PROCEEDINGS OF SCIENCE

More results from the OPERA experiment

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The OPERA experiment reached its main goal by proving the appearance of tau-neutrinos in the CNGS muon-neutrino beam. A total sample of 5 candidates fulfilling the analysis defined in the proposal was detected with a S/B ratio of about ten allowing to reject the null hypothesis with a significance of 5.1 σ. The search was extended to ν_τ-like interactions failing the kinematical analysis defined in the experiment proposal, to obtain a statistically enhanced, lower purity, signal sample. One such interesting neutrino interaction showing a double vertex topology with a high probability of being a tau-neutrino interaction with charm production will be reported. Based on the enlarged data sample the estimation of Δm^2_{23} in appearance mode will be presented and updated. The search for electron-neutrino interactions was extended over the full data set with a more than twofold increase in statistics with respect to published data. The analysis of the $\nu_\mu \to \nu_e$ channel is updated and the implications of the electron-neutrino sample in the framework of the 3+1 sterile model is discussed. An analysis of the $\nu_\mu \to \nu_\tau$ oscillations in the framework of the sterile neutrino model was also performed. Finally, the analysis of the annual modulation of atmospheric muons will be discussed.

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1. The OPERA experiment

The OPERA experiment [1] discovered the existence of $\nu_\mu \to \nu_\tau$ oscillations [2], exploiting its unique capability to observe ν_τ charged current (CC) interactions on an event-by-event basis. The detection of ν_τ CC interactions was based on the identification of τ lepton decays ($c\tau$ = 87 μm). The challenge of the OPERA experiment to identify the short-lived τ lepton over a $\mathscr{O}(100\ \mathrm{m}^3)$ volume, was achieved using an hybrid apparatus with electronic detectors and the nuclear emulsion technique featuring micrometric spatial resolution.
The OPERA detector was located in the underground Gran Sasso Laboratory (LNGS) at an average depth of 3800 meters of water equivalent. It was exposed to the high energy CERN Neutrino to Gran Sasso beam (CNGS) [3], 730 km away from the neutrino source. The average neutrino energy was about 17 GeV, the $\bar{\nu}_\mu$ contamination 2.1% in terms of ν_μ CC interactions in the target, the ν_e and $\bar{\nu}_e$ together below 1%, while the number of prompt ν_τ was negligible.
The detector was composed of two identical super-modules aligned along the CNGS beam direction, each made of a target section and an iron spectrometer. The spectrometers were used for muon charge and momentum measurements. Each target section consisted of a multi-layer array of 31 target walls interleaved with pairs of planes of plastic scintillator strips. Target walls were filled with Emulsion Cloud Chamber target units, called bricks, which were, in total, 150000. Each brick consisted of 57 emulsion films, 300 μm thick, interleaved with 56 lead plates, 1 mm thick, for a total mass of 8.3 kg. The electronic detectors were used to identify the brick containing the neutrino interaction, for muon identification and rough calorimetric measurements.
Every brick expected to contain a neutrino interaction was extracted from the detector and measured in the emulsion scanning laboratories in Europe and Japan with automated optical microscopes in order to reconstruct the neutrino interaction vertex. More details on event reconstruction procedure and detector performances are in [4, 5].

2. The ν_τ appearance

A dedicated procedure was developed to identify short-lived particle decay vertices [6]. If a short-lived particle decay vertex was found, a full kinematic analysis was performed combining the measurements in the nuclear emulsion with data from the electronic detectors. Moreover, in order to improve the S/B ratio, kinematic selection criteria, defined in the experimental proposal are then applied [4]. The OPERA experiment collected data from 2008 to 2012, corresponding to a total CNGS beam integrated intensity of 17.97×10^{19} protons on target (p.o.t.). A total number of 19505 neutrino interactions in the emulsion targets was recorded. Five ν_τ candidates, satisfying the kinematic selection criteria [2], were observed. Three sources of backgrounds, charmed particles decays, hadronic interactions and large-angle muon scattering (LAS), were expected to contribute, in total, for 0.25 ± 0.05 events to the final sample, allowing to exclude the background-only hypothesis with a significance of more than 5σ.
In order to improve the Δm^2_{23} measurement, determined for the first time in appearance mode, the ν_τ sample was increased, loosing the kinematical selections. A minimum selection, leading a negligible additional background from π and K decays, was used to limit background from hadronic interactions and LAS. Boost Decision Trees (BDT) [7] were trained with Monte Carlo events to

discriminate between ν_τ and background events using their topological and kinematical variables and their correlations. A cut on the BDT response, maximizing the product of selection efficiency and sample purity was defined. A total of 10 ν_τ-like events were selected, with an expected total background of 1.86 ± 0.5.

