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Solar Atmospheric Neutrino searches with the ANTARES neutrino telescope

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The interaction of cosmic-rays with the solar atmosphere can yield neutrinos as final state particles, the so-called Solar Atmospheric Neutrinos (SAν). Most of these neutrinos are absorbed in the interior of Sun. Neutrinos produced in the solar corona towards the Earth would escape the Sun and reach the Earth. The detection of the solar atmospheric neutrinos would be important to determine the constituents of the primary cosmic rays and the solar composition. In addition, these neutrinos would represent an irreducible source of background for indirect solar dark matter searches. The deep-sea neutrino telescope ANTARES, located in the Mediterranean Sea, is well suited to perform this search. In this work, the results after the analysis of 11 years of ANTARES data is presented. No evidence for a solar atmospheric neutrino signal over the expected background is found. Results in terms of sensitivity and upper limits for different signal models are reported. The obtained upper-limit at 90% CL in the solar atmospheric neutrino flux is about 7×10^{-11} [TeV cm^{-2} s^{-1}] at E$_{\nu}$ ~ 1 TeV.

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1. Executive summary

The ANTARES detector is the first undersea neutrino telescope. It is anchored at a depth of 2475 m in the Mediterranean Sea, 40 km offshore from Toulon. Since the deployment of its first detection line, in 2007 and its completion in 2008, it has been taking data continuously. The detector main purpose is to perform neutrino astronomy, however, it also offers tools for marine and Earth sciences.

In this contribution, we have focused in the measurement of Solar Atmospheric Neutrinos. Solar Atmospheric Neutrinos (SAνs) are yield after cosmic rays (CRs) interacting with the solar media. The majority of SAνs are absorbed in the solar inner part, but others, those produced in the corona, can escape the solar medium and reach the Earth.

The detection of SAνs can shed light on the primary CR and solar composition as well as in the parameters of neutrino oscillations. Also, its detection would characterise this potential background for solar dark matter (DM) indirect searches.

Neutrino induced events can be classified into two main groups: **track like** and **shower like**. Track like events are those that yield a muon as a final state particle after charged current (CC) ν_μ and ν_τ interactions. All neutral current (NC) interactions, as well as the ν_e and most ν_τ CC, procude shower like events.

In this work, two CR models (*H3a* and *GST4*) and two solar density profiles (*Ser+Stein* and *Ser+GS98*) have been tested. Neutrino oscillations from best-fit values and normal mass ordering are assumed. Also, three different source shapes have been considered: the Sun as a point source, as a filled disk and with ring shape.

In this search, two main background sources are present: atmospheric muons and atmospheric neutrinos. A set of parameter cuts are chosen in order to optimize the search for SAνs signatures and reject the the background. Only the track channel (ν_μ CC) is considered. In order to select the best possible reconstructed events in the sample, a cut in reconstruction fit parameter $\Lambda > -5.2$ and in the error estimate of the angular reconstruction $\beta < 1^\circ$ are established. Selecting only up-going events in the detector $\theta_{\text{zenith}} > 90^\circ$, the background is reduced considerably because the atmospheric muons are stopped by the Earth.

The search for SAνs signatures is done through the maximisation of an unbinned likelihood function.

$$\mathcal{L}(n_{\text{sig}}) = e^{-(n_{\text{sig}}+n_{\text{bkg}})} \prod_{i}^{N} \left[n_{\text{sig}} \cdot \mathcal{S}(\Psi_{\odot,i}, \beta_i, E_i) + n_{\text{bkg}} \cdot \mathcal{B}(\Psi_{\odot,i}, \beta_i, E_i) \right], \tag{1}$$

where: $\mathcal{S}$ and $\mathcal{B}$ are the signal and background PDFs, respectively. n_{sig} is a free parameter to fit in the likelihood, and represents the number of signal events in the sample. n_{bkg} is the expected number of background events within the sample. N is the total number of reconstructed events within the RoI in the data taking period. It can be expressed as $N = n_{\text{sig}} + n_{\text{bkg}}$ $\Psi_\odot$ is the angular distance to the source. β is the error estimate in the reconstructed angle. E is the energy proxy.

The significance of the signal event is established by the test statistic TS (Eq. (2)).

$$\text{TS} = \log_{10} \left(\frac{\mathcal{L}(\hat{n}_{\text{sig}})}{\mathcal{L}(0)} \right). \tag{2}$$

The denominator corresponds to the likelihood of the *null* hypothesis case, for the background only scenario. The numerator corresponds to the *alternative* hypothesis for the background + signal events within the sample, being $\hat{n}_{\rm sig}$ the best-fit parameter of Eq. (1).

The resulting TS distributions are compared with the median of the background-only distribution to obtain the 90% confidence level (CL) sensitivity on the number of signal events.

In order to convert the number of signal events $n_{\rm sig}^{90\%\ \rm CL}$ into a sensitivity to a SAν flux, the following expression is used.

$$\frac{d\Phi_{\nu_\mu}^{90\%\ \rm CL}(E)}{dE} = \frac{n_{\rm sig}^{90\%\ \rm CL}}{\bar{n}_{\rm sig}^{\rm theor}} \frac{d\Phi_{\nu_\mu}^{\rm theor}(E)}{dE} = C_{90} \cdot \frac{d\Phi_{\nu_\mu}^{\rm theor}(E)}{dE}, \tag{3}$$

After the data unblinding, the 90% CL upper limit obtained is $n_{\rm sig}^{90\%\ \rm CL} = 3.15$, and the flux scale factor $C_{90} = 8.6$. The scale factor value tells us that in order to exclude the model, we would need a flux 8.6 times larger. No signal evidence was observed, instead a 90% CL energy flux upper limit has been established to be about 7×10^{-11} [TeV cm^{-2} s^{-1}] at 1 TeV neutrino energy with a p-value 0.41.