

## Search for tau neutrinos with the MAGIC telescopes: improving selection criteria\*

Marina Manganaro<sup>1,a</sup>, Leonora Kardum<sup>1</sup>, Elisa Bernardini<sup>2,3</sup>, Michele Doro<sup>4</sup>, Dariusz Gora<sup>5</sup>, Saša Mićanović<sup>1</sup>, Tomislav Terzić<sup>1</sup>, and Martin Will<sup>6</sup> on behalf of the MAGIC Collaboration<sup>7</sup>

<sup>1</sup>University of Rijeka, Department of Physics, 51000 Rijeka

<sup>2</sup>Deutsches Elektronen-Synchrotron (DESY), D-15738 Zeuthen, Germany

<sup>3</sup>Humboldt University of Berlin, Institut für Physik D-12489 Berlin Germany

<sup>4</sup>Università di Padova and INFN, I-35131 Padova, Italy

<sup>5</sup>Institute of Nuclear Physics Polish Academy of Sciences, PL-31342 Krakow, Poland

<sup>6</sup>Max-Planck-Institut für Physik, D-80805 München, Germany

<sup>7</sup>the full list of MAGIC members is available at: [wwwmagic.mppmu.mpg.de](http://wwwmagic.mppmu.mpg.de)

**Abstract.** MAGIC, a system of two Cherenkov telescopes located at the Roque de los Muchachos Observatory (2200 a.s.l.) in the Canary Island of La Palma, has lately been engaged in an unconventional task: the search for a signature of particle showers induced by earth-skimming cosmic tau neutrinos arising from the ocean, in the PeV to EeV energy range. When pointing at the sea, the MAGIC telescopes can collect data in a range of about 5 deg in zenith and 80 deg in azimuth: the analysis of the shower images from ~30 hours of data, together with the simulations of upward-going tau neutrino showers, shows that the air showers induced by tau neutrinos can be discriminated from the hadronic background coming from a similar direction. We have calculated the point source acceptance and the expected event rates, assuming an incoming  $\nu_\tau$  flux consistent with IceCube measurements, and for a sample of generic neutrino fluxes from photo-hadronic interactions in AGNs and GRBs. A 90% C.L. upper limit on the tau-neutrino point source flux of  $2.0 \times 10^{-4} \text{ GeV cm}^{-2} \text{ s}^{-1}$  has been obtained. The presented results can also be important for future Cherenkov experiments such as the Cherenkov Telescope Array. This next generation ground-based observatory can have a much better possibility to detect  $\nu_\tau$ , given its larger FOV and much larger effective area.

## 1 Introduction

The consolidated discovery by IceCube (of an astrophysical flux of high-energy neutrinos [1] has confirmed the theoretical expectations in[2–5]: indeed those very energetic neutrinos are produced in astrophysical objects by the decays of charged pions created in cosmic-rays interactions with radiation or gas. The pions produce then neutrinos which can travel long distances undisturbed and tracking back with an impressive precision the origin of the cosmic acceleration. In this exciting picture, recently made more interesting by the first multi-messenger detection including a neutrino

\*original title was: Search for tau neutrinos with the MAGIC telescopes: the quest continues

<sup>a</sup>e-mail: [marina.manganaro@phy.uniri.hr](mailto:marina.manganaro@phy.uniri.hr)

[6], the MAGIC (Major Atmospheric gamma-ray Imaging Cherenkov) telescopes have played the role of Very-high-energy (VHE, E 100GeV) counterpart (together with H.E.S.S.–High Energy Stereoscopic System– and VERITAS–Very Energetic Radiation Imaging Telescope Array System–) in the collection of the broadband data. The observation by IceCube of the neutrino event 170922A in spatial coincidence with the  $\gamma$ -ray emitting blazar TXS 0506+056 during an active phase encourages the search for other possible blazars behaving as "neutrinos factories". After the IceCube detection of event 170922A, MAGIC went on observing the source for almost 40 hours, and the analysis of those data together with other quasi-simultaneous multi-wavelength data have been used to model the emission with a novel one-zone lepto-hadronic model, based on interactions of electrons and protons co-accelerated in the jet with external photons originating from a slow-moving plasma sheath surrounding the faster jet spine [7].

In general, the observed neutrino flux by IceCube and its composition is in agreement with equal fractions of all neutrino flavours [8, 9]. The possibility in IceCube to identify  $\nu_\tau$  is under investigation [10]: double cascade event topologies are only produced in tau-neutrino interactions above an energy threshold of  $\sim 100$  TeV. The detection of  $\nu_\tau$  is very important from both the astrophysical and particle physics point of view. It would give new information about the astrophysical  $\nu_\tau$  flux and shed light on the emission mechanisms at the source, test the fundamental properties of neutrinos over extremely long baselines, and better constrain new physics models which predict significant deviations from equal fractions of all flavors.

