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Overview on neutrino oscillations

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Summary. — I will discuss recent achievements in the study of neutrino oscillations obtained with the T2K, OPERA and ICARUS long-baseline neutrino experiments.

PACS `14.60.Pq` – Neutrino mass and mixing.

1. – Introduction

An increasing number of observations on flavour transitions in neutrino propagation (neutrino oscillations) has been performed since the late nineties when the phenomenon was first measured using atmospheric neutrinos. A rather rich and diversified data set is well described assuming that three mass eigenstates (ν_1, ν_2, ν_3) are mixed to flavour eigenstates (ν_e, ν_μ, ν_τ) through a unitary mixing matrix (U_{PMNS}, Pontecorvo-Maki-Nakagawa-Sakata).

The measurement of the θ_{13} angle at reactors and accelerator experiments in spring 2012 has been a remarkable jump forward in our knowledge of U_{PMNS}. The first measurement by Daya-Bay is based on an energy-dependent disappearance of $\bar{\nu}_e$ neutrinos produced from a nuclear reactors. The large observed value of $\theta_{13} = (8.5^{+0.20}_{-0.21})°$ [1], opens the door to the measurement of the δ phase whose value is of particular interest since it rules the possible existence of CP violation in the leptonic sector.

In addition, the last two years have been marked by the first evidence of neutrino transitions in which the charged-current interactions of oscillated species (ν_e and ν_τ) could be measured directly (in the so-called "appearance" mode) with a high signal-to-noise ratio in the J-PARC and CNGS accelerator ν_μ beams. The $\nu_\mu \to \nu_\tau$ transition has also been measured by SuperKamiokande (SK) in the atmospheric neutrino fluxes tough with a lower purity [2].

Several factors can explain the challenge of a direct experimental evidence of neutrino appearance. The traditional solar and reactor neutrino sources have energy spectra well below the τ-lepton production threshold (3.5 GeV) such that both for ν_μ and ν_τ only neutral current interactions occur. On the other hand, atmospheric or accelerator-based ν_μ sources overcome this limitation. Nevertheless the task is still demanding due to the experimental signature of the τ-lepton requiring either a micrometric tracking
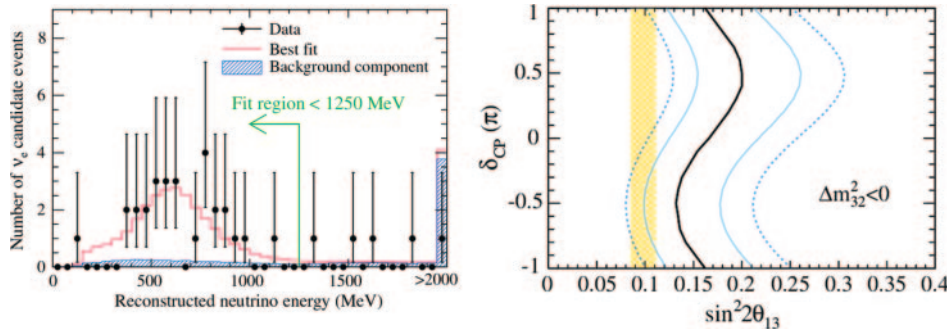
Fig. 1. – Left: Energy spectrum of ν_e candidates at SK. Right: constraints in the $\sin^2 2\theta_{13}$-δ_{CP} plane from T2K and reactor experiments.

accuracy over a large volume or a precise characterisation of the final state kinematics with a large statistical sample. The first approach was followed by OPERA while the second by SK (and ICARUS). It must also be noted that the suppression of the cross section due to m_τ requires using relatively high beam energies, well beyond the $\nu_\mu \to \nu_\tau$ oscillation maximum, unless using baselines of several thousands km. The $\nu_\mu \to \nu_e$ path to appearance requires a "light" detector with good e/μ separation power but with less stringent requirements w.r.t to τ tagging. No kinematical suppression is present in this case. This channel was for long not considered as the most favourable to due the prejudice that θ_{13} could be very small if not even null. In the end even if the mixing is not maximal it is still large enough to allow large samples without the complication of τ tagging and the kinematical suppression[1].

2. – Results from T2K with the J-PARC beam

The experiment operates over a baseline of $295\,\mathrm{km}$ from the J-PARC $30\,\mathrm{GeV}$ proton synchrotron along the Pacific coast to the SK detector in the Japanese alps. The neutrino beam, which is produced by a system of three magnetic horns, is the first exploiting the off-axis tecnique. The angle between the protons direction and the far detector direction ($2.5°$) allows to obtain a narrow ν_μ beam with a reduced ν_e contamination peaked at the energy of maximal mixing for the "atmospheric" oscillation pattern (about $0.6\,\mathrm{GeV}$). The near site at $280\,\mathrm{m}$ from the target is composed of an on-axis detector (INGRID) and an off-axis detector (ND280).

