# Measurement of Neutrino Oscillations with the ANTARES detector

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## Abstract

The data taken with ANTARES from 2007 to 2010 with a total lifetime of 863 days have been analysed in view of a possible neutrino oscillation signal. The flux of vertical upward going muon neutrinos should be completely suppressed at energies of 24 GeV due to neutrino oscillations. A dedicated algorithm is used, which allows the reliable reconstruction of muon tracks with energies as low as 20 GeV. The oscillation signal is extracted by comparing two event samples: a low energy sample of vertical upward going tracks seen on a single detector line and a higher energetic set of more isotropic events seen on several detector lines. First results of the measurements of the oscillation parameters are given.

*Keywords:* neutrino oscillations, neutrino telescope, ANTARES

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## 1. The ANTARES detector

A detailed description of the ANTARES detector can be found in [1]. In the following we briefly recall its main characteristics. The detector consists of 12 lines and a junction box which distributes the power and clock synchronization signals to the lines and collects the data. The junction box is connected to the shore by a 42 km electro-optical cable. The lines have an equipped vertical length of 350 m starting 100 m above sea floor. Their horizontal separation is about 65 m and they are arranged to form a regular octagon on the sea floor. Each line is connected to the junction box with the help of a submarine using wet-mateable connectors. It is composed of 25 storeys with a vertical distance of 14.5 m. The lines are kept straight by the floating force of a buoy at the top and an anchor at the bottom. The movement of the line elements due to the sea currents is permanently monitored by an acoustic calibration system.

Each storey contains three $45^o$ downward looking 10" photomultipliers inside pressure resistant glass spheres - the optical modules (OM) [2]. The electronics cards are inside a titanium cylinder at the center. Some of the storeys contain supplementary calibration equipment like acoustic hydrophones or optical beacons [3].

The signals of each photomultiplier are read out by two ASICs. For simple pulses charge and arrival time are digitized and stored for transfer to the shore station. For more complex pulses the pulse shape can be digitized with a sampling frequency up to 1 GHz. The time stamps are synchronized by a clock signal which is sent in regular intervals from the shore to all electronics cards. The overall time calibration is better than 0.5 nsec [4]. Therefore the time resolution of the signal pulses will be limited by the transition time spread of the photomultipliers ($\sigma \sim$1.3 nsec). All data are sent to the shore station. With an optical noise rate of 70 kHz on the one photon level this produces a data flow of several Gbit/sec to the shore. In the shore station a PC farm performs a data filtering to reduce the data rate by at least a factor of 100 [5]. Several trigger algorithms are applied depending on the requested physics channel and on the current optical noise.

## 2. Neutrino oscillations

The survival probability of atmospheric $\nu_\mu$ in the two-flavour approximation is given as:

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta_{23}\ \sin^2(\frac{\Delta m^2_{23} L}{4E_\nu}) \qquad (1)$$

with L the travel path of the neutrino through Earth and $E_\nu$ its energy, both measured in natural units ($\hbar = c = 1$). For upward going tracks L is in good approximation related to the zenith angle $\Theta$ by $L = 2R/\cos\Theta$ with R the Earth diameter. The transition probability P depends on the two oscillation parameters $\Delta m^2_{23}$ and $\sin^2 2\theta_{23}$. When using the current world average data $\Delta m^2_{23} = 2.43 \cdot 10^{-3}\mathrm{eV}^2$ and $\sin^2 2\theta_{23} = 1$ from [6] one expects the first oscillation maximum, *i.e.* $P(\nu_\mu \rightarrow \nu_\mu) = 0$ for vertical upward-going neutrinos ($\cos\Theta = 1$) of $E_\nu$ =24 GeV. This is well within the acceptance of ANTARES as such neutrinos can in principle produce a 120 m long muon track. When traveling along a detector line they could pass in the vicinity of 9 detector storeys.

