IL NUOVO CIMENTO Vol. 34 C, N. 5 Settembre-Ottobre 2011
DOI 10.1393/ncc/i2011-10979-5

Communications: SIF Congress 2010

Decay search in the OPERA experiment

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(ricevuto il 30 Dicembre 2010; revisionato il 25 Luglio 2011; approvato il 10 Agosto 2011; pubblicato online il 22 Settembre 2011)

Summary. — The CERN-Neutrinos–to–Gran Sasso project (CNGS) is devoted to prove unambiguously the $\nu_\mu \to \nu_\tau$ oscillation channel in the atmospheric sector. The high-energy and high-intensity CNGS muon neutrino beam, generated at CERN, is directed towards the Italian Gran Sasso National Laboratory (LNGS), where the OPERA long-baseline experiment searches for ν_τ appearance. In this paper, a review of the performance and physics potential of the experiment together with the description of dedicated strategies to observe events with decay topologies in the OPERA target will be given.

PACS 14.60.Pq – Neutrino mass and mixing.
PACS 13.15.+g – Neutrino interactions.
PACS 14.60.Lm – Ordinary neutrinos.
PACS 29.40.Gx – Tracking and position-sensitive detectors.

1. – Introduction

In the last decades, the mixing of neutrino flavor states and the consequent flavor oscillation hypothesis have been confirmed in the atmospheric sector by several experiments performed in disappearance mode [1]. A final proof will be set by studying the $\nu_\mu \to \nu_\tau$ oscillation channel in appearance mode.

The Oscillation Project with Emulsion tRacking Apparatus (OPERA) [2] was designed to reach this goal through the direct observation of ν_τ in an almost pure ν_μ beam.

The CERN-Neutrinos–to–Gran Sasso (CNGS) [3] high-energy neutrino beam ($\langle E_{\nu_\mu} \rangle \simeq$ 17 GeV) is produced at CERN and delivered at LNGS where the OPERA detector is located. It has been conceived in order to maximize the number of ν_τ charged-current interactions in the target. Contamination of the beam in terms of $\overline{\nu}_\mu$CC interactions is about 2%, lower than 1% from ν_eCC and $\overline{\nu}_e$CC interactions and of the order of 10^{-6} in

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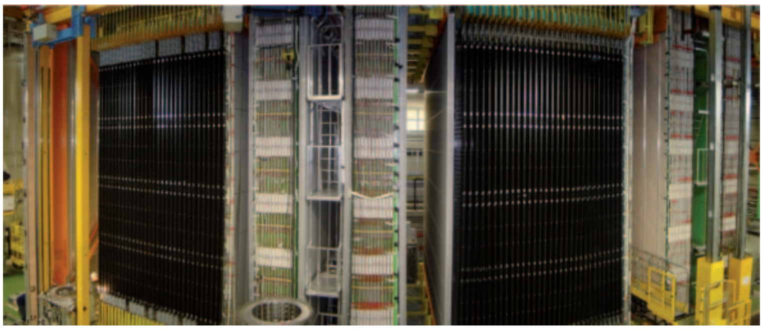

Fig. 1. – View of the OPERA detector.

case of ν_τ prompt. A nominal beam intensity of 4.5×10^{19} p.o.t. per year is expected for five years of physics runs. Accordingly, we expect about 4700 ν_μ charged and neutral current events per year.

If the $\nu_\mu \to \nu_\tau$ oscillation hypothesis would be confirmed, the number of tau events observed in the OPERA detector after 5 years of data taking is expected to be equal to 10.40 with a background of 0.75 events ($\Delta m^2_{23} = 2.5 \times 10^{-3}\,\mathrm{eV}^2$ at full mixing).

2. – The OPERA experiment

OPERA [2] has a massive detector, exploiting the advantages of nuclear emulsions detection technique.

This is the way to maximize statistics and to rely on a very high spatial accuracy and granularity that should cope with the peculiar signature of short-lived τ lepton produced in ν_τCC interactions (in the millimeter range at the CNGS beam energy).

The detector construction was completed at the beginning of 2008 and the data taking successfully started in the Summer of 2008.

The OPERA hybrid apparatus consists of two identical Super Modules (SM1 and SM2) as shown in fig. 1. Each Super Module is composed of a target section and a muon spectrometer. Each target section ($\sim 625\,\mathrm{t}$) is organized in 31 vertical "walls", transverse to the beam direction. Walls are filled with "bricks" with an overall mass of 1.25 kt. They are followed by double layers of scintillator planes acting as Target Trackers (TT) that are used to locate neutrino interactions occurred within the target.

