.o.t. and 331 beam-related events reconstructed as outside the OPERA target. As the first supermodule (SM1) was already partially filled, 38 in-target, beam-related events were also reconstructed. Meanwhile, and thereafter, OPERA took also cosmic-ray data with CNGS off. Results are summarized in this Section, apart from the neutrino interactions located in the ECC bricks, examined in next Section. The event timing information is the basic selection tool to extract beam-related events, *i.e.* events compliant with the extraction time windows of the CNGS (*e.g.* two 10.5 μs spills, 50 *ms* apart). In fact, by design of the trigger-less, distributed DAQ system, each electronic detector element in OPERA is read out by an independent micro-processor, with accurate GPS time stamping. Data are sent over a standard Ethernet network and recompiled off-line. After UTC adjustment and fine-tuning of the OPERA and CNGS synchronized GPS systems, an overall accuracy of better than 100 *ns* was achieved. By the off-line analysis of beam-related events, pattern recognition in the TT system and in the magnetic spectrometers allows a clear classification into a) external CC-like neutrino interactions (upstream and surrounding rock and other material) with μ penetrating the apparatus and eventually crossing one or both spectrometers b) CC or NC interactions in the spectrometer material c) interactions in the target area (ECC bricks, target walls and TT planes). Accurate angle measurements were made on penetrating particles. Upon crossing of one or both spectrometers, muon charge could be assigned and momentum estimated. Muon energy is also computed by range. Preliminary results, with the data-MC comparison in good progress, are shown in Fig. 3.

As the electronic detector components are meeting their design goals (TT spatial resolution 0.8 cm, $\epsilon \approx 99\%$, with a trigger rate of 20 cps/pixel at 1 p.e.; RPC spatial resolution 1.3 cm, $\epsilon \approx 96\%$; PT spatial resolution approaching 0.5 mm) and their overall alignment was accomplished, fairly good results were achieved after this first phase of data taking. The beam direction has been accurately measured (vertical angle: 56.8 ± 3.9 $mrad$). The estimated μ identification efficiency is $> 95\%$. The estimated wrong charge assignment is $0.1 \div 0.3\%$. After proper unfolding and MC tuning, accurate monitoring of the CNGS beam flux and beam energy spectrum at the LNGS site can be provided by OPERA. Further improvements of GPS synchronous timing accuracy could allow some ν time-of-flight measurements. A few remarks follow about cosmic-ray data, regularly taken and analyzed both for calibration purposes and to record occasional muons close to the beam direction. Their estimated background rate within the beam time window was about 10^{-4}. Besides, given the good acceptance of the apparatus also in the vertical directions, copious parasitic data on single-muon and multi-muon bundles are recorded, and occasional up-going muons are observed. Since muon momentum and charge can be assigned in favorable cases, some interesting cosmic-ray physics by-product is under consideration by the Collaboration.

4 Neutrino interactions in the ECC target

Schematically, neutrino interactions occurring inside the OPERA ECC target are properly tagged by electronic hit patterns in the TT detector. For CC-like interactions, penetrating μ can cross one or both magnetic spectrometers, allowing determining μ charge and momentum. The off-line event reconstruction allows predicting the individual ECC brick were the event occurred. After extraction of selected bricks, the second data taking of the hybrid procedure starts, *i.e.* the scanning of the emulsion films. State-of-art automated optical microscopes are employed both in Japanese [4], [1] and in European [5] scanning Labs. A key step in the hybrid event analysis procedure is the inter-calibration between the electronic detector and each individual ECC brick selected and extracted from the apparatus. In fact, the former provides time-stamped data pointing to the target with a few cm accuracy, the latter contains high-resolution (< 1 μm) 3-D images due to every ionizing particle leaving a latent image in the photographic emulsion films all along their lifetime, from casting to development. For this purpose, the CS doublet of emulsion films, mentioned in Sec. 2, is attached underground to a corresponding brick. After extraction, it is detached and developed, again underground, thus collecting overall a very small number of correlated background tracks. Instead, the emulsion films assembled inside the ECC brick are brought at the surface Lab, shortly exposed to cosmic-rays for alignment, and then processed. The event location procedure, schematically shown in Fig. 4, is a sequence of inter-calibration and alignment steps: a) starting with TT predictions; b) requiring confirmation and the definition of scan-back candidate tracks in the CS; c) following back the tracks in the ECC brick until they eventually stop, defining vertex candidate points; d) taking data in a volume around each vertex candidate in order to confirm it and fully reconstruct the event topology. Details of this procedure can be found in Refs. [1] and [6].

