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Neutrino oscillation experiments

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Summary. — In this paper, we give a short overview of neutrino oscillation experiments with emphasis on current European programmes of interest for INFN and on mid-term perspectives. In particular, we discuss the results that strengthen the standard three-family interpretation of leptonic mixing and the tension originating from the persistent LSND-Miniboone anomaly together with updated reactor data.

PACS `14.60.Pq` – Neutrino mass and mixing.
PACS `01.50.Pa` – Laboratory experiments and apparatus.

1. – The precision era of neutrino oscillation physics

Experimental neutrino physics has witnessed a revolution between 1998 and 2003: in those years the phenomenon of flavor oscillation has been tested by a wealth of experimental data and the standard three-family paradigm emerged [1]. The experimental results obtained so far point to two very distinct mass differences among the neutrino mass eigenstates, $\Delta m^2_{sol} = \Delta m^2_{21} \equiv m^2_2 - m^2_1 = 7.65^{+0.23}_{-0.20} \times 10^{-5}\,\mathrm{eV}^2$ [2] and $|\Delta m^2_{atm}| = |\Delta m^2_{32}| \equiv |m^2_3 - m^2_2| \simeq |m^2_3 - m^2_1| = 2.32^{+0.12}_{-0.08} \times 10^{-3}\,\mathrm{eV}^2$ [3]. Δm^2_{21} is often called the "solar mass scale" because it drives oscillation of solar neutrinos, but, if the energy of the neutrino and the source-to-detector distance are properly tuned, it can also be measured employing artificial neutrinos, *e.g.*, reactor neutrinos located about 100 km from the detector (KAMLAND). Similarly, atmospheric neutrinos mainly oscillate at a frequency that depends on Δm^2_{32} ("atmospheric scale"). Again, experiments with artificial neutrinos were able to see oscillations at the atmospheric scale using neutrinos of energy $\mathcal{O}(1)$ GeV and baselines of a few hundreds of km (K2K and, later on, MINOS).

In the last few years, this paradigm has been further supported by solar data thanks to the Borexino experiment, which is running since 2007. The main goal of Borexino is the measurement of ^{7}Be solar neutrinos (0.862 MeV) by means of neutrino-elastic scattering. Due to the kinematic of the neutrino-electron interaction, the signal of ^{7}Be neutrinos is identified through a Compton-like shoulder at about 0.66 MeV. Since 2008, the Borexino Collaboration has been able to exploit a detector whose performance significantly exceeded the expectations in terms of intrinsic radioactive background. The results from

^{7}Be have been recently updated [4] and yield $46.0 \pm 1.5(\text{stat.})^{+1.6}_{-1.5}(\text{syst.})$ counts/day/100 tons; they, hence, represent the first direct measurement of a sub-MeV solar neutrino rate with an accuracy better than 5%. These results falsify the hypothesis of no oscillation for ^{7}Be solar neutrinos at 4.9σ CL. Similarly, the null day-night asymmetry result reported in [5] confirms the Large-Mixing-Angle solution of the solar neutrino puzzle already obtained in 2003 ($\Delta m^2_{sol} > 10^{-5}\,\text{eV}^2$ and large values of θ_{12}); such confirmation, however, is now achieved without resorting to the assumption of CPT conservation when combining reactor with solar data, as it was done before with the SNO and KAMLAND data. In addition, Borexino provided the first standalone test of the Mikheyev-Smirnov-Wolfenstein mechanism, measuring simultaneously both neutrinos from ^{7}Be and from ^{8}B; in fact, the survival probability of the former is marginally affected by matter effects, while the oscillation of ^{8}B neutrinos is completely matter-dominated [6].

2. – Appearance of new flavors

The appearance of new flavors, different from the initial flavor of the source, has always been considered the most direct proof of the oscillation of neutrinos. Unfortunately, all sources we have at our disposal to observe oscillations at the solar scale (solar and reactor neutrinos) produce ν_e (or $\overline{\nu}_\text{e}$) with energy well below the kinematic threshold for muon production. As a consequence, it is impossible to test in a straightforward manner the occurrence of $\nu_e \to \nu_\mu$ or $\nu_e \to \nu_\tau$ transitions through the observation of muons or taus produced by charged-current (CC) neutrino interactions with matter.

At the atmospheric scale (atmospheric and multi-GeV artificial neutrinos from the decay in flight of pions), $\nu_\mu \to \nu_e$ transitions can be observed in appearance mode. However, the smallness of the mixing angle θ_{13} between the first and third family suppresses this transition at least by one order of magnitude [1]. Therefore, an appearance measurement that is aimed at observing a large neutrino transition probability must resort to $\nu_\mu \to \nu_\tau$. A possible exception could be due to a "large" value of θ_{13}, *i.e.* a value close to current limits from CHOOZ. In this case, an excess of ν_e CC events could be observed from artificial ν_μ sources. Such possibility is hinted by the very recent results of the T2K EXPERIMENT [7].