The brick is the basic unit of the detector: it consists of 57 nuclear-emulsion films interleaved with 1 mm thick lead plates, with a total length of 7.9 cm along the beam direction, transverse dimensions of $10.2 \times 12.8\,\mathrm{cm}^2$ and a total mass of 8.3 kg. An additional tightly packed doublet of emulsion films (Changeable Sheets, CS) is glued to the downstream face of each brick, in order to connect the electronic detectors predictions to the brick.

The spectrometers consist of a dipolar magnet instrumented with active detectors, planes of RPCs (Internal Tracker, IT) and drift tubes (Precision Tracker, PT). Tasks of the spectrometers are muon identification and charge measurement in order to minimize the background. The charge-sign misidentification probability has been estimated to be of about 0.3% up to $50\,\mathrm{GeV}/c$; the momentum resolution is about 20% in the same kinematical range.

The apparatus is equipped with an automatic machine (Brick Manipulator System, BMS), allowing the online removal of bricks from the detector, together with some ancillary facilities for the emulsions' handling. Specially designed and dedicated European and Japanese Scanning Stations take care of the nuclear emulsions films measurement.

3. – The OPERA strategy

Every time a charged particle produced in a neutrino interaction occurred in a brick produces a signal in the TT, a brick finding algorithm is applied in order to select the brick which has the maximum probability to contain the neutrino interaction. The efficiency of this procedure is as high as 83% in a sub-sample where up to 4 bricks per event were processed.

Once the selected brick is removed from the target by the BMS, the corresponding CS doublet is detached from the brick and developed in a dedicated underground facility. The two emulsion films are then scanned at LNGS or in Japan. The measurement of emulsion films is performed through fast automated microscopes with a scanning speed greater than $20\,\text{cm}^2/\text{h}$, a tracking efficiency of about 90%, sub-micrometric position resolution and angular resolution of the order of one milliradian.

The measured residuals between electronic detectors predictions and CS tracks are found to be of the order of a cm. If any track originating from the interaction is detected in the CS, the brick is exposed to cosmic rays (for alignment purposes) and then depacked. The emulsion films are developed and sent to the scanning laboratories of the Collaboration for event location studies and decay search analysis. The CS-to-brick connection is achieved with less than $100\,\mu\text{m}$ position accuracy and with a slope accuracy of the order of 10 mrad.

All tracks located in the CS are followed upstream through the brick (*scan-back*) until they stop. A general scanning (no angular pre-selection) is then performed in a $2\,\text{cm}^3$ volume around the stopping point(s) in order to reconstruct the vertex topology with micrometric precision.

In order to detect decay or secondary interaction topologies, all located vertices are studied more in details by means of a dedicated procedure.

4. – Decay search in nuclear emulsions

Photographic emulsions initiated accidentally their role in particle physics more than 100 years ago [4]. An intense R&D activity led to the development of the so called "Emulsion Cloud Chamber", a detector consisting of alternate layers of photographic emulsion and absorber, characterized by very high sensitivity and grain uniformity and capable of observing tracks of single particles with sub-micrometric space resolution. This technique is specially suitable for the observation of short-lived particles and led, in the past, to several important discoveries such as the observation of the first charmed particle [5], the first direct observation of the decay of beauty particles into charmed ones [6] and the first detection of a tau neutrino [7].

Today, the OPERA sandwich-like structure made of lead plates (passive material) and thin emulsion layers (tracking device) exploits this feature and, in addition, allows the particles identification and the measurement of their kinematical parameters by means of a detailed observation of specific ionization, showering and multiple Coulomb scattering.

Particle momenta are evaluated in the emulsion films by the multiple Coulomb scattering of tracks in the lead plates using an angular method for charged particles up to

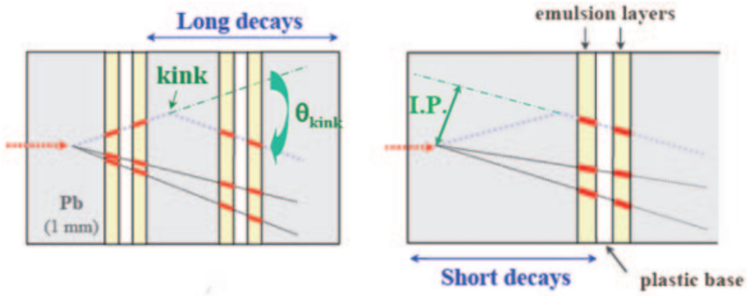

Fig. 2. – Sketches of the so-called long decay (left) and short decay (right) for the short-lived tau lepton inside an OPERA brick.

