Latest results of OPERA

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The OPERA experiment, located in the underground Gran Sasso laboratory is designed to detect muon-neutrino to tau-neutrino oscillations in appearance mode. The detector, placed on the long-baseline CERN to Gran Sasso neutrino beam (CNGS) 730 km away from the source, consists of an emulsion/lead target complemented by electronic detectors. OPERA has been taking data for five years, from 2008 to 2012, and in the analyzed statistics three tau candidate events have been identified. In this paper the detector, as well as the special procedures used to locate the interactions vertices and detect short decay topologies, are described. The three candidate events are presented as well as the latest results on muon-neutrino oscillations to tau-neutrino and to electron-neutrino.

1 The OPERA experiment

The goal of the OPERA experiment [1] is the direct observation of the $\nu_\mu \to \nu_\tau$ transition in appearance mode, by detecting the τ lepton created in charged current (CC) interactions.
OPERA is a long baseline neutrino oscillation experiment. To achieve its main objective a conventional almost pure ν_μ beam (CNGS) was produced at CERN and neutrino interactions were observed 730 km away by the OPERA detector located in the Gran Sasso underground laboratory, under 1400 m of rock overburden.

The CNGS beam was designed to maximize the ν_τ appearance in the atmospheric parameter region, first determined by Super-Kamiokande [2,3], MACRO [4] and Soudan-2 [5] experiments and then precised by K2K [6] and MINOS [7] experiments, i.e. for $\Delta m^2 \simeq 2.4\times10^{-3}$ eV^2 at full mixing. It is a wide band neutrino beam with a mean energy of about 17 GeV. The $\nu_e + \bar{\nu}_e$ contamination is quite small, at the level of 0.87 %, the $\bar{\nu}_\mu$ one of about 2.1% whereas the ν_τ proportion in the beam is negligible. The nominal number of protons on target (p.o.t.) per year was 4.5×10^{19}: in 2011 this value was exceeded reaching 4.75×10^{19} p.o.t., whereas the overall number of p.o.t. of 17.97×10^{19} for the five years run of OPERA is 20% lower than the foreseen value.

The τ lepton has a very short lifetime of $\sim 10^{-13}$ s ($c\tau$=87 μm), which makes its detection quite difficult. In OPERA its signature relies in the reconstruction of its decay topology in one prong (electron, muon, hadron) or in three prongs. The typical decay "kink" between the τ track and the daughter(s) one(s) is indeed the strongest signal selection available. Consequently, a micrometric precision is needed in order to observe the τ decay, and this is achieved thanks to the accuracy of better than 1 μm of photographic emulsions used for the charged track detection. The large mass needed in order to have enough neutrino interactions is obtained by lead mixed with the emulsions to form the target.
The lead-emulsion target is segmented in units called *bricks*: each brick is a stack of 56 lead

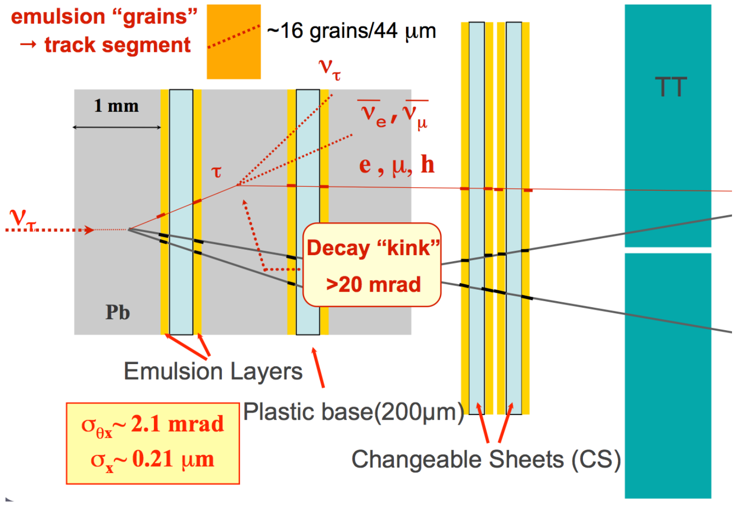

Figure 1: ν_τ CC detection principle.

sheets, 1 mm thick, interleaved with 57 films of a plastic base covered by two nuclear emulsion layers, each 44 μm thick. The dimensions of each brick are $12.5 \times 7.5 \times 10.3$ cm^3 and the weight is 8.3 kg. The total target mass is 1.25 kton which corresponds to about 150000 bricks.