Seeking for $\nu_\mu \to \nu_\tau$, *i.e.* observing final state ν_τ CC interactions, is a major experimental challenge. The source must produce neutrinos above the kinematic threshold for tau production, 3.5 GeV for scattering in nuclei. In addition, the detector must be able to select an enriched sample of tau leptons in the bulk of muons and hadrons produced by ν_μ CC and NC interactions. It comes as no surprise that the most direct test of the oscillation phenomenon through the observation of tau appearance still deserves a conclusive evidence. In 2010, however, important milestones have been achieved, especially by the OPERA EXPERIMENT.

Inclusive analyses, as the one published by Superkamiokande in 2006 [8] and recently updated in [9], try to distill a tau-enriched sample in the bulk of ν_μ and ν_e interactions and take advantage of the large statistics and of the peculiar kinematics of tau decays. Exclusive measurements are even more ambitious since they aim at observing the appearance of tau leptons on an event-by-event basis. They need a detector with high spatial resolution, such as to observe the decay in flight of the tau and, at the same time, a high-intensity source with an energy well exceeding the kinematic threshold for tau production. The only facility that is able to fulfill simultaneously these requirements is the CNGS facility in Europe. The CNGS beam is a pure ν_μ beam with a mean energy of 17 GeV produced at CERN and pointing to the Gran Sasso Laboratories of INFN in Italy (LNGS), 730 km away from the source. The intrinsic ν_τ contamination, mainly originating from the decay of D_s, is negligible ($< 10^{-6}$). The beam is also contaminated at the 0.8% by ν_e, resulting from the decay in flight of muons along the decay tunnel and from K_{e3} decays. Since the tau lepton is identified from its decay topology, background from prompt ν_e is immaterial.

Performing an event-by-event appearance measurement of the $\nu_\mu \to \nu_\tau$ transition is the main goal of the OPERA experiment [10], which has been built from 2004 to 2008 in the Hall C of LNGS as a far detector for CNGS. In OPERA, the ν_τ appearance signal is detected through the measurement of the decay daughter particles of the τ lepton produced in CC ν_τ interactions. Since the short-lived τ particle has an average decay length of about 1 mm at the CNGS beam energy, a micrometric detection resolution is needed. In OPERA, neutrinos interact in a large mass target made of lead plates interspaced with nuclear emulsion films acting as high-accuracy tracking devices. This kind of detector is historically called an Emulsion Cloud Chamber (ECC) and it has been successfully applied by the DONUT experiment to perform the first direct observation of ν_τ charged-current interactions in a ν_τ-enriched beam at Fermilab.

In 2010 [11] the OPERA Collaboration reported the observation of a first candidate ν_τ CC interaction in the detector. The primary neutrino interaction consisted of 7 tracks of which one exhibits a visible kink. Two electromagnetic showers due to γ-rays have been located; they are clearly associated with the event and were produced at the decay vertex. Figure 1 shows a display of the event, which was identified in a sample corresponding to 1.89×10^{19} p.o.t. in the CNGS ν_μ beam. The total transverse momentum P_T of the daughter particles with respect to the parent track is $(0.47^{+0.24}_{-0.12})$ GeV, above the lower selection cut-off at 0.3 GeV. The missing transverse momentum P_T^{miss} at the primary vertex is $(0.57^{+0.32}_{-0.17})$ GeV. This is lower than the upper selection cut-off at 1 GeV. The angle Φ between the parent track and the rest of the hadronic shower in the transverse plane is equal to (3.01 ± 0.03) rad, largely above the lower selection cut-off fixed at $\pi/2$. The invariant mass of γ-rays is $(120 \pm 20(\text{stat.}) \pm 35(\text{syst.}))\,\text{MeV}^2$, supporting the hypothesis that they originate from a π^0 decay. Similarly the invariant mass of the charged decay product assumed to be a π^- and of the two γ-rays is $(640^{+125}_{-80}(\text{stat.})^{+100}_{-90}(\text{syst.}))$ MeV, which is compatible with the $\rho(770)$ mass. The branching ratio of the decay mode $\tau \to \rho^- \nu_\tau$ is about 25%. The observation of one possible tau candidate in the decay channel $h^-(\pi^0)\nu_\tau$ has a significance of 2.36σ of not being a background fluctuation from a background of 0.018 ± 0.007. If one considers all decay modes included in the search, corresponding to 0.54 ± 0.13 expected taus, the significance of the observation becomes 2.01σ from the total predicted background of 0.045 ± 0.023.

