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Neutrino oscillations in the OPERA experiment

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The OPERA experiment is designed to search for $\nu_\mu \to \nu_\tau$ oscillations in appearance mode by seeing both the production and decay vertices of the τ lepton. The detector, located in the underground Gran Sasso laboratory, is based on a hybrid technique using nuclear emulsions complemented by electronic detectors. Emulsions are used as micrometric tracking devices in the target region. The experiment has been taking data for five years, since 2008, with the CERN Neutrino to Gran Sasso beam (CNGS) over a baseline of 730 km. From the analysis of a subsample of data, two ν_τ candidates have been found. We describe the candidates and discuss the significance of the result in terms of a $\nu_\mu \to \nu_\tau$ oscillation signal. We also report the results of a search for electron neutrinos.

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1. The OPERA experiment

Neutrino mass eigenstates do not coincide with flavor eigenstates as it happens also in the quark sector. Since their mass eigenstates are not degenerate, flavor transitions known as neutrino oscillations appear. Neutrino oscillations were postulated nearly 50 years ago [1, 2] while they were experimentally proved only in 1998 when the SuperKamiokande experiment provided the evidence for neutrino oscillations in the atmospheric neutrino sector [3]. This experiment showed that ν_μ were disappearing and they were not oscillating to ν_e. Experimental evidence for ν_μ disappearance was later given also with artificial beams [4, 5] and in the same years it was established that the $\nu_\mu \to \nu_e$ transition could not explain the ν_μ disappearance [6]. Only recently the amplitude of the $\nu_\mu \to \nu_e$ transition, governed by the θ_{13} angle, was measured [7] while the first evidence for a non-vanishinng θ_{13} was provided by reactor experiments [8, 9]. The only missing tile in this three flavor oscillation scenario is the evidence for the appearance of ν_τ's in a ν_μ beam.

This is the motivation of the OPERA experiment [10] designed to prove the $\nu_\mu \to \nu_\tau$ transition in appearance mode by seeing the τ lepton produced in a charged-current ν_τ interaction. To accomplish this task, several ingredients are mandatory: a high energy neutrino beam, a long baseline, a high-mass detector (kton scale) and a micrometric resolution. The CNGS beam was designed at CERN to produce 17 GeV ν_μ delivered at Gran Sasso, 730 km away. The beam contains a small (below 1%) contamination of electron neutrinos while the contamination of ν_τ is totally negligible. The OPERA detector is located in the underground Gran Sasso laboratory in Italy and it is based on the nuclear emulsion technology. The target region of about 1.2 kton has a modular structure with target units, called bricks, made of lead plates acting as the neutrino target alternated with nuclear emulsion films used as micrometric tracking devices. The target region is made of brick walls interleaved with scintillator trackers that provide the time stamp of the event and predict bricks where neutrinos interact. The target is complemented by magnetic spectrometers deputed to the measurement of the muon charge and momentum. The iron magnets are instrumented with RPC's and supplemented with sets of vertical drift tube planes.

2. Data analysis and ν_τ candidates

The CNGS has been operating for five years, since 2008 till December 2012, delivering a total of 18.0×10^{19} pot (protons on target) corresponding to about 19000 neutrino interactions collected in the target. On average about 18 interactions were collected every day. The brick where the interaction is predicted by the analysis of the electronic detector data is extracted from the target by a brick manipulator system and its films are analysed. Interface emulsion films are placed in between the brick and the scintillating target trackers. If their analysis confirms the presence of a neutrino interaction in the brick, emulsion films in the brick are developed and scanned in the different laboratories of the Collaboration. The emulsion film analysis provides the tridimensional reconstruction with micrometric accuracy of neutrino interactions and of possible secondary vertices due to short living particle decays.