A good kinematical reconstruction of the event as well as a particle identification is mandatory to discriminate between the signal and the background (e.g. charmed particle decays, hadron re-interactions, large angle muon scattering).
Charged particles passing through the emulsion layers produce 15 to 20 grains that are used to reconstruct track segments with a spatial resolution of 0.21 μm and an angular resolution of 2.1 mrad. On the reconstructed particle tracks a specific search to identify the kink signature is performed; in addition the energy reconstruction of electromagnetic showers and the determination of momenta of charged particles by multiple scattering is also made. A cartoon showing the τ detection principle inside a brick is shown in Fig. 1. Further details on the emulsion development and scanning can be found in Ref. [8,9,10].

Beside the lead-emulsion target, electronic detectors (ED) complete the OPERA experiment. They are needed to trigger on beam related events and to identify the brick in which the neutrino interaction took place. Furthermore the muon identification by the ED is mandatory to reduce the charm background.
A full picture of the OPERA hybrid detector with two identical supermodules, each one consisting of a target followed by a muon spectrometer, is shown in Fig. 2.
The ED comprise the Target Tracker (TT) [11] made of plastic scintillators planes interleaved with the target brick planes, and two spectrometers, each equipped with 6 drift tube modules [12] and 22 RPC planes placed in a magnetic field of 1.5 T. The trigger efficiency is at the level of 99% and the muon identification efficiency (all ED together) is about 95%. The ED simulation has been checked using the large available amount of data, showing a rather good agreement [13].

2 $\nu_\mu \to \nu_\tau$ analysis

OPERA data taking ended in 2012. The collected statistics corresponds to 106422 on-time events recorded out of which 60% are external rock events and 20% are interactions in the spectrometer. The total number of interactions inside the target are 19505 out of which 17057 are contained events.