## 2 Observations with MAGIC

MAGIC is a stereoscopic system of two Cherenkov telescopes, located on the Canarian island of La Palma at 2200m above the sea level. Devoted to the study of VHE  $\gamma$ -rays from extragalactic and galactic sources, they could also be pointed to a specific direction towards the surrounding Atlantic ocean and search for signatures of air showers induced by PeV-EeV  $\nu_\tau$ s skimming from the water [11] in that special configuration. If  $\nu_\tau$ s interact close to the Earth surface, the so-called Earth's skimming neutrinos [12–14] can produce tau leptons which can emerge from the Earth, decay and produce extended air showers. If the decay vertex of a  $\tau$  lepton is close enough to the telescopes, it can be detected and distinguished from proton and nuclei induced showers through event parameter selection. Above PeV energies, the Earth becomes opaque to  $\nu_e$  and  $\nu_\mu$ , while the  $\nu_\tau$  flux is regenerated through subsequent  $\tau$  lepton decays to neutrinos. At high-energies, the  $\nu_\tau$  interacts in the Earth producing a  $\tau$  lepton which in turn decays into a  $\nu_\tau$  with lower energy due to its short lifetime. The regeneration chain  $\nu_\tau \rightarrow \tau \rightarrow \nu_\tau$ , continues until the  $\tau$  lepton reaches the detector. Observing on the "sea window" ([90-95]deg in Zenith angle and [-100 20] in Azimuth angle), MAGIC collected 30 hours of data in dark time and in good weather conditions at the horizon.

## 3 Monte Carlo simulations

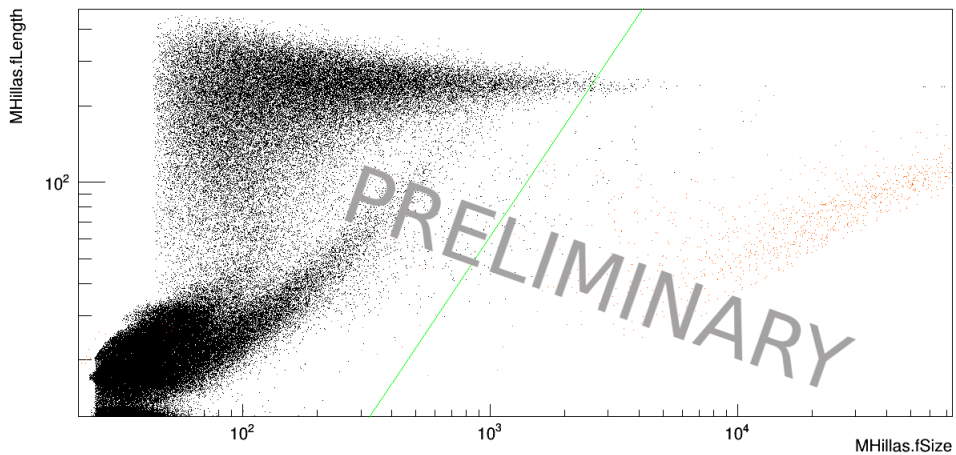
To support this unconventional datataking, special Monte Carlo simulations of  $\tau$  induced showers at different injection energies have been created. The software chain makes use of the ANIS (All Neutrino Interaction Simulation) code [15] to simulate signatures expected from neutrino-induced showers. CORSIKA [16] has been used to simulate the development of  $\tau$ -induced showers and their Cherenkov light production. The decays of  $\tau$  leptons have been simulated by PYTHIA [17]. The output of CORSIKA is then finally passed to a simulation of atmospheric extinction and MAGIC telescope response [18]. From the MonteCarlo studies it resulted that the main background is consisting in proton induced showers.

## 4 Signal-background discrimination

The details of the selection criteria and of the whole analysis performed on 30 hours of MAGIC data are reported in [20]. The main parameters characterizing the Cherenkov showers, called Hillas parameters [19] of the showers have been used to study the sample and to identify the selection criteria to be applied. In particular Fig. 2 of [20], left panel, shows the 2D distributions of measured events in the Hillas Length vs Size parameters plan and the corresponding cut. On this first sample of data, no events have survived the selection.