Although the primary goal of the OPERA experiment is the ν_τ detection, the detector shows a very high purity and good efficiency in the detection of ν_e interactions. In fact, the micrometric accuracy allows a very high discrimination between electrons and π^0's (through electron pairs produced by γ's) such that the contamination of ν_μ neutral-current interactions in the sample of ν_e events is less than 1%. A search for electron neutrinos was performed with the data of 2008 and 2009 runs and 19 ν_e candidates were collected. This result is consistent with the expectation of 19.8 ± 2.8 events in absence of oscillations, given the fact that the beam is not optimised to search for ν_e appearance.

The ν_e search has been used to constrain the parameter space of mixing angle and Δm^2 for non-standard oscillations, setting the upper limit at 90% C.L. on the mixing angle, $\sin^2(2\theta_{new}) < 7.2 \times 10^{-3}$ for large (> 0.1 eV^2) Δm^2_{new} values [11] . The exclusion plot for the parameters of non-standard $\nu_\mu \to \nu_e$ oscillation, obtained from this analysis using the Bayesian method, is shown in Figure 1. The other limits shown, mostly using frequentist methods, are from KARMEN ($\overline{\nu}_\mu \to \overline{\nu}_e$ [12]), BUGEY ($\overline{\nu}_e$ disappearance [13]), CHOOZ ($\overline{\nu}_e$ disappearance [14]), NOMAD ($\nu_\mu \to \nu_e$ [15]) and ICARUS ($\nu_\mu \to \nu_e$ [16]). The regions corresponding to the positive indications reported by LSND ($\overline{\nu}_\mu \to \overline{\nu}_e$ [17]) and MiniBooNE ($\nu_\mu \to \nu_e$ and $\overline{\nu}_\mu \to \overline{\nu}_e$ [18]) are also drawn. This result further constrains the allowed region around $\Delta m^2_{new} = 5 \times 10^{-2}$ eV^2.

The data collected in the first two years (2008 and 2009) were fully analysed for the ν_τ search. The strategy initially adopted for the ν_τ search did not foresee any kinematical cut, in order to avoid any bias before a complete understanding of the data was proven. From the analysis of these data, one event collected in 2009 showed the kink topology, i.e. an angular deflection typical of decays of a charged particle into a single charged daughter. After the full reconstruction of the event and its kinematical analysis, it became the first ν_τ candidate [19]. The event is interpretable as a τ lepton produced in a primary neutrino interaction and decaying into the $\tau \to \rho \nu_\tau$ channel with subsequent $\rho \to \pi^0 \pi$ decay. The π^0 invariant mass was reconstructed from the measured energy of the 2 γ's detected in the emulsions while an invariant mass consistent with the ρ particle was measured from π and π^0 momenta.

After the achievement of a satisfactory description of the data provided by electronic detectors [20], a muon momentum cut at 15 GeV$/c$ was applied in order to discard high energy muons coming mostly from charged-current ν_μ interactions. The analysis of 2010 and 2011 run events was also prioritising events without a muon in the final state, where the τ content is larger ($\tau \to \mu$ branching ratio is about 17%). From the analysis of this data sample, a second ν_τ candidate was found [21].

2.1 Description of the second ν_τ candidate event.

This neutrino interaction occurred on 23 April 2011 at 7:15 UTC time. The pattern of hit scintillator strips in the TT is shown in Fig. 2. The event, of which the estimated hadronic energy is (22.0 ± 6.2) GeV, is classified as 0μ and the bulk of the activity in the electronic detector is contained within about 6 to 8 brick walls (more than 60 X_0 and about 2.5 pion interaction lengths). The interaction took place in the target of the upstream Super Module and lies well within the brick-filled target region. The neutrino vertex brick (with an assigned probability of 63%) was located in the longitudinal direction (z) in the second most upstream brick layer (called W_0), in the horizontal direction (x) in the 3rd brick layer from the left side (side looking towards the CNGS) and, in the vertical direction (y) in the 19th brick layer from the bottom. In Fig. 2 the position of the brick containing the interaction is highlighted. A linear extrapolation of the vertex tracks found in the emulsions is also shown to illustrate the matching with hits in the scintillators. The event