Assuming maximal mixing $\sin^2 2\theta_{23} = 1$, the $\nu_\mu \to \nu_\tau$ oscillation probability, $P_{\mu\tau}$ can be written as:

$$P_{\mu\tau}(E) = \sin^2\left(\frac{\Delta m^2_{23} \cdot L}{4E}\right)^2 \tag{2.1}$$

Being the baseline $L = 735$ km, the mean neutrino energy $\langle E \rangle = 17$ GeV and $\Delta m^2_{23} = 2.5 \times 10^{-3}$ eV^2, the argument of the sin function is $\mathcal{O}(0.1)$ and the oscillation probability can be approximated to:

$$P_{\mu\tau}(E) \approx \left(\Delta m^2_{23}\right)^2 \cdot (L/4E)^2 \tag{2.2}$$

Consequently the number of expected ν_τ, μ, can be evaluated using the following formula:

$$\mu \approx \left(\Delta m^2_{23}\right)^2 \int k \cdot \Phi(E)\sigma(E)\varepsilon(E) \cdot (L/4E)^2 \, dE \approx \left(\Delta m^2_{23}\right)^2 \cdot k' \tag{2.3}$$

where Φ is the total muon neutrino flux, σ is the ν_τ CC interaction cross-section, ε is the ν_τ detection efficiency and E is the neutrino energy. k and k' are two constants: the former takes into account the average detector mass while the latter takes into account also neutrino flux, cross-section and detection efficiency. The value of Δm^2_{23} has be evaluated, using Eq. 2.3, to be $(2.7 \pm 0.6) \times 10^{-3}$ eV^2. Defining the likelihood as:

$$L = \frac{\mu^n}{n!} e^{-\mu} \tag{2.4}$$

where n is the number of observed ν_τ-like events and using the Feldman-Cousins method [8] the 90% C.L. interval on Δm^2_{23} is $[1.79, 3.65] \times 10^{-3}$ eV^2.

3. A peculiar event

Among the observed neutrino events, one without a reconstructed muon and with two secondary vertices within about 1 mm from the interaction point, was identified. The observation of events with two secondary vertices had been considered negligible in the experimental proposal and no analysis procedure had been designed for such an observation, consequently a dedicated analysis was performed. Several physical interpretations are possible:

- ν_τ CC interaction with charm production
- ν NC interaction with $c\bar{c}$ production
- ν_μ CC interaction with a mis-identified muon and two secondary interactions
- ν_μ CC interaction with single charm production, a mis-identified muon and one secondary interaction
- ν NC interaction with two secondary interactions
- ν_τ CC interaction with one secondary interaction

A secondary interaction can be either i) a hadronic interaction of a final state particle, ii) a short decay of a pion or a kaon, or iii) a large-angle Coulomb scattering of a hadron or of a mis-identified muon. In order to establish whether the observed event is a ν_τ CC interaction with charm production or has another origin, the expected distributions of kinematical variables for each process were obtained through a dedicated MC production.

To better discriminate between signal and background, several algorithms were tested: an Artificial Neural Networks (ANN) method [9], two kinds of Boost Decision Trees [7] and the Fisher Discriminant method [10]. The ANN, whose output variable distribution is shown in Fig. 1, is used in the following analysis, because it provides a good signal efficiencies and background rejection power together with the lowest level of overtraining.

