Observation of the cosmic ray shadow of the Sun with the ANTARES neutrino telescope

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Introduction

The ANTARES undersea neutrino telescope [1] is taking data in its final configuration since 2008. It is primarily designed for the detection of neutrino point-like sources [2, 3, 4] then both the pointing accuracy and the angular resolution of the detector are important for the evaluation of the telescope performance. This poster describes the study of the Sun shadow effect with the ANTARES detector. The shadow is the deficit in the atmospheric muon flux in the direction of the Sun caused by the absorption of the primary cosmic rays. The deficit is measured counting the number of muons detected in concentric rings with increasing radius centred on the instantaneous Sun position, resulting in an event density histogram. The analysis is based on the data collected between 2008 and 2017 by the ANTARES telescope.

The data selection optimisation

- A Monte Carlo (MC) simulation is produced and exploited in order to optimise the event selection criteria of the analysis, i.e. the cut values on two parameters determining the quality of the reconstructed tracks: the likelihood-wise parameter, Λ, and the angular error estimator of the reconstructed direction, β [2].
- The cut values on Λ and β to be used for the event selection have been chosen in order to maximise the sensitivity to the Sun shadow detection. This sensitivity has been evaluated analysing a large number of pseudo-experiments with, and without, the simulation of the presence of the Sun. For different cut values on Λ and β (Figure 1), we evaluated the p-value of the test statistic distribution under the null hypothesis, H_0 (no Sun shadow), corresponding to the median of the test statistic distribution under the H_1 hypothesis (presence of the shadow), for which 50% of the pseudo-experiments are correctly identified (Figure 2). As shown by the two figures, the selected parameters cut values, $\Lambda > -5.9$ and $\beta < 1.1°$, allow to obtain as median significance about 3.4σ.

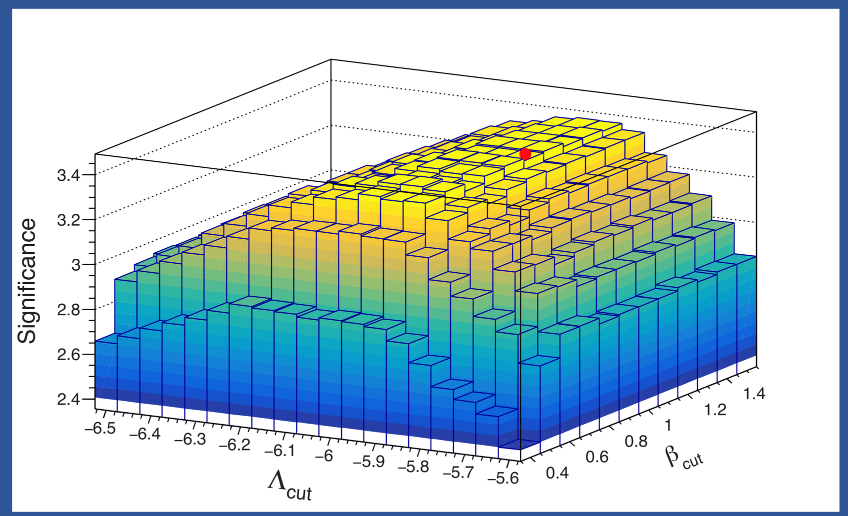

Figure 1. Expected statistical significance of the Sun shadow detection during the period from 2008 to 2017 based on MC simulations, as a function of cut values on Λ and β (Λ_{cut} and β_{cut}). The red dot points to the selected set of cut values ($\Lambda_{cut} = -5.9$ and $\beta_{cut} = 1.1°$) where the expected significance is 3.4σ.