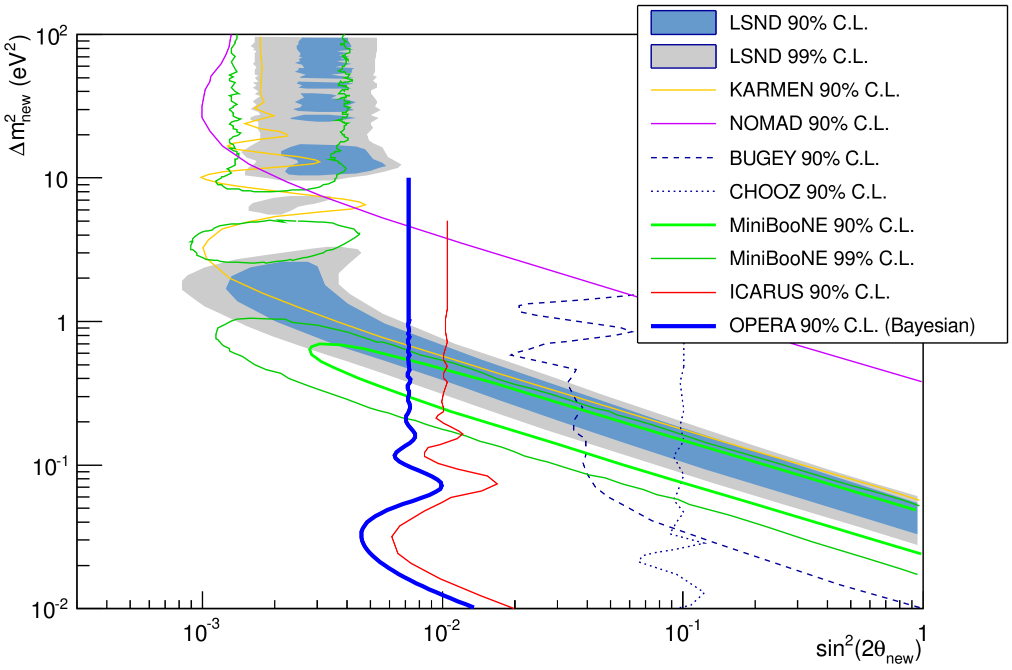

Figure 1: Exclusion plot for the parameters of non-standard $\nu_\mu \rightarrow \nu_e$ oscillation.

emulsion data has been independently measured with the European and Japanese scanning systems with consistent results. The average values are considered in the following.

The topology of the primary vertex (V_0 in Fig. 3) consists of two tracks, the τ lepton candidate and another track (called p_0). The distance of closest approach of the p_0 and τ tracks is 0.2 μm and the vertex lies close to the downstream emulsion film, at a depth in lead of 120 μm. A forward-going nuclear fragment associated to the primary vertex has also been detected at a large angle with slopes of: $(1.15, -0.28)$[1].

The flight length of the τ lepton candidate is (1466 $\pm$ 10) μm and its decay occurs in the plastic base excluding with a high efficiency (above 99.8% at 90% C.L. up to $\tan\theta = 3$, [22]) the emission of highly ionising nuclear fragments. The secondary vertex (V_1, Fig. 3) consists of three tracks (called d_1, d_2, d_3). A display of the reconstructed grains in the emulsion layers is presented in Fig. 4. The impact parameters of the decay products with respect to the reconstructed secondary vertex are 1.3, 1.2 and 0.3 μm for d_1, d_2 and d_3 respectively. After eye-inspection the background from instrumental fake tracks or tracks due to Compton electrons is negligible. In the beam transverse plane the τ and the p_0 tracks form an angle $\Delta\phi_{\tau H} = (167.8 \pm 1.1)^\circ$ (Fig. 5).

In order to strongly constrain the hypothesis that the secondary vertex could be a hadronic interaction, a search for nuclear fragments has been performed both upstream and downstream of the vertex with an automatic scanning up to $\tan\theta = 3.5$ as well as by visual inspection. No such fragment was found.

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[1] Slopes are given as tangents of the projected angles after accounting for the 58 mrad vertical tilt of the beam.

