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More results from the OPERA experiment

G. GALATI^{(1)(2)(*)}, N. AGAFONOVA⁽³⁾, A. ALEKSANDROV⁽¹⁾, A. ANOKHINA⁽⁴⁾,
 S. AOKI⁽⁵⁾, A. ARIGA⁽⁶⁾, T. ARIGA⁽⁶⁾⁽⁷⁾, D. BENDER⁽⁸⁾, A. BERTOLIN⁽¹⁰⁾,
 I. BODNARCHUK⁽¹¹⁾, C. BOZZA⁽¹²⁾, R. BRUGNERA⁽¹⁰⁾⁽¹³⁾, A. BUONAURA⁽¹⁾⁽²⁾,
 S. BUONTEMPO⁽¹⁾, B. BÜTTNER⁽¹⁴⁾, M. CHERNYAVSKIY⁽¹⁵⁾, A. CHUKANOV⁽¹¹⁾,
 L. CONSIGLIO⁽¹⁾, N. D'AMBROSIO⁽¹⁶⁾, G. DE LELLIS⁽¹⁾⁽²⁾, M. DE SERIO⁽¹⁷⁾⁽¹⁸⁾,
 P. DEL AMO SANCHEZ⁽¹⁹⁾, A. DI CRESCENZO⁽¹⁾, D. DI FERDINANDO⁽²⁰⁾,
 N. DI MARCO⁽¹⁶⁾, S. DMITRIEVSKI⁽¹¹⁾, M. DRACOS⁽²¹⁾, D. DUCHESNEAU⁽¹⁹⁾,
 S. DUSINI⁽¹⁰⁾, T. DZHATDOEV⁽⁴⁾, J. EBERT⁽¹⁴⁾, A. EREDITATO⁽⁶⁾, R. A. FINI⁽¹⁸⁾,
 F. FORNARI⁽²⁰⁾⁽²³⁾, T. FUKUDA⁽²²⁾, A. GARFAGNINI⁽¹⁰⁾⁽¹³⁾, J. GOLDBERG⁽²⁴⁾,
 Y. GORNUSHKIN⁽¹¹⁾, G. GRELLA⁽¹²⁾, A. M. GULER⁽⁸⁾, C. GUSTAVINO⁽²⁵⁾,
 C. HAGNER⁽¹⁴⁾, T. HARA⁽⁵⁾, H. HAYAKAWA⁽²⁶⁾, A. HOLLNAGEL⁽¹⁴⁾,
 B. HOSSEINI^{(1)(**)}, K. ISHIGURO⁽²⁶⁾, K. JAKOVCIĆ⁽²⁸⁾, C. JOLLET⁽²¹⁾,
 C. KAMISCIÖGLU⁽⁸⁾⁽⁹⁾, M. KAMISCIÖGLU⁽⁸⁾, S. H. KIM⁽²⁹⁾, N. KITAGAWA⁽²⁶⁾,
 B. KLICEK⁽²⁷⁾, K. KODAMA⁽³⁰⁾, M. KOMATSU⁽²⁶⁾, U. KOSE^{(10)(***)}, I. KRESLO⁽⁶⁾,
 F. LAUDISIO⁽¹⁰⁾⁽¹³⁾, A. LAURIA⁽¹⁾⁽²⁾, A. LJUBICIC⁽²⁸⁾, A. LONGHIN⁽¹⁰⁾,
