

MAGIC as a high-energy ν_τ detector: performance study to follow-up IceCube transient events

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MAGIC is a system of two Imaging Atmospheric Cherenkov Telescopes located on the Canary Island of La Palma and dedicated to the study of very high energy gamma rays above 30 GeV. MAGIC has recently demonstrated its capability as a neutrino detector, by exploiting the Earth-skimming technique. The neutrino-event selection has been studied by pointing the telescopes towards the sea a few degrees below the horizon, with no pre-defined source direction. An upper limit to the ν_τ flux was set. In this work, a follow-up strategy of given source directions is presented. This new approach is characterised by pointing to targets passing through the sea window observable with MAGIC and for which a trigger from dedicated neutrino observatories is issued with large significance. Above a few tens of PeV, the acceptance of MAGIC to ν_τ is considerably large and compelling results can be obtained for transient events of short duration. The performance of this new method is tested on a sample of data collected by pointing MAGIC for a few days from March to May 2016 towards the direction of a multi-PeV neutrino that IceCube detected on June 11th 2014 (reconstructed direction (J2000.0) RA: 110.34° and Dec.: 11.48°). A selection cut is studied in order to discriminate τ -lepton-induced air showers from the background of very inclined cosmic-ray-induced air showers. An upper limit on the neutrino flux from the above given neutrino direction is presented.

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1. Introduction

High-energy and ultra-high energy neutrinos are unique cosmic messengers: they are a probe of hadronic mechanisms at work in cosmic-ray sources and they do not suffer magnetic deflections, pointing to their production site. Neutrinos are expected to be produced by astrophysical accelerators mostly through the charged pion decay. In a low density environment, the flavour ratio at the source is therefore $(\nu_e:\nu_\mu:\nu_\tau)\sim(1:2:0)$. Because of neutrino oscillations and according to standard production scenarios, an equal flavour ratio is expected at Earth .

The IceCube experiment provided the first strong evidence for the existence of a flux of astrophysical neutrinos of energies between about 100 TeV and 1 PeV [1]. In addition, its measurements are consistent with equal fractions of all flavours [2, 3]. However, up to now astrophysical ν_τ have not been unambiguously tagged. The detection of neutrinos of this flavour would be of fundamental importance from both the astrophysics and particle physics point of view, being an additional proof of the cosmic origin of these particles and a clear sign of neutrino oscillations, which can shed light on physics beyond the standard model.

Imaging Air Cherenkov Telescopes (IACTs) are able to detect ν_τ , by using the so-called *Earth-skimming* method [4]. Up-going neutrinos interacting close to the Earth surface can produce charged leptons. A τ -lepton arising from a ν_τ propagates through the Earth. If it emerges and decays in the atmosphere, it induces an air shower that can be measured through IACTs [5].

MAGIC is a stereoscopic IACT system focused on the study of the gamma-ray universe between about 50 GeV up to 50 TeV [6]. Even if not designed nor optimised for measuring in Earth-skimming mode, MAGIC set an upper limit on the ν_τ flux in the PeV-EeV energy range by pointing the telescopes to fixed azimuth and zenith ($Az -30^\circ$, $Zd 92.5^\circ$) [7].

In this work, we present the analysis of the data collected by pointing MAGIC in Earth-skimming mode towards a multi-PeV IceCube event detected on June 11th 2014 (reconstructed direction (J2000.0) RA: 110.34° and Dec: 11.48°) [8, 9], called: IceCube-140611A. In Section 2, the strategy for analysing candidate neutrino sources with MAGIC is presented: the cuts for selecting the ν_τ -signal are discussed, and the acceptance and the expected event neutrino rate are calculated. In Section 3, we apply our analysis on IceCube-140611A data, setting an upper limit on the flux of ν_τ from this direction. The aim of this work is to implement a tool that can be used for following-up transient events in Earth-skimming mode, in case of alerts issued with a large significance from dedicated neutrino observatories.

