

# MAGIC gamma-ray telescopes hunting for neutrinos and their sources

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**Abstract.** The discovery of an astrophysical flux of high-energy neutrinos by the IceCube Collaboration marks a major breakthrough in the ongoing search for the origin of cosmic rays. Presumably, the neutrinos, together with gamma rays, result from pion decay, following hadronic interactions of protons accelerated in astrophysical objects to ultra-relativistic energies. So far, the neutrino sky map shows no significant indication of astrophysical sources. Here, we report first results from follow-up observations, of sky regions where IceCube has detected muon tracks from energetic neutrinos, using the MAGIC telescopes which are sensitive to gamma rays at TeV energies. Furthermore, we show that MAGIC has the potential to distinguish air showers induced by tau neutrinos from the background of hadronic showers in the PeV-EeV energy range, employing a novel analysis method to the data obtained with high-zenith angle observations.

## 1. Introduction

The discovery of an astrophysical flux of high-energy neutrinos by IceCube [1] is a major step forward in the ongoing search for the origin of cosmic rays, since the neutrino emission may be produced by hadronic interactions in astrophysical accelerators. While many sources of astrophysical origin have been suggested to explain IceCube signal, there is yet not enough information to narrow down the possibilities to any particular source or source classes. Gamma-ray observations of neutrino directions by imaging atmospheric-Cherenkov telescopes (IACTs) like VERITAS [2], HESS [3] or MAGIC have also a potential to find hadronic  $\gamma$ -ray emissions from the neutrino directions and to identify neutrino sources.

In this short note, we present the results of MAGIC search for the counterpart  $\gamma$ -ray emission from directions of selected IceCube events and report first results from the tau neutrino search with the MAGIC telescopes. MAGIC consists of two telescopes located on the Roque de los Muchachos Observatory (28.8° N, 17.9° W; 2200 m above sea level), at the Canary Island of La Palma (Spain). They are placed 85 m apart, each with a primary mirror of 17 m diameter. The MAGIC telescopes are able to detect cosmic  $\gamma$ -rays in the range 50 GeV - 50 TeV [4].

## 2. MAGIC search for $\gamma$ -rays from HESE

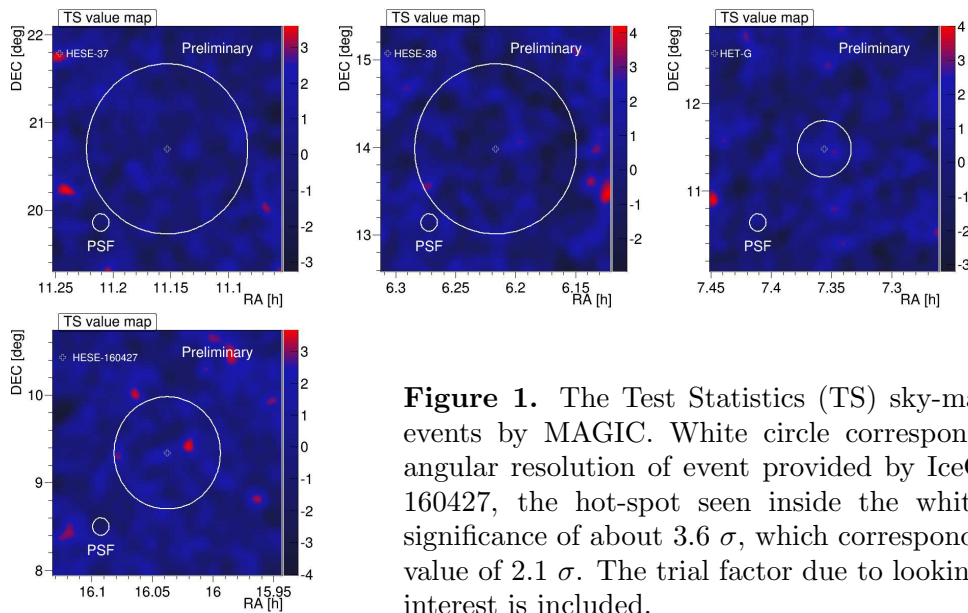
IceCube's detection was based on an analysis that searched for very energetic events that have their interaction vertex contained inside the detector volume, the so-called High Energy Starting Events (HESEs). The latest update of this analysis [5] has revealed 54 contained events in the



**Table 1.** Selected MAGIC targets; HET-Highest Energy Track event seen in IceCube [6]; HESE-160427A event seen by IceCube in April 2016 [7].