2.1. *Measurement of* $\nu_\mu \to \nu_e$ *appearance*. – The analysis [3] is performed on a data sample of 6.57×10^{20} protons on target (pot) accumulated during the period 2010–2013. The energy spectrum of the 28 ν_e candidates CC interactions selected in the SK fiducial volume is shown in fig. 1. The expected number of $\nu_\mu \to \nu_e$ events is (20.4 ± 1.8) assuming $\sin^2 2\theta_{13} = 0.1$, $\sin^2 2\theta_{23} = 1$, $\delta_{CP} = 0$ and the normal mass hierarchy (NH). The overall background contribution is estimated as (4.64 ± 0.53) events giving a signal-to-background ratio 4-5. As it can be seen from the stacked histograms of fig. 1 this sample is dominated by the intrinsic ν_e contamination in the ν_μ beam (69%) followed by a component of misidentified π^0 from neutral current interactions (19%)

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[1] The peak energies oth the CNGS and J-PARC are 17 and $0.6\,\mathrm{GeV}$, respectively.
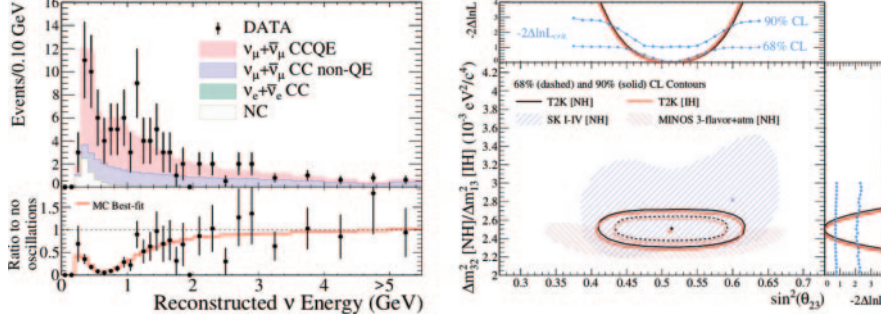
Fig. 2. – Left: Energy spectrum of ν_μ^{CC} candidates at the far detector. Right: allowed regions in the Δm_{32}^2-$\sin^2\theta_{23}$ plane.

the remaining part being due to the so-called solar term in the $\nu_\mu \to \nu_e$ oscillation probability and $\bar{\nu}$ interactions. Two analyses have been performed, the first relying on the energy spectrum of the reconstructed electron and the second also considering its expected angular distribuion (p-θ analysis). The null hypothesis ($\theta_{13} = 0$) can be excluded at the 7.5 σ level (5.5 expected). The allowed bands in the θ_{13}-δ plane are shown in fig. 1 (right) for NH or inverted mass hierarchy (IH) together with the constraint given by reactor experiments (vertical straight bands) which are insensitive to the value of δ. By comparing the two measeurements a mild preference for $\delta_{CP} \simeq -\pi/2$ is observed([2]). The confidence regions at 90% CL for $\sin^2 2\theta_{13}$ are: [0.097, 0.218] (best fit 0.150) and [0.118, 0.261] (best fit 0.182) for the NH and IH, respectively.

2˙2. *Measurement of $\nu_\mu \to \nu_\mu$ disappearance*. – The J-PARC beam was designed having a precise knowledge of the atmospheric mass splitting. The occurrence of maximal disappearance exactly at the flux peak yields a macroscopic ($\sim \times 4$) suppression of ν_μ^{CC} interactions at the far site where the beam is a relatively pure (sub-threshold) ν_τ beam. As reported in [4], a total of 446 ± 22.5 (sys.) events are expected in the no-disappearance hypothesis while 110 are actually observed (based on 6.57×10^{20} pot). The energy spectrum of these events at SK is shown in the upper plot of fig. 2 (left). The lower plot shows the ratio to the unoscillated spectra clearly evidencing the energy-dependent oscillation pattern. These data allow to measure $\sin^2\theta_{23} = 0.514(0.511) \pm 0.055$ (World leading, 11% relative error) and $\Delta m_{32}^2 = 2.51(2.48) \pm 0.10 \times 10^{-3}$ (starting to be competitive with the MINOS result) for NI (IH). The result is expressed in terms of $\sin^2\theta_{23}$ to allow for not-octant symmetric effects modulated by θ_{13} which are present in the oscillation probability([3]) in the proper 3-flavour treatment.

J-PARC has operated stably at about 220 kW for most of the latest runs accumulating 6.63×10^{20} pot corresponding to about 8% of the design sample. Anti-neutrino data collection has also started in 2014 with the goal of improving the sensitivity to the δ_{CP} phase.

3. – Results from OPERA and ICARUS with the CNGS beam

The CNGS beam has operated from 2006 to 2012 yielding about 1.8×10^{20} pot (80% of the design) and providing OPERA and ICARUS with a 17 GeV mean-energy ν_μ beam.