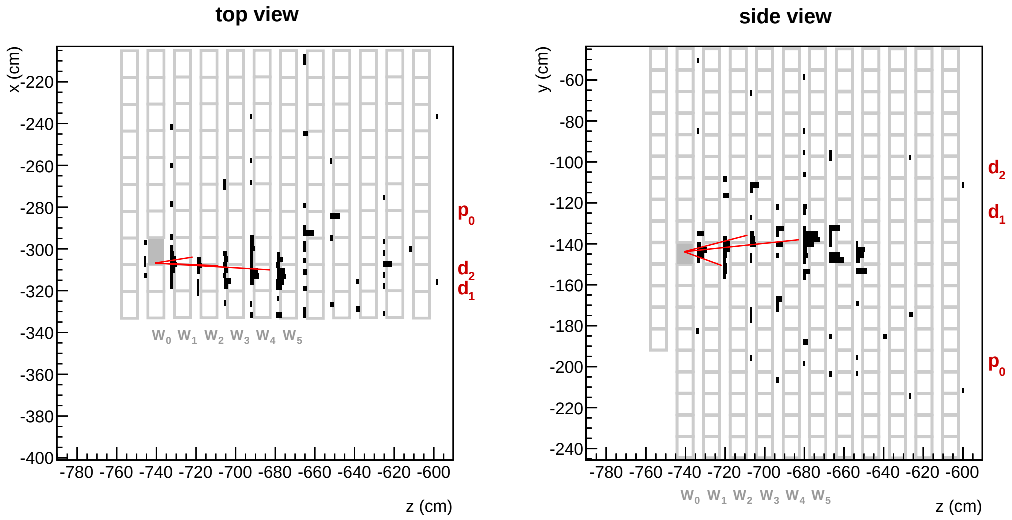

Figure 2: Event display of the second ν_τ candidate event: Target Tracker hits with reconstructed tracks super-imposed. The left panel is the top-view, the right panel the side-view. The position of the brick containing the neutrino interaction is highlighted.

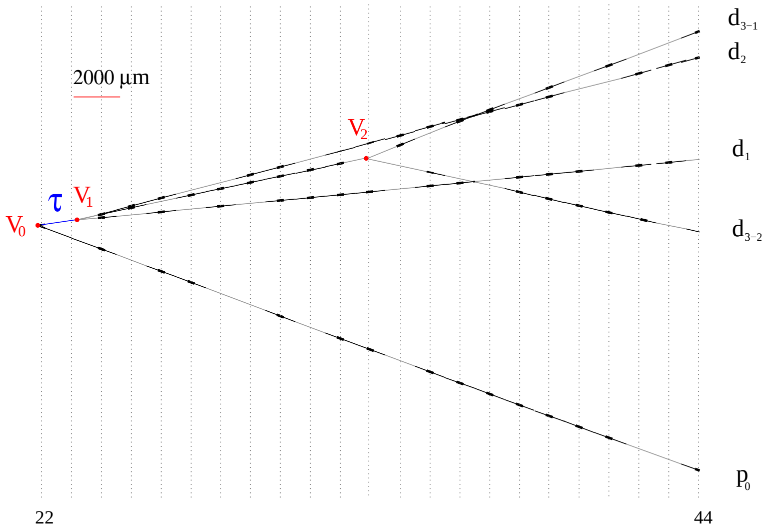

Figure 3: Event display of the second ν_τ candidate event: reconstruction in the brick (side-view). Vertical lines indicate the position of the middle-point of emulsion films 22 to 44, numbering them in order of increasing z from 1 to 57. The pitch is 1.3 mm. Black segments represent reconstructed base-tracks while the gray lines are the result of the track fit.

