

# Search for astrophysical PeV gamma rays from point sources with *Carpet-2*

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**Abstract.** Early results of the search for  $E_\gamma > 1$  PeV cosmic photons from point sources with the data of *Carpet-2*, an air-shower array equipped with a 175 m<sup>2</sup> muon detector, are presented. They include 95% CL upper limits on PeV photon fluxes from stacked directions of high-energy IceCube neutrino events and from four predefined sources, Crab, Cyg X-3, Mrk 421 and Mrk 501. An insignificant excess of events from Mrk 421 will be further monitored. Prospects of the use of the upgraded installation, *Carpet-3* (410 m<sup>2</sup> muon detector), scheduled to start data taking in 2019, for searches of  $E_\gamma > 100$  TeV photons, are briefly discussed.

## 1 Introduction

The data on astrophysical photons with energies above  $\sim 0.1$  PeV are presently very scarce (no significant detection so far), though their observation or non-observation is very important for understanding many astrophysical and particle-physics phenomena. The cosmic gamma rays of  $E_\gamma \sim (0.1 - 10)$  PeV produce electron-positron pairs on the Cosmic Microwave Background [1]. This process limits their mean free path to the size of the Galaxy. If no new physics is assumed, every single detected astrophysical photon of this energy is certainly Galactic. This makes PeV photons very useful in constraining unknown astrophysical sources, notably those of high-energy neutrinos detected by IceCube (see e.g. Refs. [2, 3] for more details). In addition, any observation of an air shower induced by a primary gamma ray of that high energy would strongly constrain hypothetical models with tiny, though presently not excluded, deviations from the Lorentz invariance [4]. Contrary, any observation of PeV photons coming from an extragalactic source would suggest new physical phenomena, for instance, the axion-photon mixing (see e.g. Ref. [5] for a review and Ref. [6] for general theory). Sadly, no astrophysical PeV photons have been firmly detected yet.

While future large-scale instruments like TAIGA [7] or LHAASO [8] aim at this energy band, this work presents early results of the search for cosmic photons with energies  $E_\gamma \gtrsim 1$  PeV with the *Carpet-2* extensive air shower array at the Baksan Neutrino Observatory of INR RAS.

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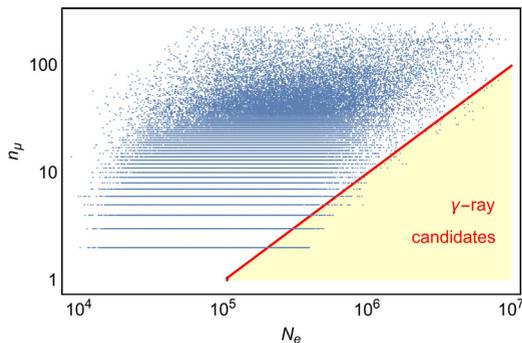
## 2 The method

*Carpet-2* detects the electromagnetic component of extensive air showers by means of its surface array of scintillator detector stations, while the muonic component is detected by the underground scintillator detector. The installation is described in detail elsewhere [9, 10]. For the present work, we use the data recorded in 1999–2011 (total of 3080 live days, 115821 events which passed the quality cuts described in Ref. [11]). The number of  $E \geq 1$  GeV muons in the 175 m<sup>2</sup> underground detector,  $n_\mu$ , together with the shower size  $N_e$ , which is reconstructed from surface-detector data, arrival direction and time represent the basic information we use for each event. Since the showers initiated by primary gamma rays are muon-poor compared to hadronic ones,  $n_\mu$  helps to distinguish the two kinds of primaries. Since both  $n_\mu$  and  $N_e$  scale roughly linearly with the primary energy, we use their ratio,  $n_\mu/N_e$ , as the observable to separate gamma-like events, while  $N_e$  is used to estimate the primary energy.