2. Search for Earth-skimming neutrinos from transient events with MAGIC

The MAGIC telescopes are able to point down to 6° below the horizontal plane and, thanks to their location, have the right distance from the Atlantic Ocean for potentially observing a full development of τ -lepton-induced air showers emerging from the sea [5]. The τ decay length is about 0.5 (50) km, for an energy of 1 (1000) PeV. Fig. 1 (left panel) shows a sketch of an up-going τ -lepton-induced air shower produced by a ν_τ . The horizon seen by MAGIC is reported in Fig. 1 (right panel): in particular, the region highlighted by the red rectangle is considered optimal for the observations in Earth-skimming mode. The zenith and azimuth ranges are respectively $[90^\circ - 95^\circ]$ and $[-100^\circ - 20^\circ]$.

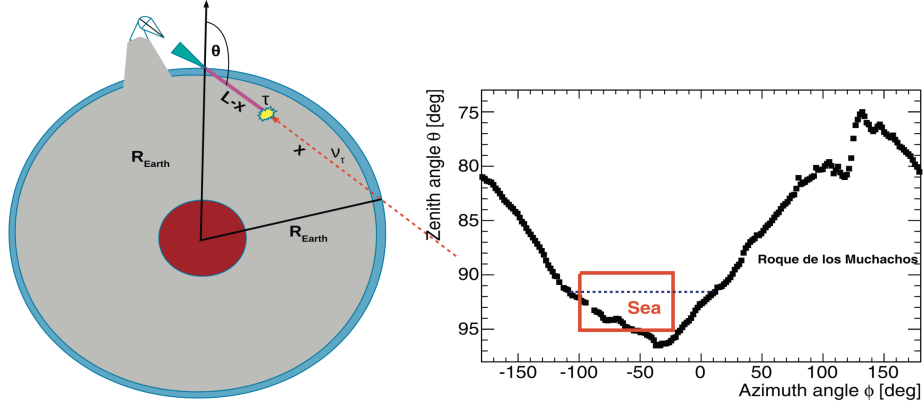


Figure 1: Left panel: sketch of ν_τ -detection in Earth-skimming mode. Right panel: horizon seen by the MAGIC telescopes. The rectangle highlights the optimal neutrino visibility window. The azimuth range between 0 and -20° is excluded because of the shadowing from the telescope access tower (see text for more details).

The effective area of MAGIC for this kind of observations was calculated analytically. For an observation angle of 1.5° below the horizon, it ranges from $\sim 10^3 \text{ m}^2$ at 100 TeV to $6 \times 10^4 \text{ m}^2$ at 300 PeV, reaching $5 \times 10^5 \text{ m}^2$ at 100 EeV [10].

A search for neutrinos in Earth-skimming mode has been already carried out with MAGIC. It was performed with about 30 h of data collected by pointing the telescopes below the horizon towards a fixed position (Az -30° , Zd 92.5°). A 90% C.L. upper limit on a hypothetical ν_τ point-source flux of $E^2 \Phi(E) < 2.0 \times 10^{-4} \text{ GeV cm}^{-2} \text{ s}^{-1}$ was obtained in the PeV-EeV energy range [7].

The predicted emission of neutrinos above PeV from candidate astrophysical sources is quite low (see e.g. [11]). The MAGIC sensitivity in Earth-skimming mode is limited mainly by the available observation time. However, the perspectives become appealing in case of short bursting episodes with high luminosities extending to the highest energies, like in case of flaring Active Galactic Nuclei or Gamma-ray Bursts. These objects can exhibit electromagnetic outbursts of duration significantly shorter than months [12]. For this reason, pointing MAGIC to potential sources of neutrinos in case of triggers from dedicated observatories like IceCube can significantly improve the probability of detecting ν_τ .