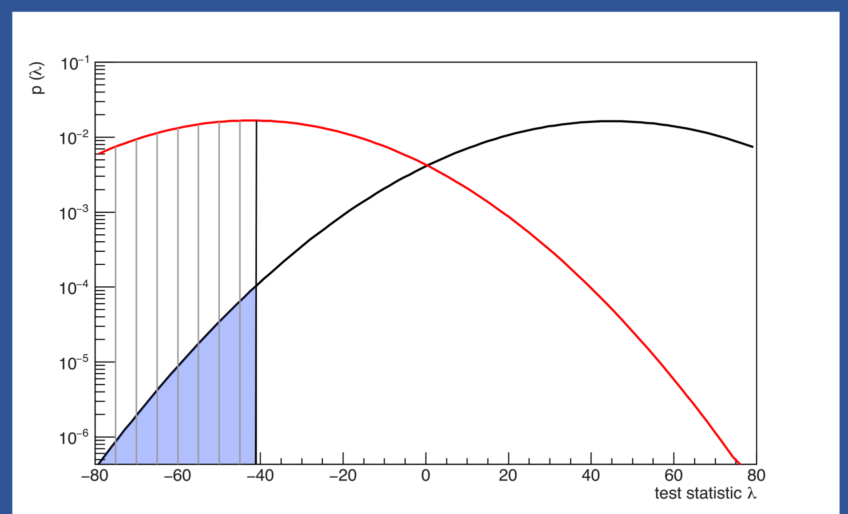

Figure 2. Distribution of the test statistic λ for the two hypotheses, H_0 (black curve) and H_1 (red curve), obtained for the optimized set of cut values ($\Lambda > -5.9$ and $\beta < 1.1°$). The coloured area corresponds to the expected median significance (3.4σ) to reject the H_0 hypothesis in favour of the H_1 hypothesis.

The angular resolution estimation

Figure 3 shows the measured muon event density as a function of the angular distance from the Sun centre δ. The detector angular resolution for downward-going muons σ_{res} is estimated by fitting the experimental data with the function (red line in the figure):

$$f(\delta) = \frac{dN}{d\delta^2} = k\left(1 - \frac{A_{data}}{\sigma_{res}} e^{-\frac{\delta^2}{2\sigma_{res}^2}}\right), \quad (1)$$

where k is the average muon event density in the H_0 hypothesis. The parameter A_{data} is fixed such that the integral:

$$\int_0^{\infty}\big(k - f(\delta)\big)d\delta = N_{abs}, \quad (2)$$

where N_{abs} is the expected number of missing events in the Sun shadow dip derived from the MC point spread function. The value of σ_{res} from the fit is $\mathbf{0.45° \pm 0.12°}$. The statistical significance of the results is $\mathbf{3.9\sigma}$.

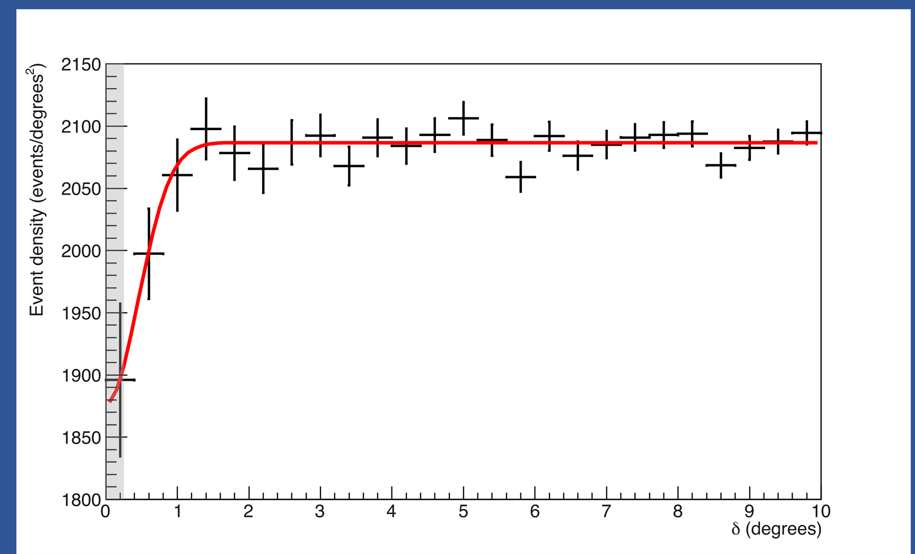

Figure 3. The muon event density as a function of the angular distance δ from the Sun centre based on the data sample taken in the period from 2008 to 2017 fitted with the Eq. 1 (red line). The shaded area corresponds to the Sun angular radius (0.26°).

Absolute pointing

- The event distribution is projected in a two-dimensional histogram in order to estimate the pointing performance of the detector.
- For the pointing accuracy estimation, the Sun shadow centre is assumed to be on each point of the two-dimensional histogram with a step size of 0.1°. The nominal Sun position is at (0°, 0°) point.
- The test statistic function, $\lambda(x_s, y_s)$, is then calculated for each assumed shift of the Sun position as the difference between χ^2 values obtained from the fit under the H_0 and H_1 hypotheses: $\lambda(x_s, y_s) = \chi^2_{H_1}(x_s, y_s) - \chi^2_{H_0}$,
- The distribution of the test statistic as a function of the assumed Sun position, $\lambda(x_s, y_s)$, has its minimum at the nominal Sun position, (0°, 0°) point on Figures 4 and 5.

