PROCEEDINGS OF SCIENCE

Atmospheric neutrino oscillations with ANTARES

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ANTARES is a large neutrino telescope located at 2475 m below the Mediterranean Sea level, 40 km offshore from Toulon (France). Data-taking started with the first 5 lines installed in 2007 and the full detector, completed in May 2008, is still taking data. The ANTARES neutrino telescope has an energy threshold of a few tens of GeV. This allows to study the phenomenon of atmospheric muon neutrino disappearance due to neutrino oscillations. An additional sterile neutrino, as proposed in the 3+1 neutrino model, will further modify the expected event rate of up-going muon neutrino events. This allows to infer limits on the existence of such a sterile neutrino. Using data collected by the ANTARES neutrino telescope from 2007 to 2016, a new measurement of Δm^2_{32} and θ_{23} has been performed and constraints on the 3+1 neutrino model have been derived.

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1. The ANTARES neutrino telescope

The ANTARES neutrino telescope is located in the Mediterranean Sea, 40 km off the coast of Toulon, France, at a mooring depth of about 2475 m. The detector was completed in 2008. ANTARES is composed of 12 detection lines, each one equipped with 25 storeys of 3 optical modules (OMs), except line 12 with only 20 storeys of OMs, for a total of 885 OMs. The horizontal spacing among the lines is ∼60 m, while the vertical spacing between the storeys is 14.5 m.

ANTARES data collected from 2007 to 2016 have been considered in the analysis. After excluding data acquired under adverse conditions, a total of 2830 days of live time has been evaluated.

Charged-current (CC) interactions of muon neutrinos produce a muon propagating through the detector and inducing Cherenkov light. They are identified as track-like events. The event reconstruction and selection used in the analysis have been optimized to select such events. The muon energy estimation is based on the fact that muons in the few GeV energy range can be treated as minimum ionizing particles, and their energy can be estimated from their track length. Due to the limited size of the detector the longest visible tracks correspond to initial muon energies of 100 GeV, while the threshold energy of the ANTARES detector in at 20 GeV. This range covers the first oscillation maximum of ν_μ disappearance for vertically up-going neutrinos at 25 GeV.

2. Results for the standard oscillation analysis

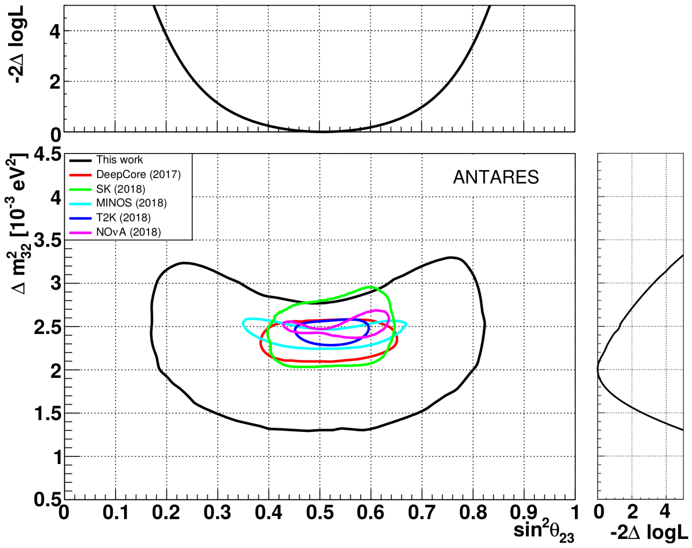

Figure 1: Contour at 90% CL in the plane of $\sin^2\theta_{23}$ and Δm^2_{32} obtained in this work (black line) and compared to the results by other collaborations: IceCube/DeepCore (red) [1], Super-Kamiokande (green) [2], NOνA (purple) [3], T2K (blue) [4], and MINOS (light blue) [5]. The lateral plots show the 1D projections on the plane of the two oscillation parameters under study.

The oscillation parameters θ_{23} and Δm^2_{32} are extracted from a fit of the 2-dimensional event distribution in energy and zenith angle for selected up-going events. Simultaneously a set of nuisance parameters is fitted, accounting, among other effects, for a free overall normalisation, energy dependency effects and neutrino/anti-neutrino asymmetries. The fit yields $\Delta m^2_{32} = (2.0{\pm}0.3){\times}10^{-3}\,\mathrm{eV}^2$ and the mixing angle θ_{23} is found at $45^\circ \pm 12^\circ$. The nuisance parameters are compatible with their expectations at only moderate pulls. In Figure 1 the 90% CL contour obtained in this work, in the plane of $\sin^2\theta_{23}$ and Δm^2_{32}, is compared to those published by other experiments. The 1D projections are shown as well. Confidence level contours have been computed by looping over a fine grid of values in Δm^2_{32} and θ_{23} and minimizing over all the other parameters. The non-oscillation hypothesis is discarded with a significance of 4.6σ, compared to 2.3σ in our previous oscillation analysis [6].