2.1 Monte Carlo simulations

In order to study the signal expected from an up-going ν_τ , a full Monte Carlo simulation chain was set up in [5, 7], based on a modified version of ANIS [13], CORSIKA (6.99)[14] and the simulation of the response of MAGIC. The simulations have been performed from 1 PeV to 1000 PeV in steps of 0.33 PeV, and for a zenith angle of 87° . Even if this analysis is focused on events with zenith angles larger than 90° , this is not a major issue: a previous work demonstrated the universal behaviour of the parameters used for identifying τ -lepton-induced air showers at large zenith angles above 80° [5, 7].

The expected signature in the MAGIC camera depends on the different decay channels of the τ -lepton, that mainly decays to hadrons, pions and kaons and in 35% of the cases to electrons and

	SeaON	IceCube-140611A
Zenith angle	92.5°	90°-93°
Azimuth angle	-30°	-80° to -75°
Observation time (h)	31.5	1.34

Table 1: Summary of data used in this work and collected by using MAGIC in Earth-skimming mode.

muons. In this work, the simulations are used for defining the selection parameters of τ -lepton-induced air showers, for studying the identification efficiency (Sec. 2.3) and for evaluating the acceptance of MAGIC (Sec. 2.4). Mainly because of the camera FoV ($3.5^\circ \times 3.5^\circ$), MAGIC observes a portion of the atmosphere even when it points below the horizon. The main background to a possible neutrino signal is therefore due to very inclined cosmic rays. In the PeV-EeV energy range, these are especially protons. A comparison between τ -lepton-induced air showers and proton-induced air showers has been carried out at MC-level [5]. In general, a τ -lepton-induced air shower will contain many more Cherenkov photons with respect to a proton-induced air shower of same energy, mainly because its decay vertex is closer to the detector.

2.2 MAGIC observations

Two main datasets were collected between 2015 and 2016 in Earth-skimming mode, i.e. by pointing MAGIC towards the window highlighted by the rectangle in Fig. 1 (right panel). They are shown in Table 1. The sample called *SeaON* was mainly taken during nights characterised by high cumulus clouds, preventing normal gamma-ray observations. *SeaON* data have been analysed, but no neutrinos have been identified [7]. For this reason, in this work, these data are used as a background sample for the optimisation of the selection cuts for short-time observations, as described in more detail in Sec. 2.3. The data named IceCube-140611A were instead collected for a few days in 2016, by pointing MAGIC towards the direction of a multi-PeV IceCube neutrino detected on June 11th 2014 [8], and tracking it when it was passing through the ν_τ visibility window. The effective duration of the observations was 1.34 h.

2.3 Optimisation of the selection cuts and trigger efficiency study

It is possible to discriminate τ -lepton-induced air showers from the background of very inclined cosmic ray-induced air showers by considering two Hillas parameters of the cleaned camera image: the *Size* and the *Length* [15]. The first one expresses the total amount of light in the camera, measured in photoelectrons, and it is correlated with the primary energy; the second quantity describes the lateral development of a shower and it is measured in degrees. Fig. 2 (left panel) shows a scatter plot of *Size* and *Length*: black points are *SeaON* data, whereas blue points are from MC simulations of τ -lepton-induced air showers at 1 PeV. Only showers with impact distances $d < 300$ m have been selected, for a better reconstruction of the camera image. The figure shows that a region in the 2D *Length-Size* plane can be defined that is strongly signal-dominated. The region can be separated by a single cut, by projecting the plane along the direction:

$$\log_{10} Y = \log_{10}(\text{Size}) \times \cos \alpha - \log_{10}(\text{Length}) \times \sin \alpha \quad (2.1)$$