	HESE-37	HESE-38	HET	HESE-160427A
<b>from IceCube</b>				
Right Ascension (hrs)	11.15	6.22	7.36	16.04
Declination ( $^{\circ}$ )	20.7	13.98	11.48	9.34
Median angular resolution ( $^{\circ}$ )	< 1.2	< 1.2	< 0.3	< 0.6
Deposit energy (TeV)	$30.8_{+3.3}^{-3.5}$	$200.5_{+16.4}^{-16.4}$	$2600_{+300}^{-300}$	not published
<b>MAGIC data taking</b>				
Zenith angle range ( $^{\circ}$ )	8 - 30	15-50	11-32	18-26
Effective observation time (m)	447	342	288	111

TeV–PeV energy range observed over the course of four years, out of which 39 are particle cascades (produced by charged interactions of  $\nu_e$ ,  $\nu_{\tau}$  or neutral interactions of any neutrino flavor) with angular resolutions of about  $15^{\circ}$  and one was determined to be a background event. The event topology of the remaining 14 is compatible with  $\nu_{\mu}$ -induced muon tracks with an angular resolution of about  $1^{\circ}$ , meaning that the pointing accuracy is attractive for IACTs. For MAGIC, targets were selected from the last up-to-date list of HESEs and requesting: to be track-like (i.e. error in the field of view (FOV) of MAGIC) and visible at La Palma, see Table 1. Analysis cuts are optimized for a Crab Nebula-like spectrum above 100 GeV. As we



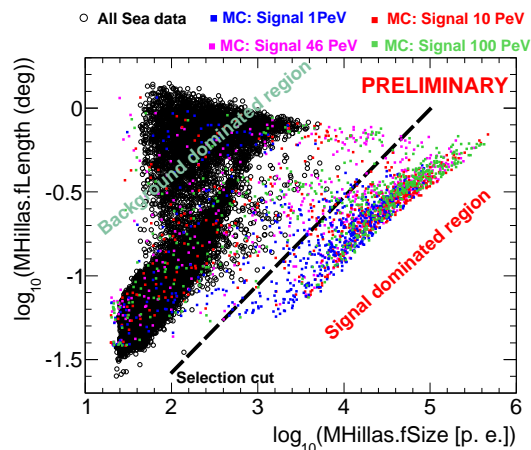
**Figure 1.** The Test Statistics (TS) sky-maps for considered events by MAGIC. White circle corresponds to the median angular resolution of event provided by IceCube. For HESE-160427, the hot-spot seen inside the white circle have the significance of about  $3.6 \sigma$ , which corresponds to the post-trial value of  $2.1 \sigma$ . The trial factor due to looking at four region of interest is included.

can see from Figure 1 no counterpart  $\gamma$ -ray emission was detected by MAGIC in the direction of considered events.

### 3. MAGIC as neutrino detector

The MAGIC telescopes were designed to be able to point to the Sea. This permits to search for signatures of air showers induced by tau neutrinos in the PeV-EeV energy range arising from the ocean [8]. As an example at zenith angle  $91.5^{\circ}$  the surface of Sea is  $\sim 165$  km away, thus telescopes can monitor a large volume in their FOV. Cherenkov telescopes can be sensitive to tau neutrino from fast transients objects like GRBs, as recently shown by the Ashra team [9]. Moreover, nights with high clouds often prevent the observation of  $\gamma$ -ray sources, but still allow

pointing the telescopes below horizon. Recently, MAGIC telescopes took data in the direction of Sea (zenith angle  $92.5^\circ$  and the effective observation time of  $\sim 29$  hrs) when high clouds were presented, demonstrating that a large amount of data can be accumulated during such conditions. In order to understand the measured background at very high zenith angles ( $< 85^\circ$ )



**Figure 2.** The Hillas-Length as a function of Hillas-Size parameter for deep  $\tau$ -induced showers with energy 1, 10, 46 and 100 PeV (SIGNAL) and data taken by MAGIC at Sea direction (BACKGROUND). The dashed lines indicates selection cut, below it the ZERO background region is present.

and study the signatures expected from neutrino-induced showers by IACTs, a full Monte Carlo (MC) simulation chain was set, which consists of three steps. First, the propagation of a given neutrino flux through the Earth and the atmosphere is simulated using an extended version of the ANIS code [10]. Second, the shower development of  $\tau$ -induced showers and Cherenkov light production from such showers is simulated with CORSIKA [11]. The results of CORSIKA simulations were used as the input for the last step i.e. simulation of the detector response for tau neutrinos by MAGIC [12].

In Figure 2 we show the results of MC simulation of Hillas parameters [13] for deep  $\tau$ -induced showers and data taken at Sea direction. In general, Hillas parameters depend on the geometrical distance of shower maximum to the detector, which for deep  $\tau$ -induced shower is much smaller than for showers from cosmic rays (mainly inclined  $p$ -induced showers) interacting at the top of the atmosphere. For example, at  $\theta > 80^\circ$  this distance is of about a few hundred kilometers for particle interacting at the top of atmosphere and only a few tens kilometers for deep  $\tau$ -induced shower. Thus, this geometrical effect leads to rather good separation of close ( $\tau$ -induced) and far-away background events in the Hillas parameter phase space. Figure 2 (for the first time) shows that MAGIC can identify tau neutrino showers from the background of  $p$ -induced showers.

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