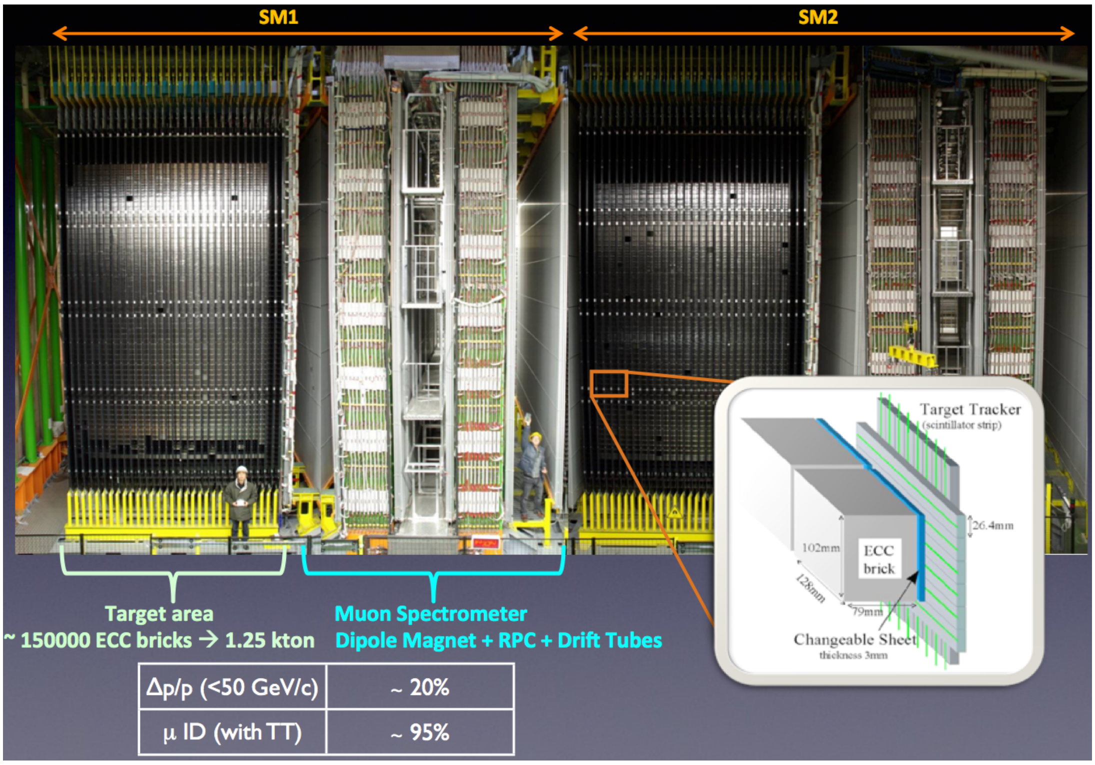

Figure 2: The OPERA detector.

For the 2008 and 2009 runs, in order to get confidence on the detector capabilities, a conservative approach was used in the analysis: no kinematical cuts were applied. Such a sample has been fully analyzed and 2783 events were scanned and went through a decay search procedure for the τ identification.
For the runs from 2010 till 2012, the analysis is still in progress. In order in a first stage to maximize the signal over noise ratio, only the most probable brick is scanned for all the events. Events without a muon and events with a muon with momentum smaller than 15 GeV were selected. The upper limit on the momentum has been set in order to reject a large amount of ν_μ CC interactions having a low probability to contain ν_τ candidate events.
The statistics currently available correspond to about 64% (about 5000 events) and in the analyzed data, three candidates were observed.

The first candidate event was found in the 2008-2009 data and it was classified as a τ decay into one prong, since its topology and kinematical parameters were compatible with those of a decay $\tau \to \rho(\pi^-\pi^0)\nu_\tau$ that has a branching ratio of $\sim 25\%$ [14]. The display of the event can be seen in Fig. 3.
Scanning the 2011 data, a second candidate was found. The event passed all selection criteria for the signal and it was consistent with the decay of a τ into 3 hadrons (branching ratio of 15%) [15]. The display of the event reconstruction can be seen in Fig. 4 (left).
A third candidate event was identified in the decay search of the 2012 data [16]. The display of the event, classified as a $\tau \to \mu$ decay (branching ratio of 17.7%), can be seen in Fig. 4 (right). Dedicated studies of the event ruled out the possible attachment of the γ to the decay vertex. The momentum/range correlation for track 2, connected to the primary vertex, is inconsistent with the one expected for a muon, and the muon track (track 1) has a negative charge at 5.6 σ C.L.

The expected number of τ events in the scanned sample is 2.22 and the total background 0.216.

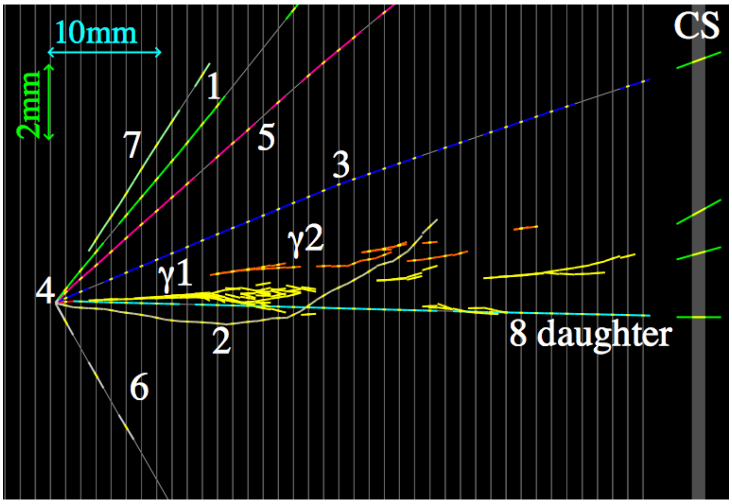

Figure 3: Display of the reconstruction of the $\tau \to h$ candidate event.