3. – Challenging the three-family interpretation

During the last decade, most of the experimental efforts have been focused on grounding the oscillation evidence at the solar and atmospheric scales and, simultaneously, on performing precision measurements of the leading oscillation parameters. An early discovery of a non-null value of θ_{13} would soon open a new phase of this precision oscillation era [12]. If θ_{13} is non-zero, the subdominant $\nu_\mu \to \nu_e$ amplitude and its T or CP conjugates encode a wealth of information. In particular, it allows for the determination of θ_{13} and the Dirac complex phase of the leptonic mixing matrix. The $\nu_\mu \to \nu_e$ transition probability is also perturbed by matter effects if the path of the neutrinos through the Earth is sufficiently large. The perturbation depends on the sign of Δm^2_{31} and, therefore, it can be used to determine the hierarchy among the neutrino masses. These consid-

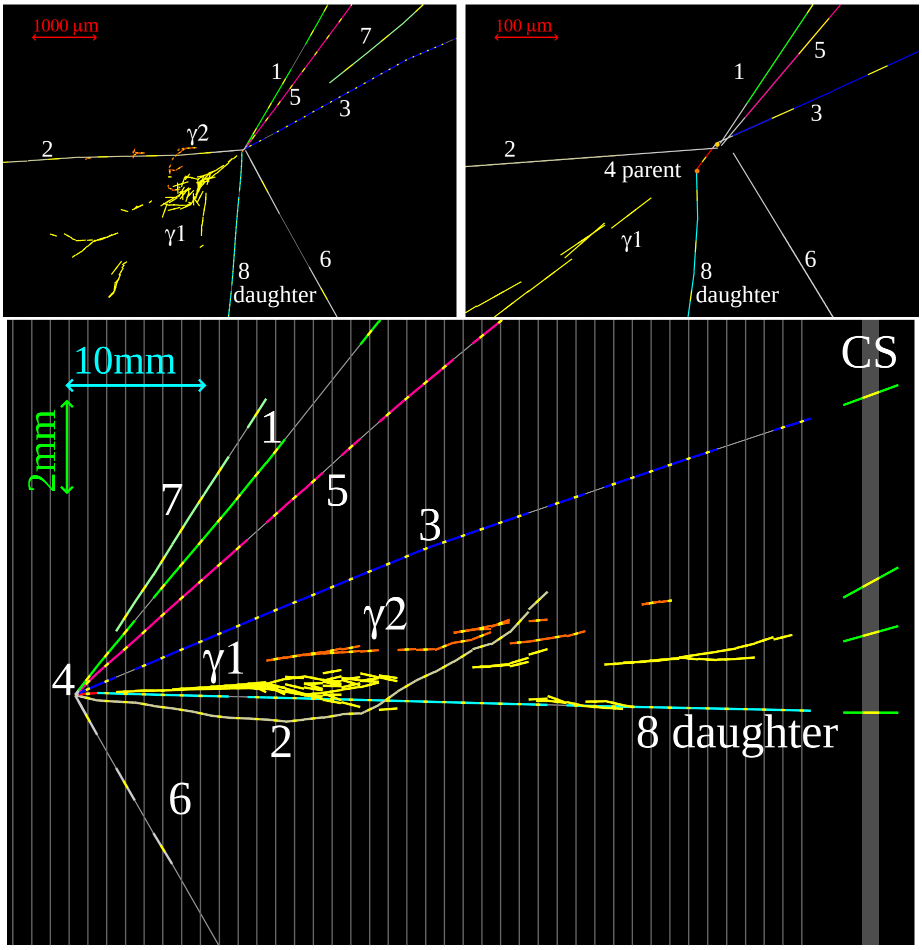

Fig. 1. – (Colour on-line) Display of the OPERA τ candidate event. Top left: view transverse to the neutrino direction. Top right: same view zoomed on the vertices. Bottom: longitudinal view.

erations explain the enormous interest toward novel neutrino sources operating at the atmospheric scale as, for instance, the Neutrino Factories or the Beta Beams [13].

On the other hand, experimental data collected outside the solar and atmospheric scale [14] show a level of precision and control of systematics errors that is often substandard compared with the previous ones. It is therefore unclear whether a few persistent anomalies, mostly pointing toward a new $\Delta m^2 \gg \Delta m^2_{32}$ are hinting toward a breakdown of the standard three-family interpretation or they are mere experimental artifacts. The persistent LSND anomaly, possibly confirmed by the antineutrino Miniboone data, remains by far the strongest from the experimental point of view. Still, none of these measurements have been done with the usual near-*versus*-far detector comparison and, in addition, any simple explanation is ruled out by the puzzling Miniboone data in neutrino mode. A vigorous programme is carried out at Fermilab and, possibly, at SNS to establish the existence of a new source of flavor conversion at a scale $\Delta m^2 \gg \Delta m^2_{32}$.

CERN could also contribute exploiting a dedicated neutrino beamline from the CERN-PS [15]. Three other anomalies currently challenge the standard scenario: a systematic deficit of events from short-baseline reactor experiments resulting from new flux calculations [16], a deficit from the calibration with radioactive sources ("Gallium anomaly") of the GALLEX and SAGE solar neutrino experiments and, finally, a slight discrepancy between the leading oscillation parameters θ_{23} and Δm^2_{32} as measured by MINOS in neutrino and antineutrino disappearance mode. None of these anomalies are compelling, especially if one accounts for full systematic uncertainties. However, major improvements could be obtained by dedicated runs of facilities that have been built to test the standard three-family model. We mention in particular, the proposal of running MINOS in parallel with NOνA (MINOS+) and the possibility of calibrating Borexino with radioactive sources at LNGS [14].

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