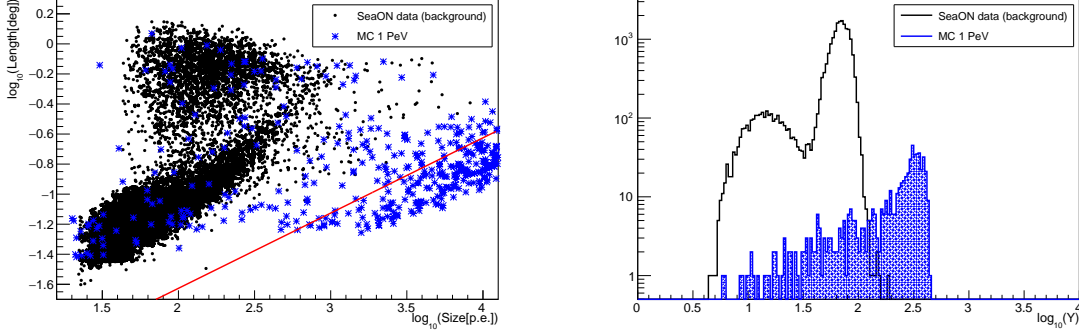


Figure 2: Left panel: scatter plot of *Size* and *Length* for background data and MC τ -lepton-induced air showers with primary energy of 1 PeV. The red line is the cut adopted in [7]. Right panel: projected distributions in the $\log_{10}Y$ direction. See text for details.

with $\alpha = 63^\circ$. The corresponding projected distributions are shown in Fig. 2 (right panel). In [7], a cut at $\log_{10}Y=2.35$ was set, shown by the red line in Fig. 2. In case of short-duration observations (one-hour time scale), as those here proposed, we expect a smaller background contamination, therefore a reduced cut strength [16]. In particular, the cut has been optimised by studying a *Model Rejection Factor* (MRF) defined as:

$$\text{MRF} = \frac{\langle \mu^{90}(n_b) \rangle}{n_s} \quad (2.2)$$

where $\langle \mu^{90}(n_b) \rangle$ is the average 90% C.L. upper limit [18], n_b is the number of SeaON data re-scaled to one hour observation time and surviving to $\log_{10}Y$ cut, n_s is the number of MC τ -lepton-induced air showers after the cut. n_b and n_s are shown in Fig. 3 (left panel) as a function of the $\log_{10}Y$ cut. The MRF is shown in Fig. 3 (right panel) for different MC energies. A method for reconstructing the primary energy of up-going τ -lepton showers has not been implemented yet, however, the figure shows that the cut does not depend on it. This is due to the fact that the $\log_{10}Y$ distributions exhibit a universal behaviour, with a negligible dependence on energy and also zenith angle [7]. The $\log_{10}Y$ cut value has been chosen to minimise the ratio between the upper limit setting capability and the expected neutrino signal after the cut. In particular, we set the cut at $\log_{10}Y=2.1$. The cut has been studied also for larger d and we found that it can be relaxed, down to $\log_{10}Y=1.9$, because of a further reduction of the background.

The MC signal efficiency is around 80%, this value is however largely reduced when one considers the trigger efficiency. We estimated it on MC simulations, including the MAGIC response. It is defined as the ratio between the number of simulated showers with positive trigger decision and the total number of showers at generation level. It depends on the energy E_τ of the τ -lepton, on the distance r between the τ decay vertex and the detector, and on the impact distance d . The latter has been randomised in CORSIKA and also over the MAGIC camera FoV [7]. The total efficiency (trigger+ $\log_{10}Y$ cut) ranges between 5% and 20%, depending on E_τ and on r : in particular, it is larger for larger energies and smaller r . The identification efficiency should depend also on the zenith angle of the shower, but this dependence is negligible for $\theta > 83^\circ$, as demonstrated in [13].