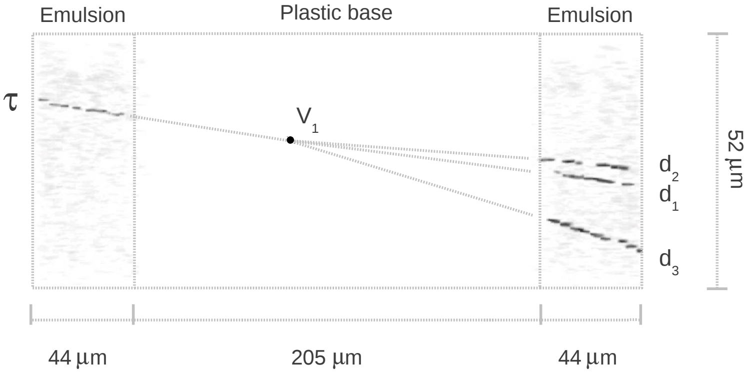

Figure 4: Top-view display of the candidate $\tau \to 3h$ decay vertex. The single grains observed by the optical microscope are visible in the emulsion layers (left-side and right-side rectangles). The directions of micro-tracks are extrapolated to the decay vertex in the plastic base region (central rectangle).

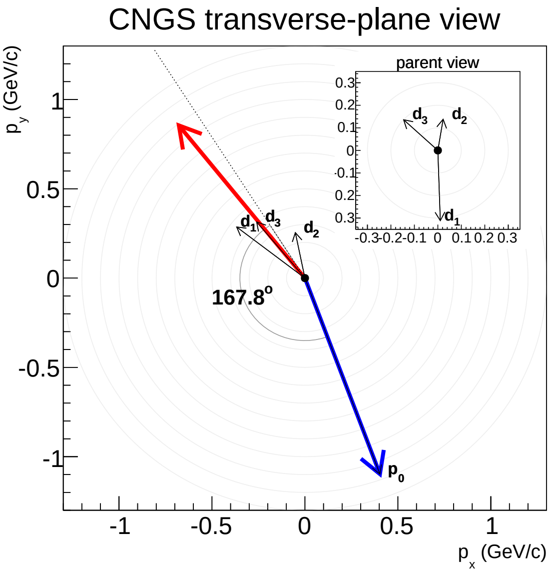

Figure 5: Event display of the second ν_τ candidate event: CNGS transverse plane momentum balancing. The red (blue) line represents the sum of the transverse momentum of the secondary (primary) vertex tracks. The dotted line marks the direction of the parent. The inset represents the transverse momenta of daughter tracks along the parent flight length direction.

A search for γ conversions has been performed up to $\tan\theta = 1$ for the 35 films (about 6 X_0) downstream of the vertex yielding no candidates.

The analysis of each track to determine its nature and momentum is described below:

- track p_0 has a measured momentum $p_{p_0} = (2.8^{+0.7}_{-0.7})$ GeV/c. This track points towards the centre of the detector in the top-view such that its signature as a hadron is already well constrained using the target tracker information only. Nevertheless the track has been followed in the downstream wall (W_1) where it is found to exit the brick to the side. Compatible tracks have neither been found in the adjacent brick in W_1 nor in downstream bricks (and CS doublets) up to W_3. Gamma rays from a possible hadronic interaction were also searched for in two bricks in W_2, however, no γ was found. This track is then assumed to interact in the dead material in-between two bricks. A muon with a momentum of the magnitude measured by MCS (using measured deviations due to Multiple Coulomb Scattering of tracks in the brick lead plates) would be expected to travel from 26 to 44 brick layers before stopping. The muon identification is improved in emulsions by using momentum-range correlations characterised by a discriminating variable defined as: $D_{TFD} = \frac{L}{R(p)} \frac{\rho}{\langle\rho\rangle}$ where L is the track length, $R(p)$ is the range in lead of a muon with momentum p, $\langle\rho\rangle$ is the average density along the path and ρ is the lead density. If $D_{TFD} > 0.8$ the track is classified as a muon [21]. This track shows $D_{TFD} = 0.05$, thus making the muon hypothesis very unlikely. Its projected slopes are $(0.155, -0.365)$, well inside the angular acceptance of the scanning. Even considering the possibility of having missed a muon track crossing the downstream emulsion detectors, the pattern in the scintillators does not allow the existence of such a track for more than about 7-8 brick walls.

