PROCEEDINGS OF SCIENCE

Carpet results on astrophysical gamma rays above 100 TeV

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Carpet is an air-shower array at Baksan, Russia, equipped with a large-area muon detector, which makes it possible to separate primary photons from hadrons. We report first results of the search for primary photons with energies $E > 100$ TeV. The experiment's ongoing upgrade and future sensitivity are also discussed.

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1. Introduction

Gamma-ray astronomy in the PeV domain has several tasks of recognized importance (for a review, see e.g. Ref. [1]). They include localization of astrophysical objects and environments where highest-energy Galactic cosmic rays are accelerated [2], distinguishing [3, 4] between Galactic and extragalactic origin of high-energy astrophysical neutrinos detected by IceCube [5], and now also by Baikal-GVD [6], and search for new physics manifesting itself in anomalies of gamma-ray propagation [7, 8]. The method to detect astrophysical gamma rays of such high energies is determined by two facts: these events are rare and the primary photon interacts in the upper atmosphere. Cosmic-ray detectors recording extensive air showers (EAS) are therefore best suited for the studies, however, special methods are required to separate events caused by primary gamma rays from huge background of hadronic cosmic rays. One of the most efficient approaches is to use separate detectors for electromagnetic and muon components of the EAS: gamma-induced showers are muon-poor as compared to cosmic-ray induced ones. Here we report preliminary results of the search for PeV astrophysical gamma rays by this method.

2. Experiment and data

2.1 The Carpet–2 experiment

Carpet–2 is a detector of extensive air showers situated at the Baksan Neutrino Observatory in Northern Caucasus. It uses the surface array of scintillator detector stations to record the electromagnetic EAS component, while the muon component is recorded by its underground scintillator detector. For a description of the experiment, see Refs. [9, 10]. The surface detector determines the arrival direction and time, the core location and the shower size N_e, while the 175 m^2 underground detector determines the number n_μ of muons which hit the detector. The threshold of the muon detector is 1 GeV for a vertical muon. We perform Monte-Carlo simulations of air showers with CORSIKA [11] (v. 7.5600), using the hadronic-interaction models QGSJET-II.04 [12] and FLUKA-2011.2c [13]. Artificial events were produced by additional Monte-Carlo simulations of the installation, recorded and processed in the same way as the real data. We used two independent data sets described below for the data analysis.

2.2 Dataset I: $E_\gamma > 1$ PeV, 1999–2011

For the data recorded during the experiment run in 1999–2011 (3080 live days), the trigger conditions included at least two muons in the 175 m^2 detector, which is not the optimal cut for the search of muon-poor photon-induced showers at low energies. Simulations indicate that, for E_γ^{-2} primary photon spectrum which we assume throughout this study, the reconstruction efficiency integrated over the field of view is $\sim 17\%$ for $E_\gamma \sim 1$ PeV. The efficiency quickly rises with energy and depends on the zenith angle. The angular resolution of the experiment for primary photons with these energies is $\sim 4.2^\circ$, determined by the Monte-Carlo simulations. Quality cuts are described in Ref. [14]); 115821 events passed the cuts. Additional cuts aimed to separate photon candidate events on the $N_e - n_\mu$ plane were determined from simulations to maximize the efficiency of photon detection and to minimize the hadronic background; they correspond to the shaded area in Fig. 1, where the data are also shown. There are 310 photon candidate events in the data set.

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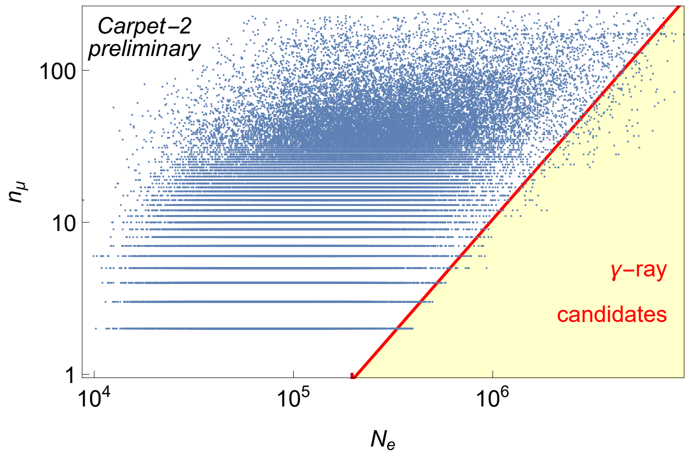