 P. F. LOVERRE⁽²⁵⁾, M. MALENICA⁽²⁸⁾, A. MALGIN⁽³⁾, G. MANDRIOLI⁽²⁰⁾,
 T. MATSUO⁽²²⁾, V. MATVEEV⁽³⁾, N. MAURI⁽²⁰⁾⁽²³⁾, E. MEDINACELI^{(10)(13)(***)},
 A. MEREGAGLIA⁽²¹⁾, S. MIKADO⁽³³⁾, M. MIYANISHI⁽²⁶⁾, F. MIZUTANI⁽⁵⁾,
 P. MONACELLI⁽²⁵⁾, M. C. MONTESI⁽¹⁾⁽²⁾, K. MORISHIMA⁽²⁶⁾,
 M. T. MUCIACCIA⁽¹⁷⁾⁽¹⁸⁾, N. NAGANAWA⁽²⁶⁾, T. NAKA⁽²⁶⁾, M. NAKAMURA⁽²⁶⁾,
 T. NAKANO⁽²⁶⁾, K. NIWA⁽²⁶⁾, S. OGAWA⁽²²⁾, T. OMURA⁽²⁶⁾, K. OSAKI⁽⁵⁾,
 A. PAOLONI⁽³¹⁾, L. PAPARELLA⁽¹⁷⁾⁽¹⁸⁾, B. D. PARK⁽²⁹⁾, L. PASQUALINI⁽²⁰⁾⁽²³⁾,
 A. PASTORE⁽¹⁷⁾⁽¹⁸⁾, L. PATRIZII⁽²⁰⁾, H. PESSARD⁽¹⁹⁾, D. PODGRUDKOV⁽⁴⁾,
 N. POLUKHINA⁽¹⁵⁾, M. POZZATO⁽²⁰⁾, F. PUPILLI⁽¹⁰⁾, M. RODA^{(10)(13)(**)},
 T. ROGANOVA⁽⁴⁾, H. ROKUJO⁽²⁶⁾, G. ROSA⁽²⁵⁾, O. RYAZHSKAYA⁽³⁾,
 O. SATO⁽²⁶⁾, A. SCHEMBRI⁽¹⁶⁾, I. SHAKIRIANOVA⁽³⁾, T. SHCHEDRINA⁽¹⁾,
 A. SHESHUKOV⁽¹¹⁾, E. SHIBAYAMA⁽⁵⁾, H. SHIBUYA⁽²²⁾, T. SHIRAISHI⁽²⁶⁾,
 G. SHOZIYOEV⁽⁴⁾, S. SIMONE⁽¹⁷⁾⁽¹⁸⁾, C. SIRIGNANO⁽¹⁰⁾⁽¹³⁾, G. SIRRI⁽²⁰⁾,
 A. SOTNIKOV⁽¹¹⁾, M. SPINETTI⁽³¹⁾, L. STANCO⁽¹⁰⁾, N. STARKOV⁽¹⁵⁾,
 S. M. STELLACCI⁽¹²⁾, M. STIPCEVIC⁽²⁷⁾, P. STROLIN⁽¹⁾⁽²⁾, S. TAKAHASHI⁽⁵⁾,
 M. TENTI⁽²⁰⁾, F. TERRANOVA⁽³¹⁾⁽³⁴⁾, V. TIOUKOV⁽¹⁾, S. VASINA⁽¹¹⁾, P. VILAIN⁽³⁵⁾,
 E. VOEVODINA⁽¹⁾, L. VOTANO⁽³¹⁾, J. L. VUILLEUMIER⁽⁶⁾, G. WILQUET⁽³⁵⁾ and
 C. S. YOON⁽²⁹⁾