By using two exclusive sets of event selection criteria, two distinct observation channels $i = 1, 2$ are defined. If

$N_i$ is the observed number of events in channel $i$, we can confront this with a Monte Carlo sample $MC_i$

$$MC_i = \sum_j \mu_j + \sum_k \nu_k P_k(\nu_\mu \rightarrow \nu_\mu) \tag{2}$$

where $\mu_j$ is the weight of the atmospheric muon event $j$ and $\nu_k$ is the weight of atmospheric neutrino event $k$. The sums extend over all events which contribute to channel $i$. Using the abbreviations

$$M_i^0 = \sum_j \mu_j + \sum_k \nu_k \tag{3}$$

$$M_i^m = \sum_k \nu_k \sin^2(\frac{\Delta m_{23}^2 L_k}{4E_{\nu,k}}) \tag{4}$$

we can define a ratio R as

$$R = \frac{N_1}{N_2} = \frac{M_1^0 - \sin^2 2\theta_{23} M_1^m}{M_2^0 - \sin^2 2\theta_{23} M_2^m}. \tag{5}$$

The index m recalls that $M^m$ depends on the second oscillation parameter $\Delta m_{23}^2$. For a given value of $\Delta m_{23}^2$ the mixing angle $\sin^2 2\theta_{23}$ can be derived analytically:

$$\sin^2 2\theta_{23} = \frac{M_1^0 - R \cdot M_2^0}{M_1^m - R \cdot M_2^m} \tag{6}$$

The error of $\sin^2 2\theta_{23}$ is directly related to the error of R - the only observable.

## 3. Data sample

The present analysis is based on data taken with the ANTARES detector between March 2007 and December 2010. Until December 2007 ANTARES operated in a 5-lines configuration, followed by several months of operation with 10 installed detector lines. The detector construction had been completed in May 2008. All physics runs which fulfill basic data quality criteria have been used. Only calibration runs and runs with obvious problems such as sparking optical modules have been excluded. Two tight trigger conditions are used which are both dominated by atmospheric muons. The final event sample consists of 293 million triggers and corresponds to a detector life time of 863 days.

## 4. Reconstruction

The reconstruction method for muon tracks is described in [7]. It assumes a simplified detector geometry composed of straight vertical lines and reaches an angular resolution for zenith angles of 0.7 degrees, equally good for atmospheric muons and atmospheric neutrinos. The method combines a strict selection of direct Cherenkov photon hits which are grouped around “hot spots” at each detector line with a $\chi^2$ like fitting procedure. A “hot spot” corresponds to a signal of 5 photoelectrons seen on two adjacent storeys of the same detector line within a narrow time window of less than 100 nsec. Only hits on detector lines with such a “hot spot” are used in the track fitting. If selected hits occur only on one detector line a single-line fit is performed. No azimuth angle is determined in this case due to the rotational symmetry of the problem. As the oscillation probability does not depend on the azimuth angle (see Equation 1) this is not a problem for the present analysis. If selected hits occur instead on several detector lines, a multi-line fit is performed which provides a three-dimensional track hypothesis as result. The inclusion of single-line events is a special feature of the used reconstruction method [7] which allows to significantly lower the energy threshold of the final atmospheric neutrino sample: whereas for multi-line events the threshold energy of the final neutrino sample is about 50 GeV, single line events are well reconstructed down to 20 GeV for close to vertical tracks, covering therefore L/E values in the vicinity of the first oscillation maximum. The different L/E distributions of the single-line and multi-line event samples makes them a natural choice for the two channels to be used to build the event ratio R, the observable to extract the neutrino oscillation parameters.

## 5. Simulations

Downward-going atmospheric muons were simulated with Mupage [8]. Upward-going neutrinos were simulated according to the parameterization of the atmospheric $\nu_\mu$ flux from [9] in the energy range from 10 GeV to 10 PeV. The Cherenkov light, produced in the vicinity of the detector, was propagated taking into account light absorption and scattering in sea water [10]. The angular acceptance, quantum efficiency and other characteristics of the PMTs were taken from [2] and the overall geometry corresponded to the layout of the ANTARES detector [1]. The optical noise is simulated from counting rates observed in real data. Active and inactive channels have been mapped from real data runs as well. The generated statistics corresponds to an equivalent observation time of 100 years for atmospheric neutrinos and three months for atmospheric muons.