Nowadays, PeV gamma-ray astronomy is in high demand after the IceCube discovery of PeV neutrino events [12], because neutrinos and photons are expected to be co-produced in hadronic interactions. However, at the time the installation started data taking, its primary goal was to study the structure of hadronic showers and not to search for elusive photon-induced events. Therefore, unfortunately, the condition  $n_\mu > 1$  was included in the trigger, so that muon-poor ( $n_\mu = 0$  and 1) events were not recorded. This criterion reduced considerably the efficiency of the detector for gamma-ray primaries at lower energies; however, at  $E_\gamma \gtrsim \text{PeV}$ , even photon-induced showers normally have  $n_\mu \geq 2$ .

To estimate quantitatively the efficiency of the detection of primary photons and the precision of the reconstruction of EAS parameters, Monte-Carlo (MC) simulations were performed with the CORSIKA package [13] (v. 7.4003), using the hadronic-interaction models QGSJET-01c [14] and FLUKA-2011.2c [15]. Simulated showers were thrown randomly on the installation, whose response was simulated with additional dedicated MC procedures (full simulation, to be published). For the resulting artificial events, observable parameters (geometry,  $N_e$  and  $n_\mu$ ) were reconstructed in the same way as it is done for the data. The reconstruction efficiency for primary photons integrated over the field of view (zenith angles  $\theta \leq 40^\circ$ ) is  $\sim 16\%$  at  $E_\gamma \sim 1$  PeV and quickly reaches  $> 95\%$  at  $E_\gamma \sim 5$  PeV. The arrival directions of  $E_\gamma > 1$  PeV photons are reconstructed with an accuracy of  $1.8^\circ$  (68% CL),  $2.65^\circ$  (90% CL).

Based on the MC simulations, we determined (see Ref. [11]) the following conditions for an event to be considered as candidate for a  $E_\gamma > 1$  PeV photon:  $N_e \geq N_e^0$ , where  $N_e^0$  is chosen in such a way that this condition selects 95% of  $E_\gamma > 1$  PeV MC photons;  $n_\mu/N_e \geq C$ , where  $C$  determines the median of the distribution in  $n_\mu/N_e$  among simulated photons with  $E_\gamma > 1$  PeV. Figure 1 presents these cuts on the  $N_e - n_\mu$  plane with real events superimposed; 523 events find themselves in the shaded area and are considered as photon candidates. Though some or all of them might be actually unusual muon-poor showers caused by primary hadrons (dedicated MC simulations to determine the probability of such fluctuations are ongoing: since we are discussing the very tail of the distribution, these simulations require very large total number of generated events and a careful account of the primary composition), their total number is sufficiently low that any significant directional correlation with a source would serve as an alert of their possible photon nature. Therefore, we search for statistically significant excesses in the number of observed photon candidates with arrival directions close to predefined sources. The angle at which the correlation is searched for is determined as that containing 90% of reconstructed photons potentially coming from the source. The observed number of events within this angle from the source is then compared to that expected for isotropic distribution of arrival directions (with the zenith-angle dependence of the efficiency



**Figure 1.** Selection of photon candidate events on the  $N_e - n_\mu$  plane. Blue dots represent all Carpet-2 events which passed the quality cuts. Photon candidates (muon-poor events) are in the shaded region. See the text for more details.

**Table 1.** Upper limits on the integral flux of gamma rays above 1 PeV from four pre-defined sources. For Mrk 421, the best-fit flux is  $7.6 \times 10^{-14} \text{ cm}^{-2} \text{ s}^{-1}$ .