⁽¹⁾ INFN, Sezione di Napoli - 80125 Napoli, Italy⁽²⁾ Dipartimento di Fisica dell'Università Federico II di Napoli - I-80125 Napoli, Italy

(*) Corresponding author.

(**) Now at Imperial College, London, UK.

(***) Now at CERN, Geneva, Switzerland.

(***) Now at Osservatorio Astronomico di Padova, Padova, Italy.

(***) Now at University of Liverpool, Liverpool, UK.

- (³) *INR, Institute for Nuclear Research of the Russian Academy of Sciences - RUS-117312 Moscow, Russia*
- (⁴) *SINP MSU, Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University RUS-119991 Moscow, Russia*
- (⁵) *Kobe University - J-657-8501 Kobe, Japan*
- (⁶) *Albert Einstein Center for Fundamental Physics, Laboratory for High Energy Physics (LHEP), University of Bern - CH-3012 Bern, Switzerland*
- (⁷) *Faculty of Arts and Science, Kyushu University - J-819-0395 Fukuoka, Japan*
- (⁸) *METU, Middle East Technical University - TR-06800 Ankara, Turkey*
- (⁹) *Ankara University - TR-06560 Ankara, Turkey*
- (¹⁰) *INFN, Sezione di Padova - I-35131 Padova, Italy*
- (¹¹) *JINR, Joint Institute for Nuclear Research - RUS-141980 Dubna, Russia*
- (¹²) *Dipartimento di Fisica dell'Università di Salerno and "Gruppo Collegato" INFN - I-84084 Fisciano (Salerno), Italy*
- (¹³) *Dipartimento di Fisica e Astronomia dell'Università di Padova - I-35131 Padova, Italy*
- (¹⁴) *Hamburg University - D-22761 Hamburg, Germany*
- (¹⁵) *LPI, Lebedev Physical Institute of the Russian Academy of Sciences - RUS-119991 Moscow, Russia*
- (¹⁶) *INFN, Laboratori Nazionali del Gran Sasso - I-67010 Assergi (L'Aquila), Italy*
- (¹⁷) *Dipartimento di Fisica dell'Università di Bari - I-70126 Bari, Italy*
- (¹⁸) *INFN, Sezione di Bari - I-70126 Bari, Italy*
- (¹⁹) *LAPP, Université Savoie Mont Blanc, CNRS/IN2P3 - F-74941 Annecy-le-Vieux, France*
- (²⁰) *INFN, Sezione di Bologna - I-40127 Bologna, Italy*
- (²¹) *IPHC, Université de Strasbourg, CNRS/IN2P3 - F-67037 Strasbourg, France*
- (²²) *Toho University - J-274-8510 Funabashi, Japan*
- (²³) *Dipartimento di Fisica e Astronomia dell'Università di Bologna - I-40127 Bologna, Italy*
- (²⁴) *Department of Physics, Technion - IL-32000 Haifa, Israel*
- (²⁵) *INFN, Sezione di Roma - I-00185 Roma, Italy*
- (²⁶) *Nagoya University - J-464-8602 Nagoya, Japan*
- (²⁷) *Center of Excellence for Advanced Materials and Sensing Devices, Rudjer Bošković Institute - HR-10002 Zagreb, Croatia*
- (²⁸) *Rudjer Bošković Institute - HR-10002 Zagreb, Croatia*
- (²⁹) *Gyeongsang National University - 900 Gazwa-dong, Jinju 660-701, Korea*
- (³⁰) *Aichi University of Education - J-448-8542 Kariya (Aichi-Ken), Japan*
- (³¹) *INFN, Laboratori Nazionali di Frascati - I-00044 Frascati (Roma), Italy*
- (³²) *Dipartimento di Fisica dell'Università di Roma "La Sapienza" - I-00185 Roma, Italy*
- (³³) *Nihon University - J-275-8576 Narashino, Chiba, Japan*
- (³⁴) *Dipartimento di Fisica dell'Università di Milano-Bicocca - I-20126 Milano, Italy*
- (³⁵) *IIHE, Université Libre de Bruxelles - B-1050 Brussels, Belgium*

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Summary. — The OPERA experiment reached its main goal by proving the appearance of ν_τ in the CNGS ν_μ beam. Five ν_τ candidates were detected with a S/B ratio of ~ 10 , allowing to reject the null hypothesis at 5.1σ . The search has been extended by loosening the selection criteria in order to improve the statistical uncertainty. One of the ν_τ candidates selected with the new strategy shows a double vertex topology and, after a dedicated multivariate analysis, is compatible with being a ν_τ interaction with charm production. Based on the enlarged data sample the estimation of Δm_{23}^2 in appearance mode is being performed. The search for ν_e interactions has been extended over the full data set with a more than twofold increase in statistics: data are compatible with the non-oscillation hypothesis in the three-flavour mixing model. The implications of the electron neutrino sample in the framework of the 3+1 sterile mode will lead to exclusion limits on $\sin^2 2\theta_{\mu e}$. Finally, the analysis of the annual modulation of cosmic muons is introduced.

1. – The CNGS beam and the OPERA detector

The OPERA experiment was designed to conclusively prove the existence of $\nu_\mu \rightarrow \nu_\tau$ oscillations. The direct appearance search was based on the detection of τ leptons produced in ν_τ charged current interactions (CC). The challenge to detect the short-lived τ lepton ($c\tau = 87 \mu\text{m}$), produced in the CC ν_τ interactions, out of almost twenty thousands ν_μ interactions was achieved exploiting the nuclear emulsion technique that features micrometric spatial resolution.