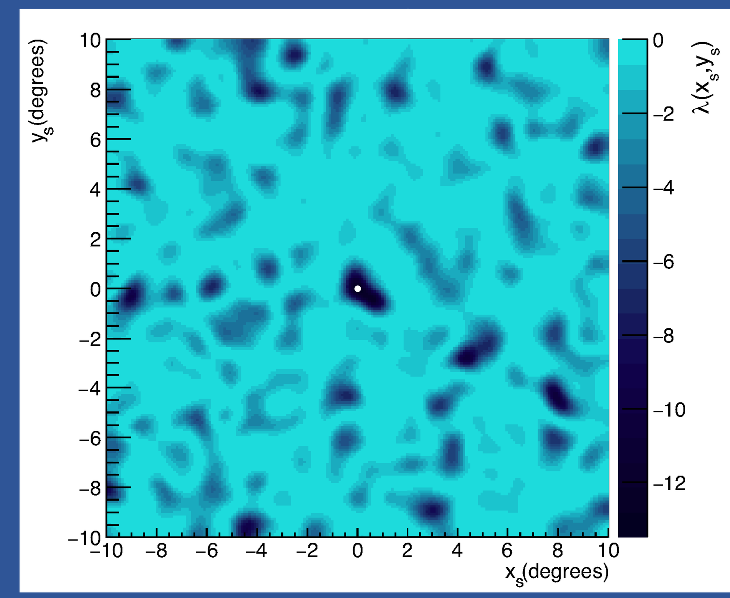

Figure 4. The distribution of the test statistic values $\lambda(x_s, y_s)$. The minimum value of $\lambda(x_s, y_s)$ is found at the nominal Sun position (white dot).

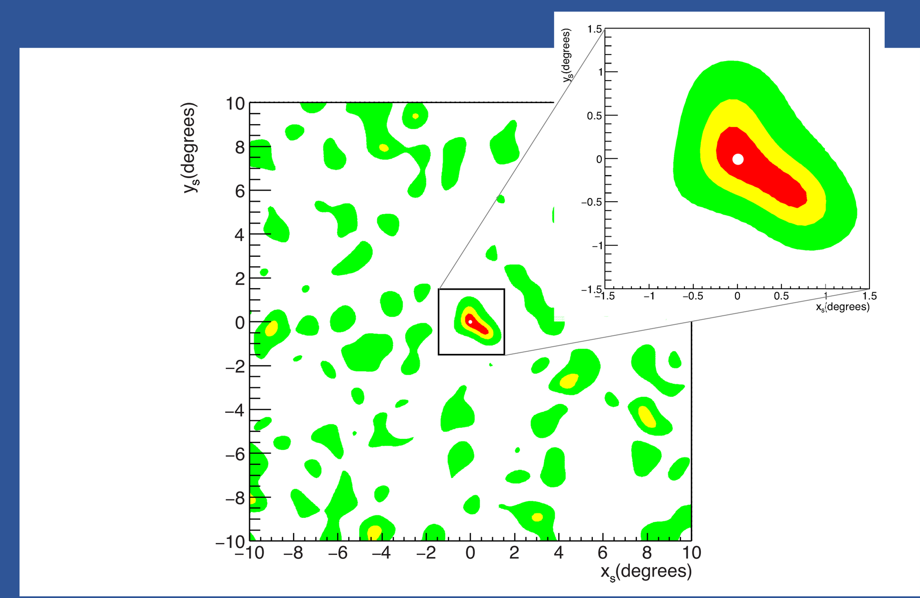

Figure 5. Contour plots corresponding to different confidence levels (red: 68.27%; yellow: 95.45%; green: 99.73%). The white dot indicates the nominal position of the Sun for which a minimum value of $\lambda(x_s, y_s)$ is obtained.

Conclusions

- A valid evaluation of the angular resolution of the ANTARES detector is essential since one of the main goals of the telescope is the search for point-like sources.
- The Sun shadow effect is studied by means of two complementary approaches which allow to determine the angular resolution for downward-going atmospheric muons and to verify the pointing performance of the detector.
- The shadow effect is observed with $\mathbf{3.9\sigma}$ statistical significance. The angular resolution for downward-going muons is found equal to $\mathbf{0.45° \pm 0.12°}$. The obtained angular resolution for the ANTARES telescope is compatible with the one found in the Moon shadow analysis (0.73° ± 0.14°) [5]
- No evidence of systematic pointing shift is found and the resulting pointing accuracy is consistent with the expectations.

References

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