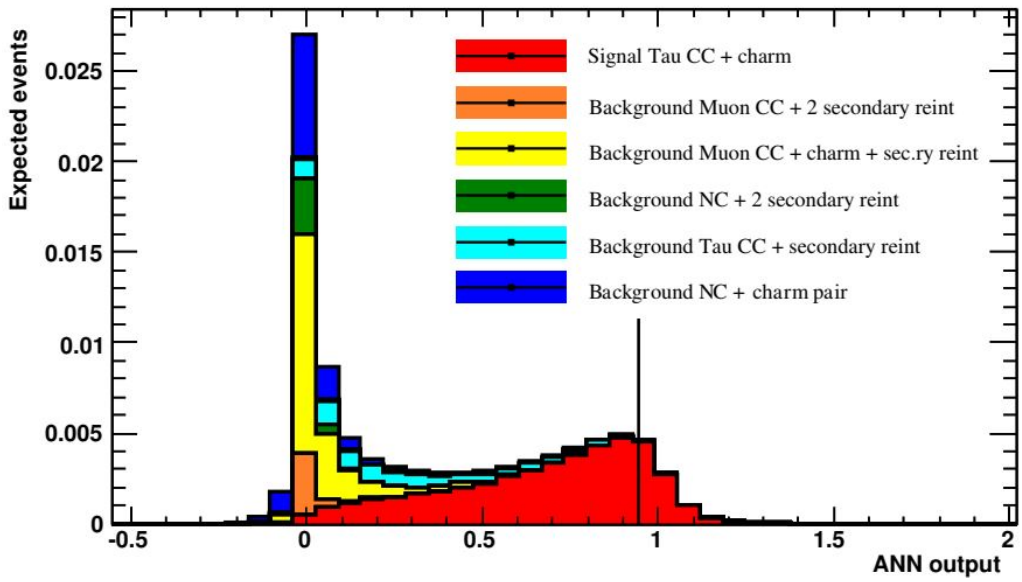

Figure 1: Distribution of the ANN output variable. The contribution of each process is shown with a different colour. The vertical black line represents the ANN output for the event taken into account in this analysis.

Using as observable the ANN output variable and the profile likelihood ratio as test statistic, the probability to observe events less likely compatible to the background than the measured one, under the background-only hypothesis, is $(2.6 \pm 0.2)10^{-4}$. This result provides evidence for the first observation of a ν_τ CC interaction with charm production candidate with tau and charm particles. The significance of this observation is 3.5 σ.

4. Search for ν_e CC interactions

The nuclear emulsion granularity allows the reconstruction of electromagnetic showers and consequently the identification of ν_e CC interactions. A dedicated procedure [11], balancing computation time and efficiency, was defined to systematically search for ν_e events. A total of 35 ν_e events were observed. Their energy distribution, together with the expected energy distribution is shown in Fig. 2. The number is compatible with the expected ν_e from the beam contamination (30.4 ± 3), together with two main sources of background: π^0 misidentified as electron in neutrino interactions without a reconstructed muon (0.5 ± 0.5) and ν_τ CC interactions with the decay of the τ into an electron (0.8 ± 0.2).
Using PDG values [12] for θ_{13}, θ_{23} and $\Delta m^2_{\rm atm}$, assuming $\delta_{\rm CP} = 0$ and neglecting matter effects, 2.7 ± 0.3 ν_e CC events were expected from $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations in the whole energy range. The number of observed events is compatible with the 3-flavour oscillation model.

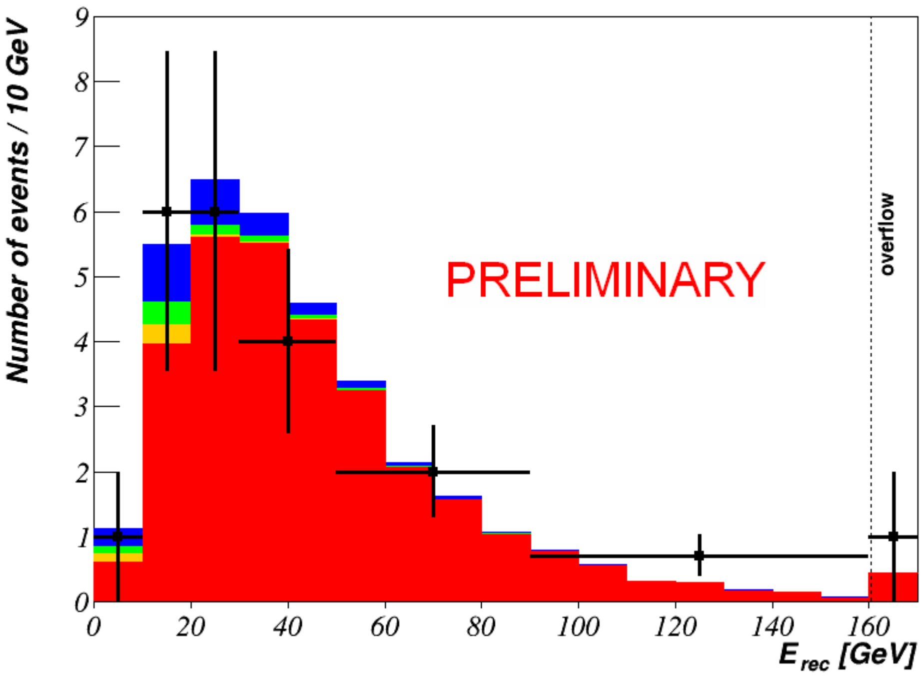

Figure 2: The plot shows the distribution of the reconstructed energy of the observed ν_e events (black crosses) and of the expected contribution from beam contamination (red), π^0 misidentified as electron (yellow), ν_τ CC interactions with the decay of the τ into an electron (green) and neutrino oscillations (blue).