The OPERA detector (fig. 1(a)) was located in the underground Gran Sasso Laboratory (LNGS), 730 km away from the neutrino source, in the high energy long-baseline CERN to LNGS beam (CNGS) [1, 2]. The average neutrino energy was about 17 GeV, the $\bar{\nu}_\mu$ contamination 2.1% in terms of interactions, the ν_e and $\bar{\nu}_e$ together below 1%, while the number of prompt ν_τ negligible. The detector was an hybrid apparatus consisting of an emulsion/lead target complemented by electronic detectors. It was made up of two identical super-modules aligned along the CNGS beam direction, each made of a target section and a muon spectrometer. 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 made of Emulsion Cloud Chamber target units, called bricks (fig. 1(b)). Each brick consists 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 its charge and momentum determination.

2. – Discovery of $\nu_\mu \rightarrow \nu_\tau$ appearance in the CNGS neutrino beam

Runs with CNGS neutrinos were successfully carried out from 2008 to 2012, with a total CNGS beam intensity of 1.8×10^{20} protons on target. Five ν_τ candidates were observed, satisfying kinematical selection criteria: three in the $\tau \rightarrow 1h$ decay channel [3-5], one in the $\tau \rightarrow 3h$ [6] and one in the $\tau \rightarrow \mu$ [7] decay channel. In the analysed sample, 0.25 ± 0.05 background events are expected, coming mainly from charmed events with an undetected primary muon, hadronic re-interactions (for the hadronic decay channels) and large angle muon scattering (for the $\tau \rightarrow \mu$ channel). Taking into

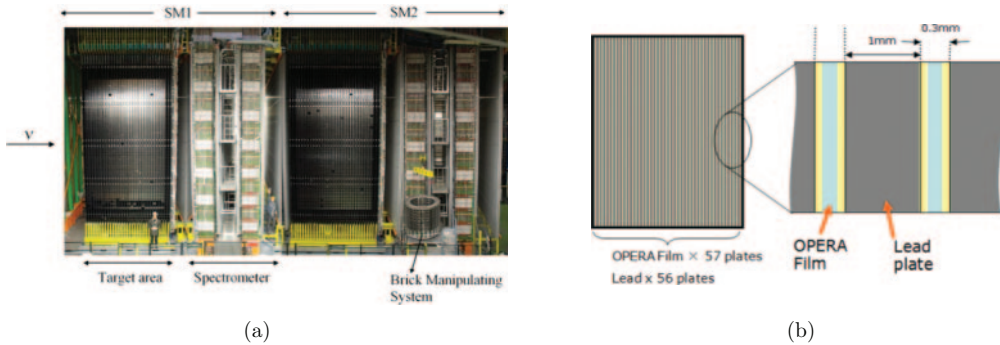


Fig. 1. – (a) The OPERA detector; (b) schematic drawing of an Emulsion Cloud Chamber (ECC).

account the background and observed events in each tau-decay channel, the observation of five candidates results in 5.1σ significance for the exclusion of the background-only hypothesis [5].

3. – Extended analysis

After discovering the ν_τ appearance in a ν_μ beam [5], a new goal has been set: estimate the oscillation parameters in appearance mode and exploit the unique capability of the OPERA experiment to identify all 3 neutrino flavours in order to put constrain the oscillation parameters by a joint oscillation fit of all datasets. A new strategy has been defined with looser kinematical cuts and a multivariate analysis: this allows a larger data sample with a lower purity, in order to decrease the statistical errors on atmospheric oscillation parameters measured in appearance mode.