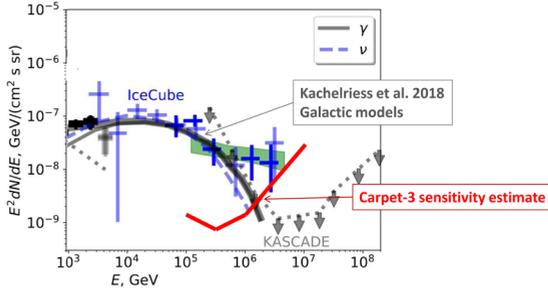
Source	photon candidates:		Flux ( $E_\gamma > 1 \text{ PeV}$ ), 95% C.L. upper limit, $\text{cm}^{-2} \text{ s}^{-1}$
	expected	observed	
Crab	0.4	0	$2.1 \times 10^{-13}$
Cyg X-3	1.2	2	$2.0 \times 10^{-13}$
Mrk 421	1.1	3	$2.7 \times 10^{-13}$
Mrk 501	1.1	1	$1.4 \times 10^{-13}$

taken into account). The flux, or the upper limit on it, may then be determined with the account of the direction-dependent exposure of the experiment [11].

### 3 Results

To avoid multiple tries and hardly controllable corrections to significance, targets for the point-source search were determined before looking at the data. They include: (i) stacked arrival directions of high-energy IceCube neutrino events; (ii) individual arrival directions from public IceCube alerts in the field of view of *Carpet-2*, for both directional and temporal correlations; (iii) four predefined astrophysical sources listed in Table 1. The searches related to IceCube neutrinos are discussed in detail in Ref. [11]. We selected 34 published IceCube track-like events with declinations in the field of view when *Carpet-2* was taking data. Given individual geometry uncertainties of these events and the *Carpet-2* angular resolution, 90% of the signal is expected to be found within  $3.0^\circ$  from the directions. We found 10 photon candidate events within  $3.0^\circ$  from these 34 IceCube arrival directions, while 13.6 are expected from isotropy. This resulted in the 95% CL upper limit on total steady flux of  $E_\gamma > 1 \text{ PeV}$  photons from these 34 directions of  $8.5 \times 10^{-15} \text{ cm}^{-2} \text{ s}^{-1}$ . In addition, one event was in the *Carpet-2* field of view, a  $\approx 100 \text{ TeV}$  neutrino detected on December 10, 2016. Within a period of 3 days centered on the neutrino arrival time, no candidate events within  $3.0^\circ$  were observed while 0.02 are expected from isotropy; the resulting 95% CL upper limit on the fluence of the corresponding flare in  $E_\gamma > 1 \text{ PeV}$  photons is  $4.4 \times 10^{-5} \text{ PeV/cm}^2$ .

For astrophysical point sources, whose positions are known exactly, the optimal search angle is just the 90% CL angular resolution of the experiment,  $2.65^\circ$ . The results of the search are summarized in Table 1. A weak excess from the direction of Mrk 421 is statistically consistent ( $2.4\sigma$ ) with a fluctuation of the isotropic background. We will monitor it in future data.



**Figure 2.** Estimated Carpet-3 sensitivity (95% CL, one year of live time) to the diffuse gamma-ray flux (red line) superimposed on the plot with Galactic model predictions from Ref. [16].

## 4 Conclusions and outlook

These results are based on the data obtained with the 175 m<sup>2</sup> muon detector, shower cores in the central unit of 200 m<sup>2</sup> area and the trigger of  $n_\mu > 1$ . In 2018, the installation started to collect data with the new, “photon-friendly” trigger which accepts also events with  $n_\mu = 0$  and 1. This would allow to lower the energy threshold for photon searches. But a truly big step towards a better gamma-ray sensitivity will be made in 2019, when it is planned that the upgraded *Carpet-3* installation will start taking data. Its 410 m<sup>2</sup> muon detector, already installed, will allow for a crucial improvement in the gamma-hadron separation, while additional surface-detector stations will increase the collecting area. Preliminary MC estimates demonstrate that one year of *Carpet-3* live data taking would be sufficient to probe Galactic models of IceCube neutrinos with the diffuse flux of  $E_\gamma > 100$  TeV photons, see Fig. 2. The corresponding improvement is expected for point sources as well. A similar sensitivity at PeV, though on longer time scales, is expected by TAIGA and LHAASO.

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