- track d_1 has slopes of (-0.056, 0.101) and a measured momentum $p_{d_1} = (6.6^{+2.0}_{-1.4})$ GeV/c. A hadronic interaction is detected in the emulsions of the brick in wall W_4 (see Fig. 2) producing two charged tracks with slopes of (0.234, 0.489) and (0.034, -0.305). The signature of the interaction is also indicated by the target tracker scintillators.

- track d_2 has a slope of (-0.041, 0.260) and a measured momentum $p_{d_2} = (1.3^{+0.2}_{-0.2})$ GeV/c. It has not been found in W_2 or in the following walls corresponding to a range-momentum correlation parameter $D_{TFD} = 0.25$.

- track d_3 has a slope of (-0.134, 0.220) and a measured momentum $p_{d_3} = (2.0^{+0.9}_{-0.6})$ GeV/c. This track interacts in the brick containing the neutrino vertex, after 11 lead plates i.e. about 1.3 cm downstream (V_2 in Fig. 3). The interaction occurs inside the emulsion resulting in a very clear signature. The final state is composed of two charged tracks (d_{3-1} and d_{3-2}) and four back-scattered nuclear fragments.

The scalar sum of the momenta of all the measured charged particles in the event is $12.7^{+2.3}_{-1.7}$ GeV/c.

3. Results

The main background source for the ν_τ search is charmed hadron production in ν_μ charged-current interactions when the muon is undetected. The muon identification at the level of the

Table 1: Background sources in the ν_τ search and their yield in the different channels.

Decay channel	Background	Charm	Had. interactions	μ scattering
$\tau \to h$	0.027	0.011	0.016	
$\tau \to 3h$	0.12	0.11	0.002	
$\tau \to e$	0.020	0.020		
$\tau \to \mu$	0.011	0.0023		0.009
Overall	0.175 ± 0.024	0.15 ± 0.02	0.018 ± 0.005	0.009 ± 0.005

electronic detector is complemented by a procedure that exploits the emulsion information. All the tracks at the primary vertex are followed down along their trajectory until they stop or interact. The interaction is a clear evidence of the hadronic nature of the particle while, when the track stops, the momentum correlation efficiently separate muons and hadrons. This procedure is being further optimised. The present level of charm background in the analysed sample amounts to 0.15 ± 0.02 events as reported in Table 1. Minor background sources are coming from hadronic interactions, simulating a τ signal when no nuclear break-up is detected, and large angle muon scattering affecting only the muonic decay channel. These processes are quite rare and their yield is reported in Table 1. When summed up to the charm background, the total yield in the analysed sample is 0.175 ± 0.024 events.

Given the background yield, the two observed events can be turned into a significance of the observation of $\nu_\mu \to \nu_\tau$ oscillations. Four random integers n_i are extracted according to the Poisson distributions of the background in the four τ decay channels, respectively. The p-values, p_i, are then calculated as the Poissonian probability to observe at least n_i events in the $i-th$ channel for each pseudo-experiment and the estimator p^* used is their product, i.e. $p^* = p_h p_{3h} p_\mu p_e$. The fraction of pseudo-experiments with $p^* < p_{obs}$ corresponds to a significance of 2.4 σ for the non-null observation.

4. Conclusions

The OPERA experiment has carried out the analysis of a subsample of its data set integrated along five years of data taking in the CNGS beam, since 2008 until December 2012. From this analysis, two ν_τ candidates have been found with an expected background of 0.18 ± 0.02 events. The background estimate is conservative and lever arms to further increase the muon identification capabilities are being explored. The analysis of the data is still in progress and will last for about two more years with the goal of achieving the observation at the 4 σ level.

Moreover, a search for electron neutrinos has been performed with the data collected in the first two years of data taking. The analysis has provided stronger constraints on the parameters of non-standard $\nu_\mu \to \nu_e$ oscillations. The search for ν_e will be extended to the whole data sample, thus increasing the statistics by a factor of about 3.

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