In the minimum bias (M.B.) selection, which is reported in table I, compared with the previous selection criteria (PREV.), decay topologies are searched for requiring: the average 3D angle between the parent and its daughters $\theta_{kink} > 0.02$ rad and the z -coordinate of the decay vertex with respect to the downstream face of the lead plate containing the primary vertex $z_{dec} < 2600 \mu\text{m}$ for all decay channels. The total momentum of the visible tracks coming out from the secondary vertex (p_{2ry}) has been lowered to 1 GeV, with an upper limit of 15 GeV only for $\tau \rightarrow \mu$ decay channel, in order to reduce the background from the decay of charmed hadrons decay. Moreover, to reduce the background from hadron re-interactions and large angle scattering for 1-prong decays, the cut on the transverse component of daughter momentum with respect to the parent direction (p_{2ry}^T) was optimised in order to minimise the uncertainty on the number of expected ν_τ events taking into account the background contribution. Therefore, since the number of expected ν_τ is proportional to $\Delta m_{23}^2 \cdot \sigma_{\nu_\tau}$, the uncertainty on the measurement of these parameters is minimised as well. All remaining selection cuts have been removed to enhance the signal sample.

Among the minimum bias observed events there is a $\tau \rightarrow 1h$ candidate showing a very peculiar topology, with two secondary vertices about 1 mm from the primary one, as shown in fig. 2. Possible interpretations include ν_τ CC interaction with charm production or ν NC interaction with double charm production. Given the peculiar topology, a dedicated analysis was performed using multivariate analysis methods. The event turned out to be likely a ν_τ CC interaction with charm production [8,9].

TABLE I. – Comparison between the selection cuts used to establish the ν_τ appearance (PREV.) and the minimum bias ones (M.B.). Cuts marked with \star are not applied for Quasi-Elastic event. p_{2ry}^T cut is 0.3 in the presence of γ particles associated to the decay vertex.

Variable	$\tau \rightarrow 1h$		$\tau \rightarrow 3h$		$\tau \rightarrow \mu$		$\tau \rightarrow e$	
	PREV.	M.B.	PREV.	M.B.	PREV.	M.B.	PREV.	M.B.
z_{dec} (μm)	[44, 2600]	< 2600	< 2600		[44, 2600]	< 2600	< 2600	
θ_{kink} (rad)	> 0.02		< 0.5	> 0.02	> 0.02		> 0.02	
p_{2ry} (GeV/c)	> 2	> 1	> 3	> 1	[1, 15]		[1, 15]	> 1
p_{2ry}^T (GeV/c)	> 0.6 (0.3)	> 0.15			> 0.25	> 0.1		> 0.1
p_{miss}^T (GeV/c)	< 1 \star	–	< 1 \star	–	–	–	–	–
ϕ_{lH} (rad)	> $\pi/2\star$	–	> $\pi/2\star$	–	–	–	–	–
m, m_{min} (GeV/c ²)	–	–	[0.5, 2]	–	–	–	–	–

3.1. Multivariate analysis. – To improve the significance evaluation and perform signal to background separation, a multivariate analysis was implemented. Different techniques have been considered and their performances for signal to background discrimination compared. The one with the best discrimination power is the Boosted Decision Tree (BDT). In the $\tau \rightarrow 1h$ decay channel, in particular, where the background sharply increases due to the looser cuts, the BDT method helps rejecting it. A sample of signal and background Monte Carlo events surviving the minimum bias requests in table I has been used as input for the BDT. As an example, the distribution of one of the variables used, the angle in the transverse plane between the parent track and the hadron shower direction (ϕ_{lh}), is shown in fig. 3.

The BDT output for the $\tau \rightarrow 1h$ decay channel is shown in fig. 4.

As already mentioned, OPERA is the first experiment that can measure Δm_{23}^2 in appearance mode. The number of expected events, indeed, is proportional to the oscillation probability $\mathcal{P}_{\nu_\mu \rightarrow \nu_\tau}$ and the ν_τ cross-section: $N_{\nu_\tau} \propto \mathcal{P}_{\nu_\mu \rightarrow \nu_\tau} \cdot \sigma_{\nu_\tau}$.

The ν_τ cross-section has been measured so far only by the DONuT experiment, which observed 9 ν_τ CC interactions, out of a total of 578 observed neutrino interactions, but could not separate ν_τ from $\bar{\nu}_\tau$ [10]. Based on the observed ν_τ interactions, assuming best fit values for Δm_{23}^2 and $\sin^2 2\theta_{23}$, OPERA can determine σ_{ν_τ} .