## 5 Improving selection criteria with machine learning techniques

In [20] a 90% C.L. upper limit on the tau-neutrino point source flux of  $2.0 \times 10^{-4} \text{GeV cm}^{-2} \text{s}^{-1}$  has been obtained: the result is not competitive with IceCube or Pierre Auger Observatory, due to the larger duty-cycle of those instruments (see Fig. 11 of [20]). However, MAGIC limits are almost

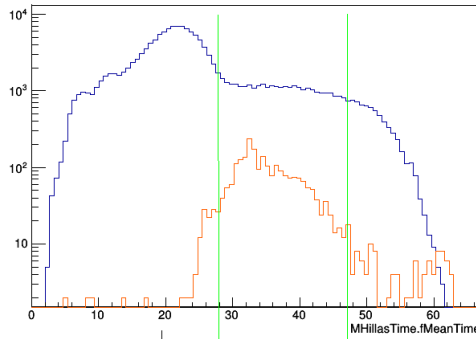


**Figure 1.** New selection cut (green line) on a larger sample of data (40 hours), obtained using a Fisher Discriminant analysis. Black points are the measured events (background + signal), orange the simulated signal. Survived events from the present cut will have to pass a further selection step which is shown in Fig.2.

background free, differently from IceCube detector, thus the tau neutrino sensitivity would increase linearly with the accumulated observation time. The next-generation Cherenkov telescopes, i.e. the Cherenkov Telescope Array, will have much larger FOV (in extended observation mode), and consequently a larger effective area. As recently shown in [21] the expected event rate will be at level of 1 event during 200 hours making CTA tau neutrino searches more promising. Thus, such additional data can be also useful when CTA prospects will be considered and quantitatively evaluated.

Further observations of the sea with MAGIC would help to improve and further develop the technique used in [20]. In particular a way of making the analysis more efficient and sensitive in prevision of more data to process is under development and includes the employment of machine learning techniques. Fisher Discriminant (see Fig. 1) and Genetic Algorithms are being tested to both observed and simulated data in order to create a more complex selection criteria based also on a further Hillas parameter, the Mean Time (Fig. 2).

The possibility to observe  $\tau$ -induced showers tracing back to a neutrino from an astrophysical source are very low being the MAGIC sea window just 5 deg in Zenith angle, but still exciting enough to pursue the quest.



**Figure 2.** Distribution of the Hillas Mean time parameter (blue data, orange simulations). The green lines individuate identify the most efficient cut as found by the application of the Genetic algorithm.

## References

- [1] Aartsen M. G. et al., *Phys. Rev. Lett.* **113**, 101101 (2014)
- [2] Margolis, S. H. Schramm, D. N. and Silberberg, R., *Astrophys. J.* **221**, 990 (1978)
- [3] Stecker, F. W. *Astrophys. J.* **228**, 919 (1979)
- [4] Biermann, P. L. *Cosmic Gamma Rays, Neutrinos, and Related Astrophysics*, in Proc. of the NATO Advanced Study Institute, Erice, Italy, pp. 21 (1989)
- [5] Michalak, W., Wdowczyk, J. and Wolfendale, A. W. J. *Phys. G* **16**, 1917 (1990)
- [6] The IceCube Coll., *Science* **361**, eaat1378 (2018)
- [7] Ansoldi S., et al. *ApJL*, **863**, L10 (2018)
- [8] Aartsen M. G. et al., *Phys. Rev. Lett.* **114**, 171102 (2015)
- [9] Aartsen M. G. et al., *ApJ*, **809**, (1), 98 171102 (2015)
- [10] Stachurska, J, et al., *Neutrino 2018 - XXVIII International Conference on Neutrino Physics and Astrophysics*, <https://zenodo.org/record/1301122#.W-WBjHBRfCJ> (2018)
- [11] Gaug M. , et al., *Proc. of I.C.R.C. 2007 (Merida)* 1273 (2007)
- [12] Fargion D., *ApJ*, **570**, 909 (2002)
- [13] Feng, J.J., et al. *Phys. Rev. Lett.*, **88**, 161102 (2002)
- [14] Bertou, X., et al., *Astropart. Phys.* **17**,183 (2002)
- [15] Gazizow A. Z., and Kowalski M., *Comput. Phys. Commun.*,**172** 203 (2005)
- [16] Heck D., et al., *Report FZKA 6019* (1998)
- [17] Sjöstrand, T., *JHEP* **0605**, 026 (2006)
- [18] Zanin R. *Proc. of 33rd I.C.R.C. (Rio de Janeiro)* (2013)
- [19] Hillas, M. A. *Nucl. Phys. Proc. Suppl.*, **52B**, 29 (1997)
- [20] Ahnen M. L., et al. , *Astropart. Phys.* **102**, 77 (2018)
- [21] Góra D. , and Bernardini E., *Astropart. Phys.* **82**, 77 (2016)
- [22] Góra D. et al., *Proc of EPS-HEP (Venice) (2017)*, PoS(EPS-HEP2017)017, arXiv:1710.04165