5. Sterile neutrino search using the ν_τ and ν_e sample

Some experimental results [13, 14, 15, 16] may hint to possible oscillations involving additional sterile neutrinos with a mass of $\mathcal{O}(1\ \mathrm{eV}^2)$. In presence of a fourth sterile neutrino (3+1 model), the oscillation probability is a function of a 4×4 mixing matrix U and of three squared mass differences. OPERA can constrain combinations of the sterile neutrino parameters, comparing the predictions of the 3+1 model with the observations. The predictions of the 3+1 model was evaluated using the GLoBES software [17, 18]. The parameter Δm^2_{21} was fixed to the PDG value [12], a Gaussian prior on Δm^2_{31} was set using mean and sigma from PDG values while only positive values of Δm^2_{41} were considered since negative values are disfavoured by results on the sum of neutrino masses from cosmological surveys [20]. Matter effects were taken into account with the Earth density approximated by a constant value estimated with the PREM [18, 19] onion shell model. The profile likelihood ratio was used as test statistic. The 90% C.L. exclusion region on $\sin^2 2\theta_{\mu\tau} = 4|U_{\mu 4}|^2|U_{\tau 4}|^2$ and Δm^2_{41} plane, shown in Fig. 3, was obtained comparing the number of observed ν_τ events, in an energy range ($E_{rec} < 30$ GeV) which maximizes the sensitivities on the parameters of interest, with the expected one. For $\Delta m^2_{41} \gtrsim 1$ eV^2, the 90% C.L. upper limit on $\sin^2 2\theta_{\mu\tau}$ is 0.116, independently of the mass hierarchy of the three standard neutrinos. The OPERA experiment extends the exclusion limits on Δm^2_{41} in the $\nu_\mu \to \nu_\tau$ appearance channel down to values of $\sim 10^{-2}$ eV^2 for $\sin^2 2\theta_{\mu\tau} < 0.5$.

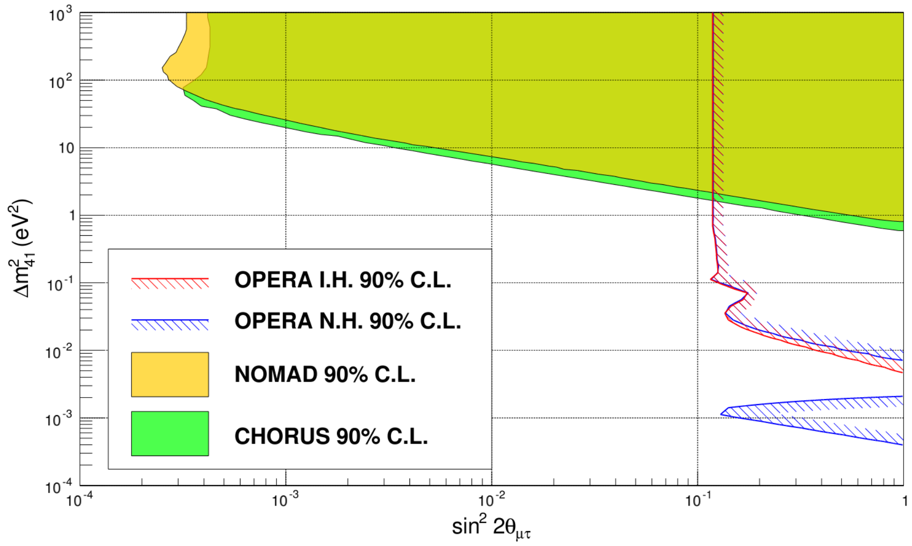

Figure 3: 90% C.L. exclusion region on $\sin^2 2\theta_{\mu\tau} = 4|U_{\mu 4}|^2|U_{\tau 4}|^2$ and Δm^2_{41} plane for normal neutrino mass hierarchy (blue) and for inverted one (red). Yellow and green areas are the 90% C.L. exclusion regions obtained respectively by NOMAD experiment [21] and CHORUS experiment [22].