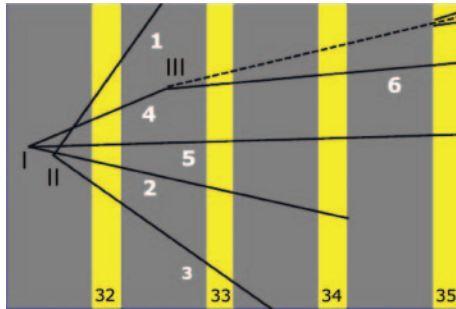


Fig. 2. – Schematic drawing of the muon-less ν interaction with three vertices.

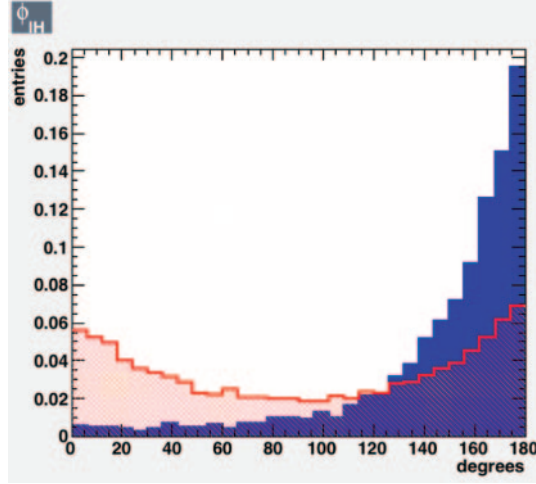


Fig. 3. – Distribution of the ϕ_{lH} angle for signal (blue) and background (red) for the $\tau \rightarrow 1h$ decay channel.

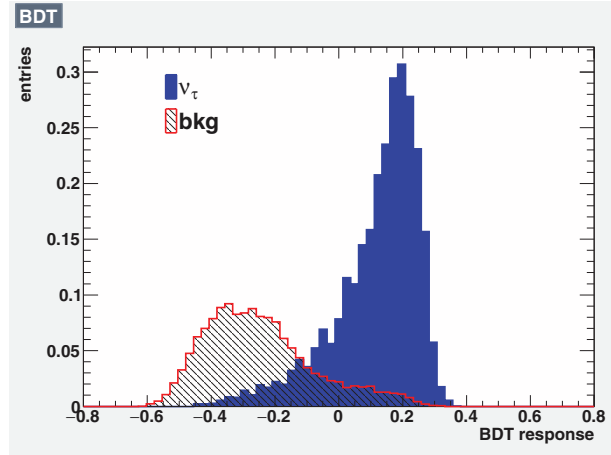


Fig. 4. – BDT output for the $\tau \rightarrow 1h$ decay channel.

4. – $\nu_\mu \rightarrow \nu_e$ oscillations

The tracking capabilities of nuclear emulsions also allow to identify electrons from ν_e CC interactions, and therefore to search for $\nu_\mu \rightarrow \nu_e$ oscillations [11]. In the final sample, 34 ν_e candidate events have been observed. This number is compatible with what expected from the beam contamination, 33 ± 5 , and 1.2 ± 0.1 events from the two main sources of background, *i.e.* π^0 's misidentified as electrons in neutrino interactions without a reconstructed muon and ν_τ CC interactions with τ decaying into an electron. With $\sin^2(2\theta_{13}) = 0.098$, $\sin^2 2\theta_{23} = 1$, $\Delta m_{32}^2 = \Delta m_{31}^2 = 2.5 \times 10^{-3} \text{eV}^2$, assuming $\delta_{CP} = 0$ and neglecting matter effects, 2.9 ± 0.4 oscillated ν_e CC events are expected in the whole energy range. The number of observed events is compatible with the 3-flavour oscillation model, as shown in fig. 5.

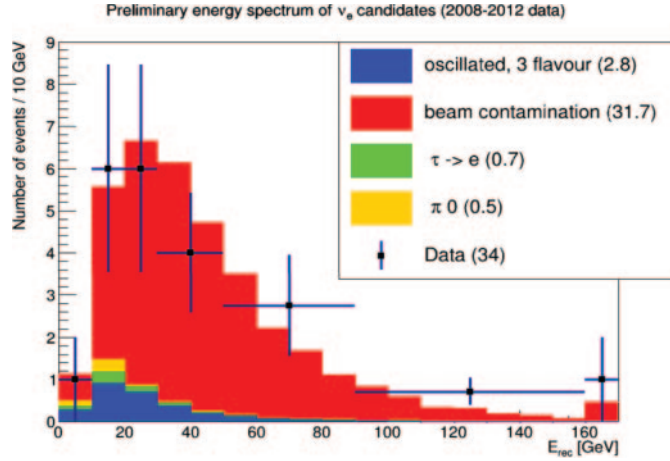


Fig. 5. – Comparison between the ν_e expected events and data.