6 GeV/c with a resolution better than 22% and a position deviation method for higher-energy particles with a resolution better than 33% on $1/p$ up to 12 GeV/c. Muon momentum is measured in spectrometers, as already mentioned in sect. **2**.

Gamma-ray search is performed in the measured volume by means of electromagnetic shower detection or visual inspection of e-pair at its starting point and its energy is estimated by a dedicated Neural Network algorithm.

As mentioned above, ν_τ appearance search at LNGS is made possible by means of τ decay topologies detection inside the OPERA target.

Tau decays inside a brick may be classified into two categories shown in fig. 2: short and long ones. In the first case the ν_τCC interaction and the subsequent τ decay occur in the same lead plate: no track associated to τ lepton can exist in the brick. Long decays are characterized by longer τ decay length that means there is a chance to reconstruct its passing through the emulsion film(s) and therefore the peculiar kink topology.

Depending on the decay channel, different strategy to look for τ decays are referred to.

At first, a dedicated procedure has been applied to all located vertices in order to select interesting topologies by means of topological criteria. This study is realized including 10 nuclear emulsion films downstream with respect to the primary neutrino interaction and 5 films upstream, for an overall volume of 2 cm^3.

In order to detect interesting topologies, a check on impact parameters (ip) of tracks that have been reconstructed as interaction daughters is mandatory. Only tracks with impact parameter with respect to the vertex less than 10 μm are confirmed to be primary tracks. Tracks not verifying the selection, have to be further studied to investigate the reason for such anomalous value (*e.g.* scattering in the traversed lead thickness), and possibly reconsidered in the determination of the vertex position. A so-called "*in-track*" decay search is then applied to confirmed primary tracks: for each track, the largest slope difference in the first 4 films downstream with respect to the vertex is computed as shown in fig. 3 and compared with a mean reference value estimated taking into account the particle multiple Coulomb scattering in lead. This compatibility check is performed to identify possible small kink angles ($\theta_{kink} > 15$ mrad), signatures of decaying particles to be analyzed more in detail.

Extra tracks originated from neutral decays, interactions and gamma ray conversions are searched for inside the measured volume, too. Different Monte Carlo optimized selection criteria are applied for events with the primary neutrino interaction clearly

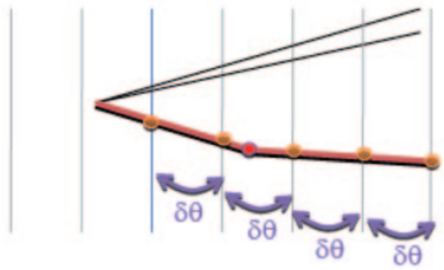

Fig. 3. – In-track decay search: a schematic view.

identified([1]) and events where an ambiguity exists on the main vertex definition. The impact parameter of each extra-track with respect to the main vertex, together with the longitudinal distance between the vertex and the most upstream segment of the track, has to be considered as the relevant observable, in both cases.

Selected tracks are visually inspected in order to reject electron-positron pairs from gamma-conversion and then investigated more in details as short decays' daughter candidates or long decays' daughter/parent candidates, according as they stop in the vertex emulsion film or in any other one.

Once an interesting secondary vertex topology is found in the event, it is analyzed through kinematical criteria depending on the decay channel to be investigated. Selection criteria are based on the evaluation of the missing transverse momentum and the ϕ angle between the parent track and the rest of the hadronic shower in the transverse plane at the primary vertex, on the daughter particle momentum, on the missing transverse momentum and on the kink angle at secondary vertex. By way of example, selection criteria to be applied to interesting single-hadron long-decay topologies will be listed in the following.

For the primary vertex it is required that

- there are no tracks compatible with that of a muon or an electron;
- the missing transverse momentum is smaller than $1\,\mathrm{GeV}/c$;
- the angle ϕ in the transverse plane between the τ candidate track and the hadronic shower direction is larger than $\pi/2$.

For the secondary vertex, it is required that

- the kink angle is larger than 20 mrad;
- the secondary vertex is within two lead plates immediately downstream of the primary vertex;
- the momentum of the charged secondary particles is larger than $2\,\mathrm{GeV}/c$;

([1]) For example, muon neutrinos charged current interactions in case of reconstructed muon at the primary vertex.