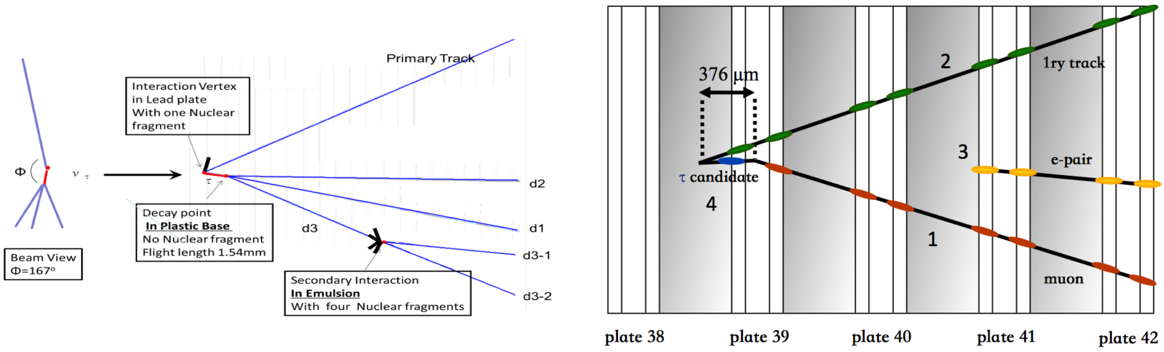

Figure 4: Display of the reconstruction of the $\tau \to 3h$ (left), and of the $\tau \to \mu$ candidate events (right).

The probability of the observed three candidates to be a background fluctuation is therefore very small, at the level of $\sim 7.29 \times 10^{-4}$. This corresponds to a 3.4 σ significance of non-null observation [16].
The charm lifetime and decay topologies are analogous to those of the τ lepton. Therefore the charm events can be used as a control sample to benchmark the τ decay finding efficiency.
Studying the 2008-2010 data sample 50 charm events where observed against an expectation value of 53±5. This result, together with the very good agreements between data and Monte-Carlo of the different kinematical distributions studied (see Fig. 5), confirm our understanding of the detection efficiencies.

3 $\nu_\mu \to \nu_e$ analysis

The sensitivity of OPERA on the mixing angle θ_{13} is not comparable to dedicated experiments such as T2K [17]. The beam energy is too high and it does not match the region corresponding to the maximum of $\nu_\mu \to \nu_e$ oscillations (i.e. about 1.5 GeV at the CNGS baseline).
A dedicated ν_e search was anyhow performed on the data collected in the 2008 and 2009: out of 505 neutrino events classified as Neutral Current like (NC) interactions (events without an identified muon), 19 ν_e candidates were found, in agreement with the expectations of 19.4 events [18]. The dominant component is due to the ν_e beam contamination, therefore in the three flavor oscillation scenario, the events found are compatible with a background only hypothesis. This allows us to set an upper limit on the value of $\sin^2(2\theta_{13})$ of 0.44 at 90% C.L., which is much larger than the current value set by reactor experiments of ~ 0.09 [19].