Furthermore a 90% C.L. exclusion region on $\sin^2 2\theta_{\mu e} = 4|U_{\mu 4}|^2|U_{e4}|^2$ and Δm^2_{41} plane, shown in Fig. 4, was evaluated comparing the reconstructed energy distribution of the observed ν_e events (Fig. 2) with the expected one. Systematic errors, due to beam normalization and efficiency uncertainties, are estimated to be 10% for events with energy above 10 GeV and 20% below. At large $|\Delta m^2_{41}|$ values, the 95% C.L. upper limit on $\sin^2 2\theta_{\mu e}$ is 0.022.

6. Annual modulation of atmospheric muons

Atmospheric muons reaching the OPERA detector arise mostly from the decay of π and K

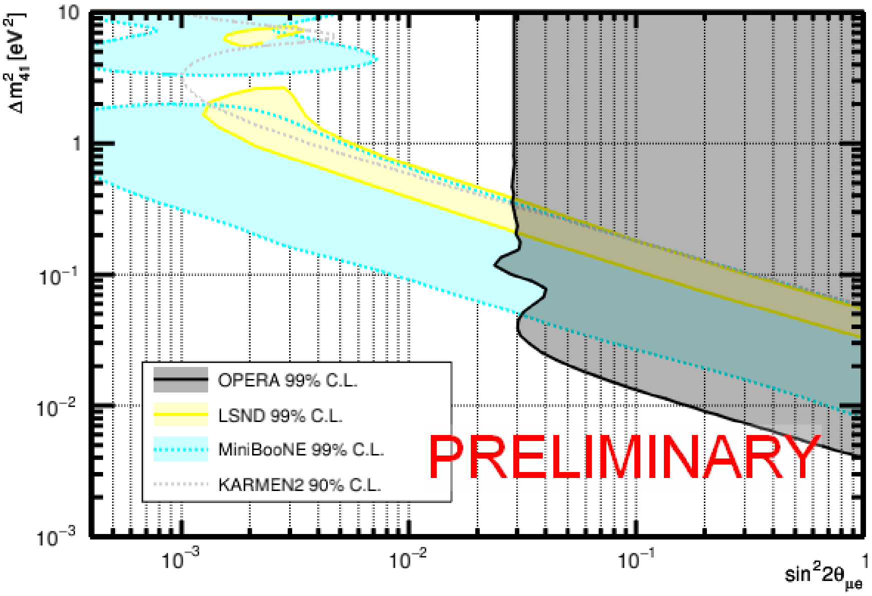

Figure 4: The grey area is a 90% C.L. exclusion region on $\sin^2 2\theta_{\mu e} = 4|U_{\mu 4}|^2|U_{e4}|^2$ and Δm^2_{41}. plane. Yellow and cyan areas are 90% C.L. allowed regions obtained respectively by the LSND [16] and MiniBooNE experiments [15]. The grey dotted line is the 90% C.L. exclusion region obtained by KARMEN2 [23].

produced by the interaction of primary cosmic rays with the nuclei of the upper atmosphere. During summer, air temperature increases and the average gas density decreases. The less dense medium allows a longer mean free path of the mesons and increases the fraction of them that decay to produce muons before their first interaction, so the atmospheric muon rate (R_μ) varies during the year. The variation was modelled as a sinusoidal function. The fit gives a period and a phase of (365 ± 2) days and (176 ± 4) days respectively. The cross-correlation between R_μ and the effective air temperature (T_{eff}) has been evaluated and shows a narrow peak at zero day shift. Muon rate fluctuations are shown to be positively correlated with atmospheric temperature, with a coefficient $\alpha_T = \Delta R_\mu / \Delta T_{eff} = 0.94 \pm 0.04$.

7. Conclusions and perspectives

The OPERA experiment has been taking data from 2008 to 2012. Five ν_τ candidates have been observed and the non-null observation of $\nu_\mu \to \nu_\tau$ oscillations has been excluded with a significance grater than 5 σ. The ν_τ selection criteria has been loosed in order to increase sample statistics and improve Δm^2_{32} measurement. A peculiar event with two secondary vertices has been found. After a dedicated analysis, it turned out to be a ν_τ CC interaction with charm production with a significance of 3.5 σ. The systematics ν_e search lead to an observed number of ν_e interactions compatible with the 3ν model expectations. The ν_e and ν_τ sample were used to derive limit on parameters of the 3+1 neutrino model. The complete OPERA data set is being used also for studying annual modulation of atmospheric muons. Results are in agreement with expectations.

The unique feature of the OPERA experiment to identify all 3 flavours at the same time will be exploited in order to put constraints on the oscillation parameters by doing a joint oscillation fit of all datasets.

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