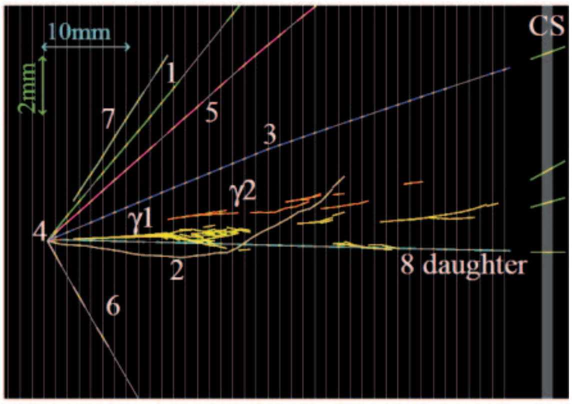

Fig. 4. – Display of the ν_τCC candidate event.

– the total transverse momentum of the decay products is larger than 0.6 GeV/c if there are no photons emitted at the decay vertex, and 0.3 GeV/c otherwise.

Charmed particles have similar lifetimes as τ lepton and, if charged, share the same decay topologies. At the time of this writing, taking into account the sample of analyzed events from 2008 and 2009 runs [8], the OPERA Collaboration has observed 18 charm decay candidates and 6 charged-current electron-neutrino interactions in good agreement with expectations. This demonstrates that the efficiency of the search for short-lived decay topologies is understood.

Moreover, the first charged-current tau neutrino candidate has been detected (0.5 ν_τ expected with respect to the analyzed statistics) [8].

5. – The first tau neutrino candidate

The first ν_τCC candidate in the OPERA detector is shown in fig. 4. The primary neutrino interaction is a seven-prong vertex occurred in a brick situated in wall 11 of the first SM and well inside the target, allowing a deep analysis of the event.

One daughter track exhibits a visible kink. All kinematical variables are satisfying all selection criteria established for hadronic kinks (see table I). None of the charged particles

TABLE I. – *First tau neutrino candidate: kinematical variables.*

Variable	
kink (mrad)	41 ± 2
decay length (μm)	1335 ± 35
P_{daugh} (GeV/c)	12^{+6}_{-3}
P_t decay (MeV/c)	470^{+230}_{-120}
missing P_t (MeV/c)	570^{+320}_{-170}
ϕ (°)	173 ± 2

at the primary and secondary vertex is compatible with being an electron. For tracks that are not hadrons (no interaction seen), the probability that are left by a muon is less than 10^{-3}. The residual probability of ν_μCC event (possibly undetected large angle μ) is about 1%; the nominal value of 5% is assumed. Two electromagnetic showers caused by γ-rays, associated with the event, have been located and studied. Their emission at the secondary vertex is the favored hypothesis and the evaluation of their invariant mass $((120 \pm 20\ \text{(stat.)} \pm 35\ \text{(syst.)})\ \text{MeV}/c^2)$ supports the fact that they originate from a π^0 decay.

The secondary vertex is compatible with the tau one-prong hadronic decay mode:

$$\tau^- \to \mathrm{h}(\mathrm{n}\pi^0)\,\nu_\tau$$

The main sources of background for this channel are hadronic re-interactions and decays of charmed particles produced in ν_μ interactions.

The charm background produced in muon neutrinos interactions amounts to 0.007 ± 0.004 (syst.) events in the reference data sample; it is less than 10^{-3} events if coming from ν_e interactions. The dominant background from hadron re-interactions has been evaluated with a FLUKA based Monte Carlo code to be $(1.9 \pm 0.1) \cdot 10^{-4}$ kinks/NC. When misclassified CC events are included, a total of 0.011 ± 0.006 (syst.) background events are foreseen. Consequently, the total background in the tau decay channel to a single charged hadron is 0.018 ± 0.007 (syst.) and its probability to fluctuate into one event is 1.8% (2.36 σ). If the search for tau decays is extended to all decay modes, the background expectation is equal to 0.045 ± 0.020 (syst.) events which correspond to a fluctuation probability to one event of 4.5% (2.01 σ).

6. – Conclusions

The OPERA experiment was designed to explore in appearance mode $\nu_\mu \to \nu_\tau$ oscillations in the almost pure CNGS ν_μ beam. The detection of decay topologies in the OPERA target is therefore mandatory to reach the goal of the experiment.

Topological and kinematical selection criteria were defined and optimized in order to locate short-lived particles decays in an OPERA brick. They have been systematically applied to located neutrino interactions that means, at the time of this talk, on a sub-sample of neutrino data taken in the CNGS beam 2008–2009 runs. Several interesting topologies such as charm decays candidates have been reconstructed in agreement with the expectations. One muonless event showing a $\tau \to$ 1-prong hadronic decay topology has been detected and studied in detail. It passes all kinematical cuts required to reduce the physics background, being the first ν_τ candidate event in OPERA with statistical significance of 2.36 σ (for one-prong hadronic decay mode) and 2.01 σ (for all decay modes).

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