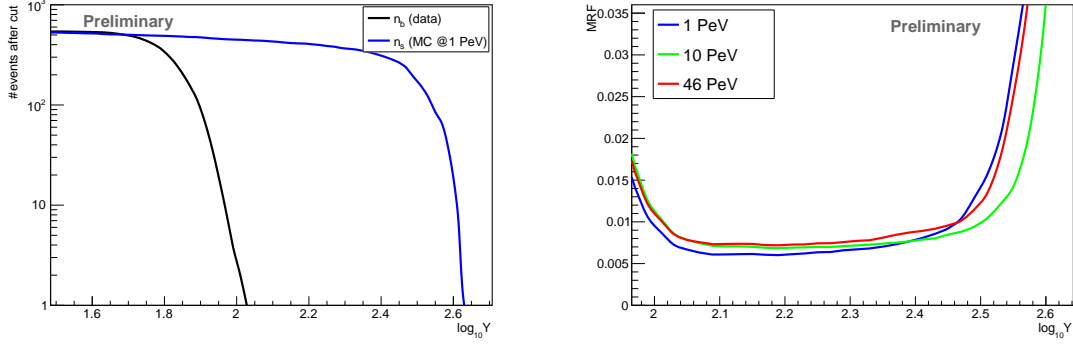


Figure 3: Left panel: cumulative distributions of events as a function of the $\log_{10} Y$ cut value. The black line refers to background data re-scaled to an equivalent of 1 hour; the blue line represents the MC signal at 1 PeV. Right panel: MRF as a function of $\log_{10} Y$.

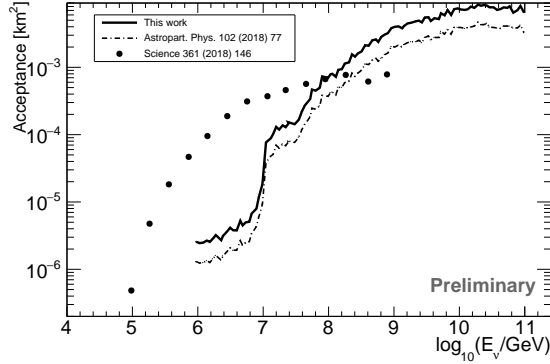


Figure 4: MAGIC acceptance to τ -lepton-induced air showers compared to previous work of MAGIC [7] and to IceCube acceptance as evaluated in [17]. See text for details.

2.4 Acceptance and event rate calculation

In order to estimate the neutrino flux from a given source, it is necessary to know the detector acceptance, i.e. the ratio between the number of reconstructed events N_{rec} and the number of generated events N_{gen} . In particular, the point-source acceptance A^{PS} for MAGIC has been evaluated as follows:

$$A^{PS}(E_{\nu\tau}, \theta, \phi) = \frac{\sum_{i=1}^{N_{FoVcut}} P_i(E_{\nu\tau}, E_{\tau}, \theta) \times \sigma_i(\theta) \times \epsilon_{\text{eff},i}(E_{\tau}, r, d)}{N_{gen}}. \quad (2.3)$$

$P_i(E_{\nu\tau}, E_{\tau}, \theta)$ is the probability that a neutrino of given energy $E_{\nu\tau}$ and zenith θ produces a τ -lepton of energy E_{τ} . $\sigma_i(\theta)$ is the cross-section evaluated for an interaction volume given by a cylinder of radius 50 km and height 10 km. The calculation takes into account the density profile of the Earth and a water layer of thickness of 3 km (for more details see [13]). $\epsilon_{\text{eff},i}(E_{\tau}, r, d)$ is the trigger+cut efficiency described above. N_{FoVcut} is the number of τ -leptons with decay vertex inside the MAGIC FoV. The acceptance of MAGIC is shown in Fig. 4 between 1 PeV and 100 EeV. The dashed line corresponds to the acceptance evaluated with the cuts adopted in [7], whereas the solid line is the acceptance evaluated in this work, showing an improvement by a factor ranging between 1.8 and

2, depending on the energy. The performance of MAGIC is compared to IceCube. The points in Fig. 4 show the effective area of IceCube evaluated for the online through-going track ("EHE") selection at the most favourable conditions (in energy and direction) [17]. The total number of expected signal events has been finally evaluated by considering the flux prediction evaluated for the AGN PKS 2155-304 in high-state activity as a benchmark flux [19], and the acceptance shown in Fig. 2.4 (solid line). The resulting expected event rate is $n_s=1.4 \times 10^{-4}/3\text{h}$. The systematic uncertainties of the event rate are related to the neutrino-nucleon cross section and to the τ -lepton energy loss. They range between 10% and 40% as shown in [7].