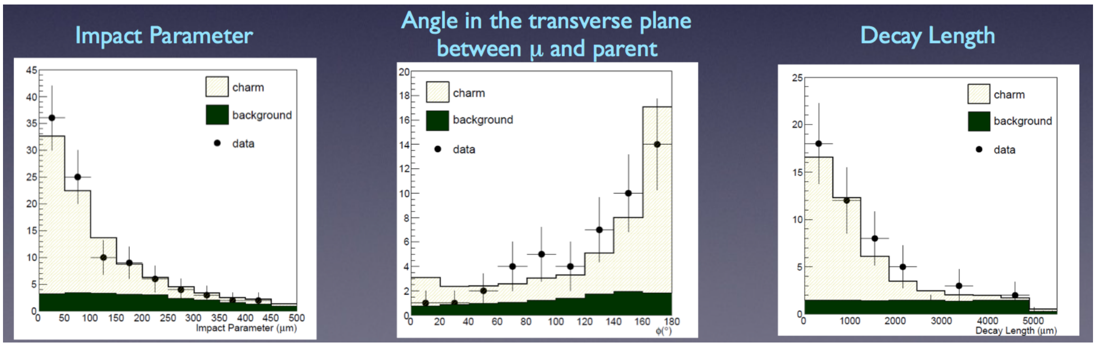

Figure 5: Data / Monte-Carlo comparison of different kinematical distribution for the charm events sample.

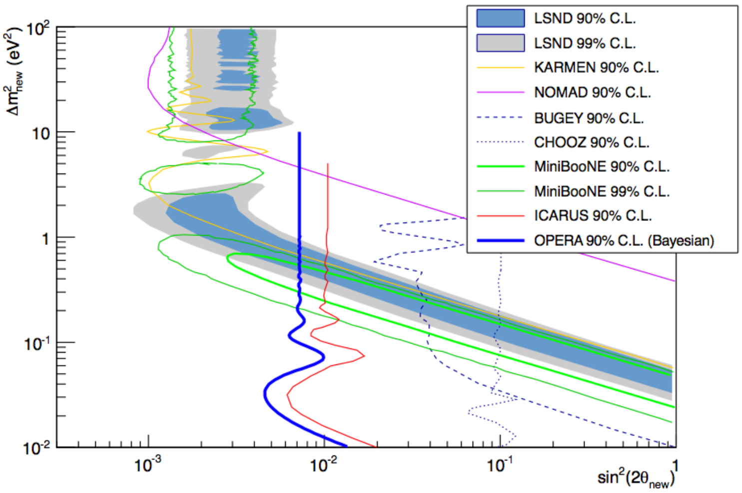

Figure 6: Exclusion plot for the parameters of the non-standard $\nu_\mu \to \nu_e$ oscillation taken from Ref. [18].

The high energy of the CNGS neutrino beam becomes however, an important asset for OPERA when investigating non-standard oscillation at large Δm^2 as suggested by the results of LSND [20] and MiniBooNE [21]. The upper limit on the new possible mixing angle $\sin^2(2\theta_{new})$ of 7.2×10^{-3} in the large Δm^2 region is indeed a stringent bound in the present situation as it can be seen in Fig. 6 [18].

4 Conclusions

The OPERA detector has been taking physics data for 5 years (2008 -2012), for a total number of p.o.t. of 17.97×10^{19}, corresponding to 80% of the nominal proposal value.
The detector is still recording cosmic muons data with the Target Tracker sub detector and the oscillation data analysis is ongoing. So far by analyzing 64% of the data, three τ candidates were observed; taking into account the expected background, a 3.4 σ significance of non-null observation is claimed. Background studies, in particular on the charm sample, showed good agreement between data and MC confirming our understanding of the detection efficiency.
At the time of the preparation of these proceedings, a fourth candidate event was announced [22]. OPERA performed also a $\nu_\mu \to \nu_e$ oscillation analysis providing a competitive bound on non standard oscillations at large Δm^2: $\sin^2(2\theta_{new}) < 7.2 \times 10^{-3}$ at 90% C.L. By increasing the statistics, OPERA should be able to access the parameter region below $\sin^2(2\theta_{new}) = 5.0 \times 10^{-3}$.

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