3. Results for the sterile oscillation analysis

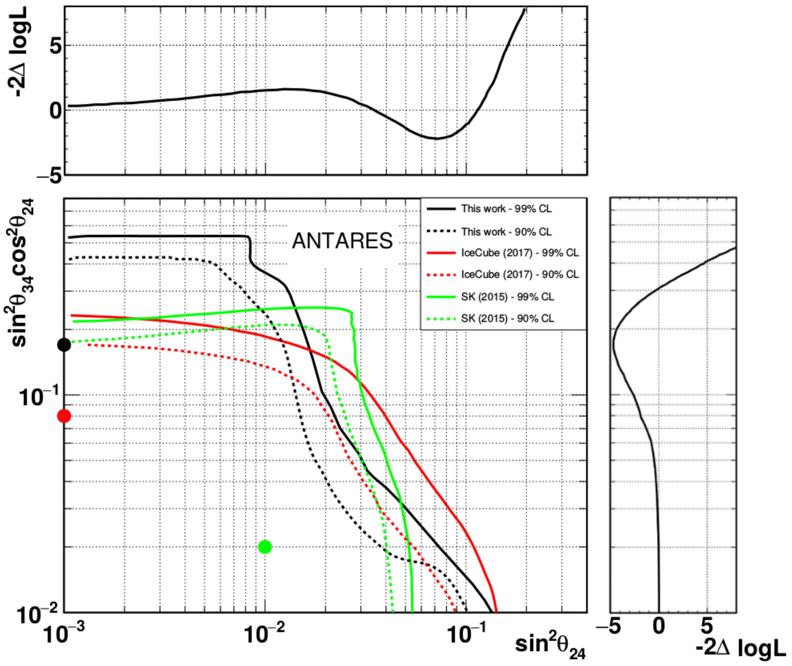

Figure 2: 90% (dashed lines) and 99% (solid lines) CL exclusion regions for the 3+1 neutrino model in the parameter space of $|U_{\mu 4}|^2 = \sin^2\theta_{24}$ and $|U_{\tau 4}|^2 = \sin^2\theta_{34}\cos^2\theta_{24}$ obtained in this work with respect to the non-sterile hypothesis (black lines), and compared to the ones published by IceCube/DeepCore [7] (red lines) and Super-Kamiokande [8] (green lines). The colored markers indicate the best-fit value for each experiment. The 1D projections are also shown for the result of this work.

In the most simplistic 3+1 neutrino model, namely the one which foresees the existence of just one sterile neutrino in addition to the three standard ones, six new real mixing parameters have to be accounted for [9]: three new mixing angles, θ_{14}, θ_{24} and θ_{34}, a new mass splitting, Δm^2_{41}, and two new phases, δ_{14} and δ_{24}. In particular, for up-going ν_μ in the energy range of 20-100 GeV, not null values of θ_{24} and θ_{34} can lead to distortions in their survival probability.

The same analysis chain and data sample can be exploited to constrain the 3+1 neutrino model parameters. The fit described above is modified by adding the mixing angles θ_{24} and θ_{34} as additional free parameter. The mass splitting Δm^2_{41} is fixed to 0.5 eV^2. The obtained limits are valid for the full range $\Delta m^2_{41} \geq 0.5$ eV^2 as the resulting fast oscillations due to large values of Δm^2_{41} are unobservable due to detector resolution effects.

The non-sterile hypothesis is found to be slightly disfavored (at 2.2 σ), similar to what is observed in the other analyses. To calculate exclusion contours $\Delta \log \mathscr{L} = 0$ is defined for the non-sterile hypothesis, *i.e.* at $\theta_{24} = \theta_{34} = 0$. In Figure 2 the resulting 90% and 99% CL exclusion limits have been computed on a 2D grid in the plane of the two matrix elements, namely $|U_{\mu 4}|^2 = \sin^2\theta_{24}$ and $|U_{\tau 4}|^2 = \sin^2\theta_{34}\cos^2\theta_{24}$. The results are compared to the limits published by IceCube/DeepCore [7] and Super-Kamiokande [8]. All three find the best fit for $|U_{\tau 4}|^2$ to differ from zero. In some regions of the plane, ANTARES limits are more stringent.

The analysed energy range is different among the three results illustrated in the figure. The IceCube/DeepCore analysis [7] is limited to events with a reconstructed energy lower than 56 GeV, while the distortion on the oscillation pattern eventually produced by the presence of a sterile neutrino would be evident also at higher reconstructed energies. The present analysis includes events with a reconstructed energy up to 100 GeV; this could be the reason for better sensitivity to some values of the sterile mixing parameters.

References

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