## 6. Event selection

Downward-going atmospheric muons are not affected by neutrino oscillations. But they might pollute the event sample of upward-going atmospheric neutrinos if misreconstructed. As they are simulated with a lower equivalent life time and as their predicted rate suffers from larger theoretical errors, a clean separation of genuine upward-going atmospheric neutrinos and misreconstructed downward-going muons is needed to reliably derive oscillation parameters from the event ratio R.

For the multi-line selection only events are kept which have hits on more than 5 storeys to allow a non-degenerate track fit. Further the fit must not converge on a physical boundary of one of the fit parameters. In particular fit results which yield precisely $\cos\Theta = 1$ are excluded. As the pollution of misreconstructed atmospheric muons is particularly strong close to the horizon a further condition $\cos\Theta > 0.15$ is imposed, *i.e.* tracks closer than 9° to the horizon are excluded. These events have anyway too small values of L to contribute to the oscillation parameters measurement.

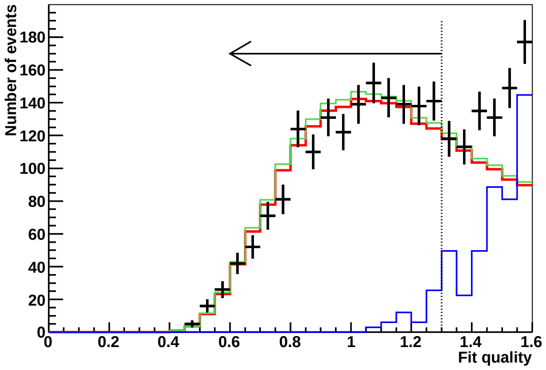

Figure 1: Normalised fit quality of the final multi-line sample. Data (black) are compared to simulations from atmospheric neutrinos with (red) and without (green) oscillations and atmospheric muons (blue). The arrow indicates the chosen region.

The goodness of the track fit is measured by the "normalised fit quality" as introduced in [7], a quantity equivalent to a $\chi^2$ per number of degrees of freedom (NDF). The distribution of the normalised track fit quality of the resulting event sample for data and simulations is shown in Figure 1. The neutrino Monte Carlo sample is scaled down by a factor 0.85 to match the data. The observed 15% mismatch between Monte Carlo and data is well within the uncertainty of the detector acceptance as well as that of the predictions for the atmospheric neutrino flux. For the present analysis a global scale factor is unimportant as it cancels when building R. It is used here for illustrative purposes. Figure 1 shows that a final cut in the normalised fit quality allows to cleanly separate the downward-going muons from the upward-going neutrinos. A final cut $\chi^2 < 1.3$ is chosen.

For the single-line selection events are kept which have hits on more than 7 storeys. This yields a minimal track length for a vertical upward-going muon of about 100 m which can be produced by a muon of 20 GeV. This is sufficiently low to cover the first oscillation maximum at 24 GeV. Again it is required that the fit must not converge on a physical boundary of one of the fit parameters and the fitted zenith angle must indicate an upward-going track, *i.e.* $\cos\Theta > 0$.

The distribution of the normalised track fit quality of the resulting single-line event sample for data and simulations is shown in Figure 2. The neutrino Monte Carlo sample is again scaled down by a factor 0.85 to match the data. Figure 2 shows that also for this data set a final cut in the normalised fit quality allows to cleanly separate the downward-going muons from the upward-going neutrinos. A final cut $\chi^2 < 0.95$ is chosen.

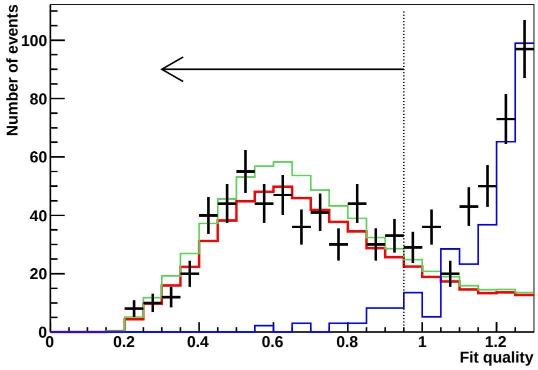

Figure 2: Normalised fit quality of the final single-line sample. Data (black) are compared to simulations from atmospheric neutrinos with (red) and without (green) oscillations and atmospheric muons (blue). The arrow indicates the chosen region.