([2]) $\delta = -\pi/2$ is the value which enhances the $\nu_\mu \to \nu_e$ transition probability.
([3]) $P(\nu_\mu \to \nu_\mu) \simeq 1 - 4\cos^2\theta_{13}\sin^2\theta_{23}[1 - \cos^2\theta_{13}\sin^2\theta_{23}]\sin^2(1.267\Delta m^2 L/E_\nu)$.
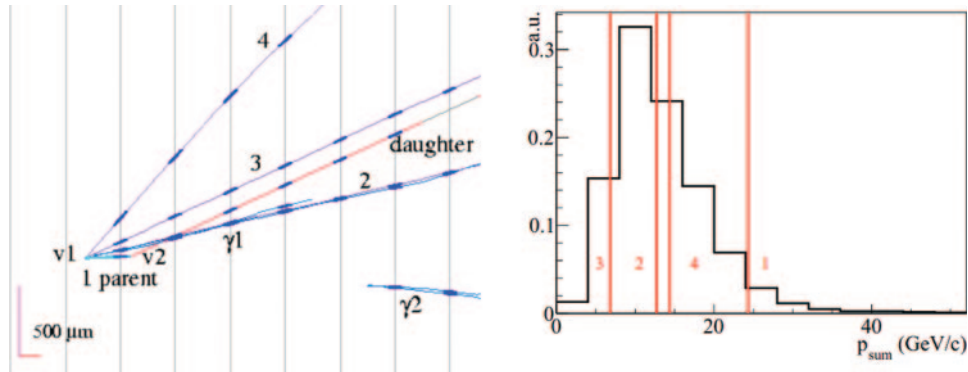
Fig. 3. – Left: Display of the fourth ν_τ candidate. Right: Distribution of the scalar sum of the momenta of tracks in the emulsion detectors. Red lines show the central values measured for the four ν_τ candidates.

3.1. *Measurement of $\nu_\mu \rightarrow \nu_\tau$ appearance*. – The number of oscillated τ is only a small fraction of the total flux occurring mostly at low energy of about 1.5 GeV where the flux is low. The oscillated component at higher energy where the bulk of the flux sits is much reduced but it can be detected having a large-enough interaction cross section (threshold at 3.5 GeV) and a detectable average decay length for the produced τ lepton.

OPERA is essentially a largely modular high-granularity "vertex detector" composed of emulsion detectors (bricks) interspersed with electronic tracking planes and a muon spectrometer system. Electronic detectors determine the position of the bricks containing the neutrino interaction and reduce the background exploiting muon charge determination. The target active mass is about 1.2 kt for a total of about 140000 bricks. The micrometric tracking available over such a large active mass allows the detection on an event-by-event basis (S/N $\sim$ 10) of the rare ν_τ^{CC} interactions. The experimental signature is given by a kink or displaced vertex topology (decay lengths of about 600 μm) or by the occurrence of a high-impact parameter track from a τ decay.

The dominant background is charm production in ν_μ^{CC} events with an undetected primary muon and to a lesser extent hadronic interactions and large-angle Coulomb scattering of ν_μ^{CC} muons (LAS), for the $\tau \rightarrow \mu$ channel. The charm background is benchmarked on the sample of fully reconstructed charm ν_μ^{CC} events (50 observed with 54 ± 4 expected.) and the CHORUS charm sample. The hadronic background is tuned on real data from test-beam exposures while the LAS is currently constrained by simulations and scattering data in the literature.

Bricks are ranked according to the probability of containing the neutrino interactions. All highest-probability bricks have been fully analysed while 2nd bricks in the probability ranking have been analysed only for the 2008-09 run. The expected number [5] of detected ν_τ interactions with the presently analysed sample and the kinematical selection defined already at the level of the experiment proposal is (2.1 ± 0.42) events while 4 candidates have been observed with the following final states: one μ, one $3h$ and two $1h$. The latest $\tau \rightarrow h$ candidate [6] has been announced on 25 March 2014 and it is shown in the left plot of fig. 3. Given the expected background level of (0.233 ± 0.041) events, it is possible to reject the no-appearance hypothesis at the 4.2σ level using Poisson statistics and the information on the observed decay channels.

3˙2. *Measurement of $\nu_\mu \to \nu_e$.* – Both ICARUS and OPERA presented measurements characterising the ν_e component of the CNGS beam thanks to their remarkable electron reconstruction capabilities. On the full data-set ICARUS observes 4 candidate events with $E_\nu < 30\,\mathrm{GeV}$ [7,8] having an expectation of 6.4 ± 0.9. The major background is the instrinsic ν_e in the beam with a contribution from $\nu_\mu \to \nu_e$ and $\nu_\mu \to \nu_\tau$. Using half of the available sample, OPERA [9] observes 19 ν_e candidates (6 of which below $20\,\mathrm{GeV}$) with an expected background of 19.8 ± 2.8 events. Parametrizing the transition probability with an effective 2-flavour formula these observations translate into a 90% CL upper limit on $\sin^2 2\theta_{\mathrm{eff}}$ at 6.8 (7.2) $\times 10^{-3}$ for ICARUS (OPERA).

4. – Conclusions

The last two years have been rich in results involving neutrino appearance channels both at the CNGS ($\nu_\mu \to \nu_{\tau,e}$) and J-PARC ($\nu_\mu \to \nu_e$) beams providing important achievements to the collaborations involved in these demanding programs. Appearance is a key-point in the framework of neutrino oscillations and will continue to play such a role within future high-statistics programs for the measurement of δ_{CP}, the mass hierarchy and eventually exotic or unexpected effects.

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