3. Analysis of IceCube-140611A with MAGIC

The analysis described above has been applied on IceCube-140611A observations. About 1.34 hours of data were collected by following the source when it was passing in the optimal neutrino visibility window. The observations have been performed in standard observation mode, usually adopted for gamma-ray sources. The number of reconstructed stereo events with MAGIC pointing below the horizon ($Z_d > 90^\circ$) and here selected is 3643. The *Size*- and the *Length*-parameters of

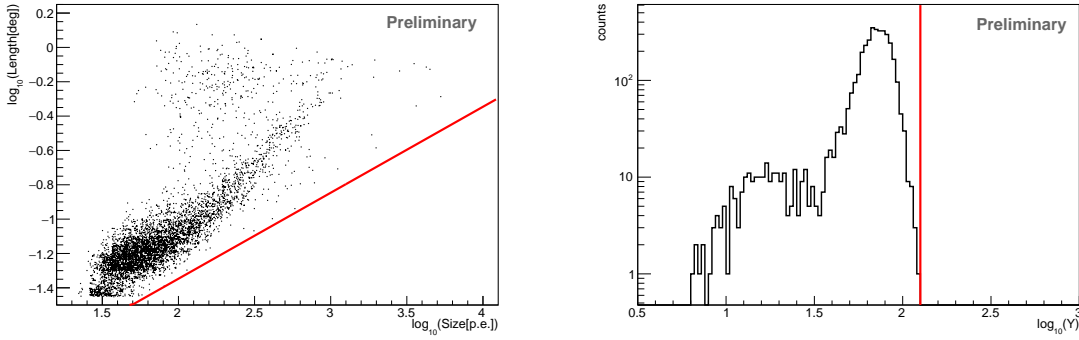


Figure 5: Left panel: scatter plot of *Size* and *Length* for IceCube-140611A data. Right panel: distributions of IceCube-140611A data projected along the selection line $\log_{10}Y$. The cut at $\log_{10}Y=2.1$ is highlighted by the red line.

those data are shown in Fig. 5 (left panel). The corresponding $\log_{10}Y$ distribution are reported in Fig. 5 (right panel).

The neutrino flux upper limit has been calculated at 90 % C.L. as follows:

$$\Phi^{90\text{C.L.}} = \frac{\mu^{90\text{C.L.}}(n_b, n_{obs})}{n_s} \times \Phi(E_{\nu_\tau}), \quad (3.1)$$

where $\mu^{90\text{C.L.}}(n_b, n_{obs})=2.44$, as no candidate neutrino events are observed and $\Phi(E_{\nu_\tau})$ is a reference spectrum. We assume $\Phi(E_{\nu_\tau})=10^{-8}E^{-2} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$. Since $\Delta T=1.34 \text{ h}$, the 90% C.L flux limit on IceCube-140611A is therefore:

$$E^2 \Phi^{90\text{C.L.}} < 4 \times 10^{-4} \text{ GeV cm}^{-2} \text{ s}^{-1}. \quad (3.2)$$

4. Conclusions

In this work, we have investigated the capabilities of MAGIC as a high-energy neutrino detector. MAGIC can observe neutrinos in the PeV-EeV energy range, through the Earth-skimming channel, by discriminating the τ -lepton signal from the background of very inclined cosmic rays. An upper limit on the flux of neutrinos from the direction of IceCube-140611A has been calculated. Even if the sensitivity of MAGIC is limited by the short observation time, we have demonstrated that for energies above \simeq PeV its acceptance is comparable to (or larger than) IceCube effective area (the latter being evaluated in the most favourable conditions [12]). For neutrino sources with hard spectra and short outbursts (up to week time scales), MAGIC data-taking in Earth-skimming mode can therefore potentially complement the observations by conventional neutrino telescopes, especially if the observations are performed following a trigger issued by dedicated experiments like IceCube.

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