Figure 1: Photon candidate region on the $N_e - n_\mu$ plane, Dataset I, $E_\gamma > 1$ PeV (shaded). Blue dots represent data for all events in the dataset.

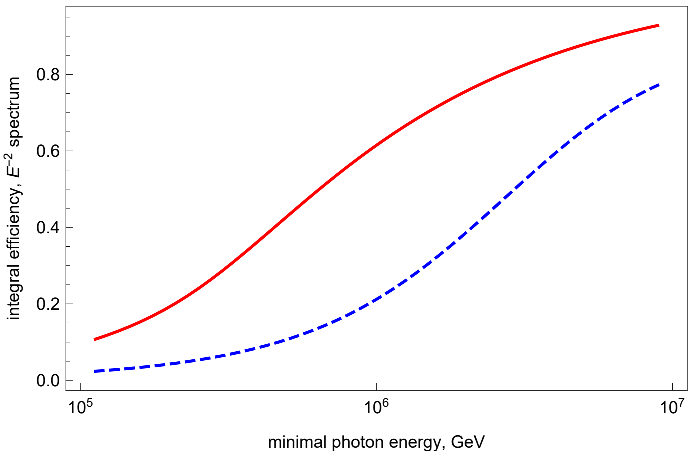

Figure 2: Efficiency of detection of gamma rays with $E_\gamma > E_{\min}$, assuming E_γ^{-2} primary spectrum. Blue dashed line: Dataset I, red full line: Dataset II.

2.3 Dataset II: $E_\gamma > 0.3$ PeV, 2018-2019

Motivated by post-IceCube interest in PeV gamma-ray astronomy, the experiment was relaunched in 2018 with the new trigger which allowed to record also events with zero or one muon in the detector. This resulted in lowering the threshold to $E_{\gamma,\min} = 300$ TeV, with the efficiency of $\sim 26\%$. Figure 2 compares the efficiencies for the two data sets. Here, we report results for 342 live days recorded in 2018-19; quality cuts were passed for 25876 events. For these trigger conditions and threshold energy, different photon-candidate cuts are optimal, see Fig. 3. There are 399 photon candidate events in this data set.

3. Results

3.1 Sky map of excesses

Point sources of gamma rays are expected to reveal themselves on the isotropic background,

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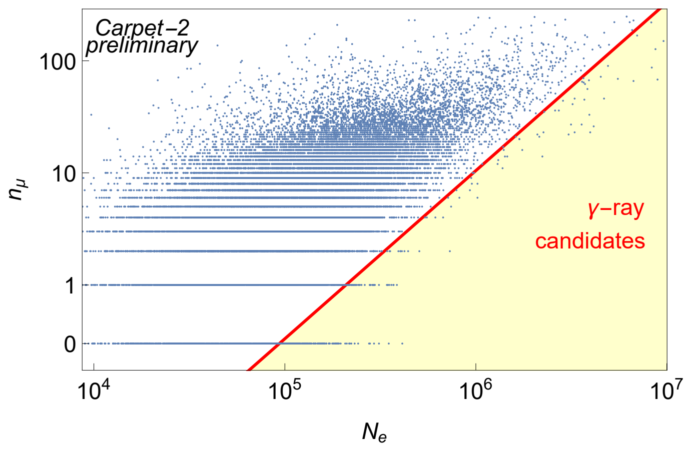

Figure 3: Same as Fig. 1 but for Dataset II, $E_\gamma > 300$ TeV.