During the very short CNGS run of 2007, unfortunately aborted due to problems in cooling and temperature control units at CERN, 38 beam-related events were reconstructed pointing to target walls of SM1 filled with ECC bricks (60,000 were already inserted). For 36 of them, the step from TT to CS was successful, and then the scan-back inside the ECC brick allowed the location of CC-like and NC-like neutrino interactions.

Despite the meager statistical sample, extensive event study was performed, allowing the application of methods and algorithms ready beforehand, developed on test beam data and MC [7]. In fact, precise tracking and vertex reconstruction were achieved (impact parameter at the m level); momentum estima-

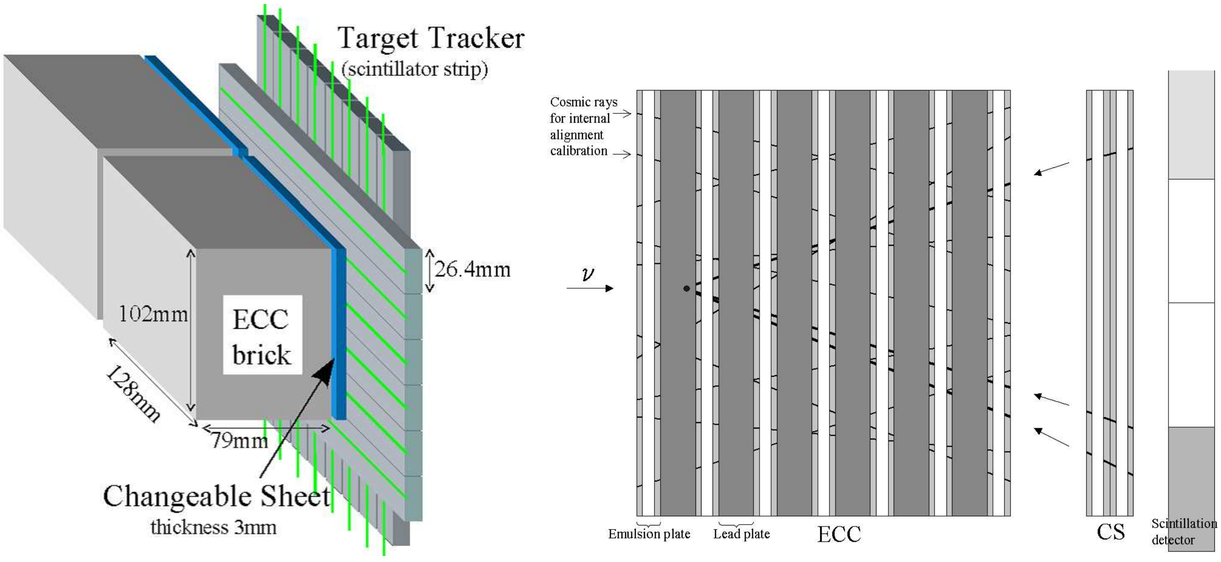

Figure 4: Schematics of neutrino event location in the OPERA target units, the ECC bricks equipped with CS doublets.

