Search for time and space correlations between ANTARES data and IceCube high energy neutrino events

G. Illuminati\textsuperscript{1}, A. Coleiro\textsuperscript{1,2}, on behalf of the ANTARES Collaboration

\textsuperscript{1}Instituto de Física Corpuscular - Universitat de València / CSIC
\textsuperscript{2}APC, Université Paris Diderot, CNRS/IN2P3, CEA/IRFU

- A high-energy neutrino diffuse flux of cosmic origin has been observed with the IceCube telescope \cite{1}, the sources of which still have to be identified.
- Two of the neutrino events from the high-energy starting events sample (HESE) occurred within 1 day of each other with a p-value of 1.6\% \cite{2}, which could be interpreted as the signature of a possible flaring emission.
- The ANITA data-set is scanned to look for time and space correlation with 54 IceCube neutrino candidates selected from two high-energy samples, treating each IceCube event as a potential transient neutrino source.

A maximum likelihood estimation is performed to identify clusters of cosmic neutrinos over the background of randomly distributed atmospheric neutrinos:

$$\log \mathcal{L}_{\text{max}} = \sum_{i \in \text{tr}} \sum_{s \in J} \log \left[ \mu_{i,s} S_{i,s} + N_{i,s} B_{i,s} \right] - \mu_{i,s}.$$ 

- $S_{i,s}$ and $B_{i,s}$: signal and background PDFs for the event $i$ in the sample $J$ (tr for tracks, sh for showers).
- $\mu_{i,s}$ and $N_{i,s}$: number of unknown signal events and total number of data events in the $J$ sample.
- The combined information of three parameters: direction, energy, and observation time is included in the definition of the PDFs.

- A generic Gaussian shape is assumed for the signal time-dependent PDF, with mean value being the observation time of the IceCube candidate, and sigma the unknown flare duration $\sigma_f$.
- The likelihood is maximised with respect to four parameters: the number of signal events $\mu_{i,s}$, the flare duration $\sigma_f$, the signal spectral index $\gamma$ and the position of the fitted source.

- No excess over the expected background is observed.
- Investigated candidate with the largest excess: HE15 (89\% post-trial significance).
- Best-fit flare duration $\sigma_f$ for the investigated IceCube events consistent with a positive fluctuation in fitted number of signal events:

\begin{tabular}{|c|c|c|c|}
\hline
HESE ID & $\sigma_f$ [days] & HESE ID & $\sigma_f$ [days] \\
\hline
HE15 & 15 & HE16 & 20 \\
HE17 & 25 & HE18 & 30 \\
HE19 & 35 & HE27 & 75 \\
\hline
\end{tabular}

The non-observation of time correlation within a time window $\leq 0.1$ days is translated into a limit on the number of ANTARES events in time correlation with an IceCube HESE/HE candidate equal to $n^\text{UL} = 2.3$ (assuming Poisson statistics), which can be converted into a limit on the neutrino fluence normalization for different spectral indices $\Phi_E^{-L}$. From this, the 90\% C.L. upper limit on the number of signal events expected to be observed by IceCube from a neutrino fluence $\Phi_E^{-L}$ is calculated as $N_{\text{obs}}^{\text{IC}} = \int \Phi_E^{-L} A_{\text{eff}}^{\text{IC}} \, dE$ with $A_{\text{eff}}^{\text{IC}}$ being the IceCube effective area.

The limits are shown for the two most energetic IceCube events of each sample. Where $N_{\text{obs}}^{\text{IC}}$ is less than 1 (number of observed events), a transient origin with flare duration $\leq 0.1$ days can be excluded at 90\% C.L.

Only IceCube events classified as muon tracks, within the ANTARES field of view are included in the candidate list:

- 20 neutrino events from the HESE sample \cite{3}\cite{4}\cite{5} (green stars).
- 34 neutrino events from charged current $\nu_E$ from the Northern Hemisphere sample (HE) \cite{6} (yellow squares).

ANTARES data sample:

- events recorded between April 2009 and August 2016 (2157 days livetime) in order to overlap the IceCube events observation time and allow the search for flares lasting up to four months.
- 6310 track-like events (blue circles), 147 shower-like events (magenta circles).

When dealing with transient emissions, the background of atmospheric neutrinos can be significantly reduced by limiting the search to a small time window around source flares. When emission durations of a few hours are considered, only about one third or less of the events needed in a time integrated analysis is necessary for a 5\% significant detection, depending on the assumed signal energy spectrum $S(E) = E^{-\gamma}$ or $S(E) = E^{-\gamma-2}$.

Upper limits of 90\% C.L. on the flare (orange triangles) and sensitivity (blue dots) calculated for the time windows reported in the tables (hence only for sources consistent with a positive fluctuation in fitted number of signal events) for two assumptions of the signal energy spectrum $S(E) = E^{-\gamma}$ and $S(E) = E^{-\gamma-2}$.

We gratefully acknowledge the financial support of Ministerio de Economía y Competitividad (MINECO): Plan Estatal de Investigación (ref. FPA2015-6515B-C3-1-P), (MINECO/FEDER), Severo Ochoa Centre of Excellence (MINECO), and Prometeo and Grisola programs (Generalitat Valenciana), Spain.