OPERA ν_e appearance results have been used to derive limits on the mixing parameters of a massive sterile neutrino. In presence of a fourth sterile neutrino with mass m_4 , the oscillation probability is a function of the 4×4 mixing matrix U and of the three squared mass differences. Observed neutrino oscillation anomalies, if interpreted in terms of one additional sterile neutrino, suggest $|\Delta m_{41}^2|$ values at the eV^2 scale. We extend the exclusion limits on $\sin^2 2\theta_{\mu\tau} = 4|U_{\mu 4}|^2|U_{e 4}|^2$ below 0.1 at 95% C.L.

5. – Study of charged particle multiplicity distributions

The study of multiplicity distributions of charged particles in neutrino interactions is important to improve models of particle production in Monte Carlo event generators. A dedicated analysis was performed on a sub-sample of ν_μ CC interactions in the OPERA target.

The results are the object of a forthcoming publication.

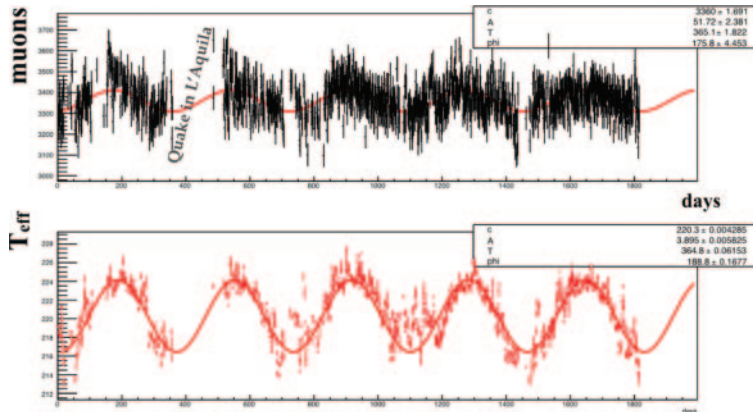


Fig. 6. – Upper panel: measured cosmic muon signal as a function of time. Lower panel: effective temperature. Daily binning is used. The curves show the sinusoidal fit to the data.

6. – Annual modulation of atmospheric muons

Underground muons arise mostly from the decay of π and K produced in 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, thus the fraction of those decaying to muons before interacting increases. As a result, an annual modulation is expected in the rate of atmospheric muons detected in OPERA at the underground Gran Sasso Laboratory. The observed modulation has a phase of (176 ± 4) days, as shown in fig. 6. Muon rate fluctuations are shown to be positively correlated with atmospheric temperature, in good agreement with expectations.

7. – Conclusions

After the discovery of $\nu_\mu \rightarrow \nu_\tau$ appearance in the CNGS neutrino beam with a significance of 5.1σ , a new analysis strategy has been applied for the selection of ν_τ candidates, in order to measure the oscillation parameters in appearance mode. The measurement of Δm_{23}^2 based on ν_τ appearance can be obtained with an accuracy of about 20%.

The update of $\nu_\mu \rightarrow \nu_e$ oscillation search is also being carried out: the number of observed events is in agreement with the expected background and the 3-neutrino flavour framework oscillation. This agreement can be turned into an upper limit to the mixing with a fourth sterile neutrino.

The multiplicity distribution of charged hadron particles in neutrino-lead interactions has been studied to help tuning interaction models of the Monte Carlo event generators.

Moreover, OPERA cosmic muon data set is used to determine the annual modulation of atmospheric muons flux: the observed modulation has a phase of (176 ± 4) days, with an effective coefficient in good agreement with expectations.

Results about the on-going analyses reported in these proceedings will appear in forthcoming papers.

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