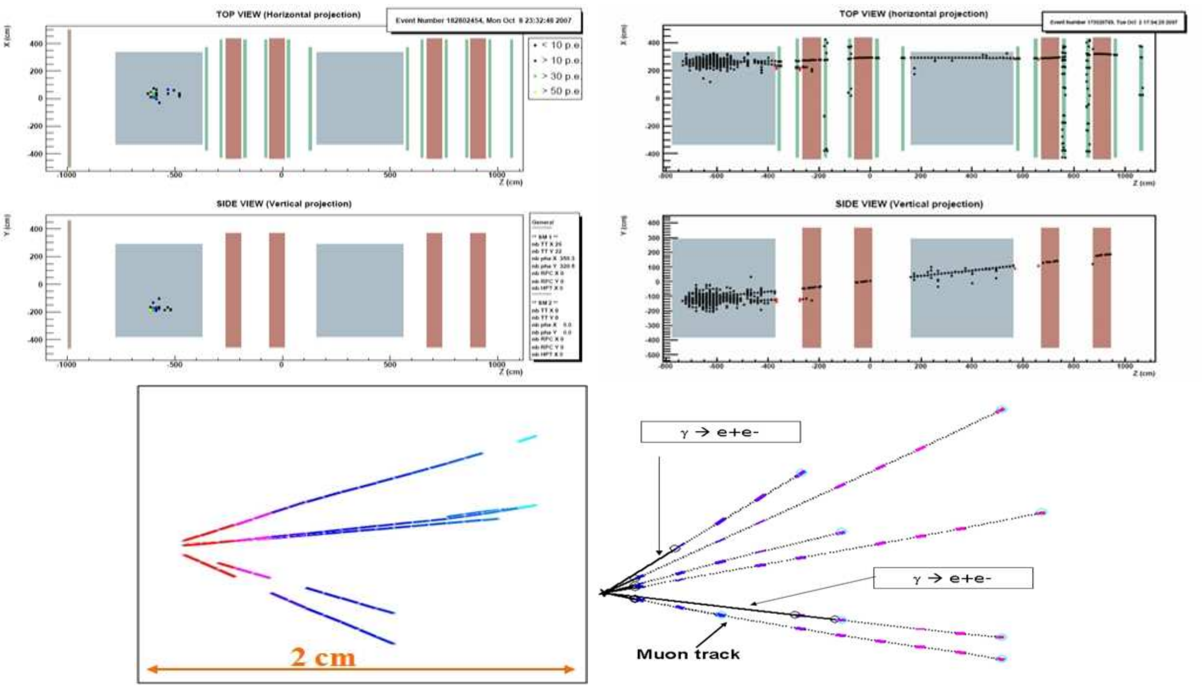

Figure 5: A NC-like interaction (left) and a CC-like interaction (right). Top: OPERA display. Bottom: emulsion reconstruction (longitudinal scale: invisible path between emulsion tracks is 1 mm Pb).

tion by multiple Coulomb scattering was applied; shower detection for e/π separation was performed; kinematical event analysis was attempted.

At this stage of the experiment, a few pictures may give a better feeling about the potential physics output and the background rejection capability, event-by-event (Fig. 5,6).

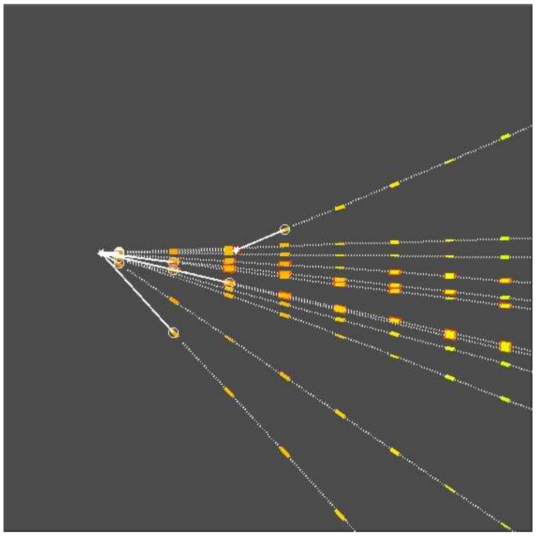

Figure 6: A neutrino interaction with charm decay candidate topology.

The top part of Fig. 5 shows hits in the electronic detector for a NC-like (left) and CC-like (right) interactions. After event location and study in the ECC brick a rich event description emerges (bottom part, emulsion data after alignment), with full topological details, momentum measurements and particle id. Notably, in the case of the CC event shown, the two electromagnetic pairs are compatible with π^0, with a π^0 mass of 110 ± 30 MeV. In Fig. 6, an event with a decay topology (kink) similar to that expected for a τ decay (Flight length: 3247.2 μm; θ_{kink}: 0.204 rad; $P_{daughter}$: 3.9 $(+1.7 - 0.9)$ GeV; P_T: 796 MeV). However, a prompt μ^- attached to the primary vertex and transverse-plane balance put a clear signature of a ν_μ CC interaction likely to produce a charmed particle.

5 Outlook

As shown in the previous Sections, the OPERA experiment had a successful start-up with CNGS in 2006 and 2007, the first year as empty-target, the second year with only one supermodule partially filled with ECC target units. In both cases, very limited integrated beam intensity has been collected. Both components of the hybrid data taking and analysis, the electronic detectors and the ECC, performed according to their design goals. Neutrino interactions were recorded, reconstructed, located and analyzed, featuring fairly good efficiency, clean physics output and very high background rejection capability.

Now the target filling is close to completion, approaching a final mass of 1.35 $kton$, and the detector and its infrastructure are fully commissioned. In the near future, starting from summer this year, the CNGS facility is expected to run with continuity and increasing intensity, to match the expected nominal figure of 4.5×10^{19} p.o.t. per year. If so, in 5 years OPERA is expected to observe 10.4 to 15.0 ν_τ events after oscillation at full mixing and $\Delta m^2 = 2.5 \times 10^{-3}$ to $3.0 \times 10^{-3} eV^2$, respectively, with a background of 0.76 events. Already in 2008, with about half of the nominal intensity expected, a first candidate could be observed. With event-by-event topology and lepton id capability, sub-dominant oscillation modes can be somehow investigated, and exotic scenarios eventually ruled out.

Acknowledgment

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