After applying the chosen cuts the following final event numbers are obtained:

| | single-line | multi-line |
|---|---|---|
| data | $494 \pm 22$ | $1632 \pm 40$ |
| $\nu$ MC | $651 \pm 3$ | $1971 \pm 6$ |
| $\mu$ MC | $25 \pm 15$ | $10 \pm 10$ |
| Total MC | $676 \pm 15$ | $1981 \pm 12$ |

Table 1: Event numbers of the final data set. Neutrino Monte Carlo numbers are without the inclusion of neutrino oscillations. Errors are statistical.

## 7. Systematic error

Most systematic uncertainties affect overall event rates and their effect will largely cancel when working with the event ratio R. To estimate the systematic error of R itself, simulations are repeated with a modified absorption length and a modified angular acceptance of the phototubes. These two effects are suspected to affect the two chosen channels (single-line and multi-line events) in a slightly different manner as single-line events are more vertical and typically closer to the detector lines. Furthermore, the cuts in the normalised fit quality are varied in two steps of 0.05 around the chosen values. As a result 24 new event ratios can be derived and compared to the one given in Table 1. It is observed that R remains stable within 3% of its original value. This will be used as the systematic error on R to derive final results.

## 8. Results

From Table 1 an event ratio

$$R = 0.303 \pm 0.018 \tag{7}$$

can be derived from data. The error is the quadratic sum of the statistical errors for data and MC and the 3% systematic error. The found value of R is incompatible with the non-oscillation hypothesis $R^0 = 0.341$ at 2.1 $\sigma$.

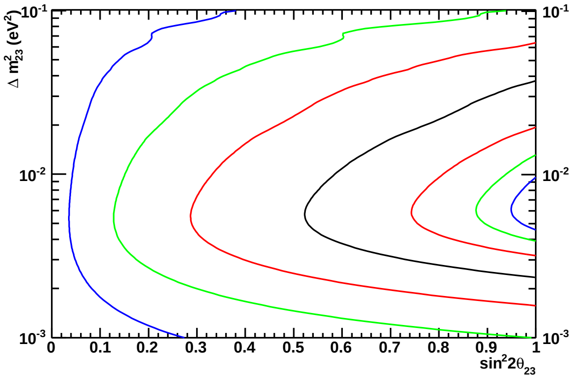

Figure 3: Neutrino oscillation parameters derived from the event ratio R. Along the black line R is precisely reproduced whereas it is compatible within $1\sigma$, 90%, $2\sigma$ in the area between the red, green, blue lines respectively.

Using Equation 6 this measurement can be converted into a measurement contour of the oscillation parameters which is shown in Figure 3. For each $\Delta m^2_{23}$ one obtains a mixing angle for which the observed value of R exactly matches. These values can be read along the black line. Using the global error on R one can further define C.L. contours in the mixing angle for a given value of $\Delta m^2_{23}$. In Figure 3 these contours are shown for C.L.s of 68%,90% and 95%. When imposing maximal mixing ($\sin^2 2\theta_{23} = 1$) and restricting to $\Delta m^2_{23} < 10^{-2}$ eV$^2$ one can further extract a measurement for $\Delta m^2_{23}$:

$$\Delta m^2_{23} = 2.4^{+0.9}_{-0.7} \cdot 10^{-3} \mathrm{eV}^2 \tag{8}$$

at 68% C.L. This is fully compatible with the present world average $(2.43 \pm 0.13) \cdot 10^{-3}\mathrm{eV}^2$.

## 9. Conclusion

Based on the data taken from 2007 to 2010 ANTARES has demonstrated its sensitivity to neutrino oscillations. The non-oscillation hypothesis is disfavoured at $2.1\sigma$ based on a simple analysis of event ratios. The obtained measurement contours for the oscillation parameters are compatible with world data. It is the first time that such a measurement has been performed by a high energy neutrino telescope experiment.

More sophisticated analyses which exploit distributions in variables such as E/L and which use an enhanced data set with an even lower energy threshold are foreseen in the near future.

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