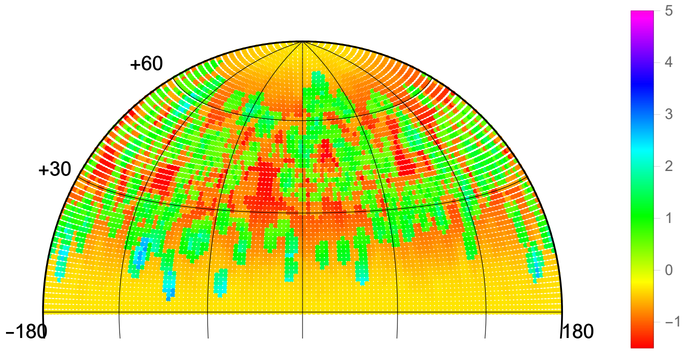

Figure 4: Skymap of excesses of counts of events for Dataset I, $E_\gamma > 1$ PeV. The inset presents the colour code of significances, in standard deviations corresponding to the observed Poisson probability. Note that the fluctuations are asymmetric because the number of events is always positive.

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which includes both diffuse photons and possible hadrons contaminating the data set. Assuming isotropy, one calculates the expected background for any given direction in the sky and compares with the real number of observed events from this direction, taking into account the angular resolution. A blind search for excesses may be performed with excess sky maps presented in Fig. 4 and Fig. 5 for two datasets.

3.2 Predefined sources

We have defined in advance the list of four sources to be monitored, in order to avoid additional, hard to calculate, corrections to the significance related to the "look-elsewhere effect". Preliminary results of the analysis above 1 PeV have been reported in Ref. [15] (see also Ref. [14] for PeV photons from the directions of IceCube events); here we refine these results and present also those for Dataset II of lower energies, see Table 1. Interestingly, Mrk 421 demonstrates a weak, $\sim (2-3)\sigma$, excess in both independent data sets (for Dataset I, this was pointed out in Ref. [15]). Gamma rays of the energies considered here should not arrive from extragalactic objects because of intense pair production on the cosmic microwave background [16]. With rather poor angular

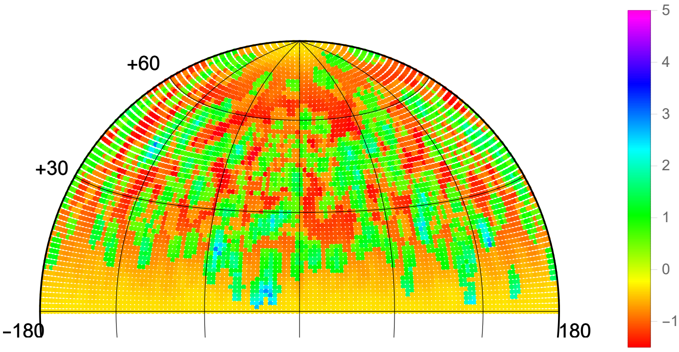

Figure 5: Same as Fig. 4 but for Dataset II, $E_\gamma > 300$ TeV.

Source name	Dataset I: $E_\gamma > 1$ PeV expected	observed	flux, cm^{-2} s^{-1}	Dataset II: $E_\gamma > 0.3$ PeV expected	observed	flux, cm^{-2} s^{-1}
Crab	0.69	0	$< 4.69 \times 10^{-13}$	0.95	4	$< 1.57 \times 10^{-11}$
Cyg X-3	1.75	2	$< 3.00 \times 10^{-13}$	2.08	1	$< 1.83 \times 10^{-12}$
Mrk 421	1.59	5	$< 6.32 \times 10^{-13}$	1.90	4	$< 5.45 \times 10^{-12}$
Mrk 501	1.70	0	$< 8.8 \times 10^{-14}$	1.93	1	$< 2.00 \times 10^{-12}$

Table 1: Results of the photon search from four predefined sources. Flux upper limits are 95% CL.

resolution of *Carpet-2*, one cannot exclude that these photons arrive from a different, Galactic, source, though a candidate source is unknown. Alternatively, this may be a statistical fluctuation. A more detailed study of this direction in the sky will be reported elsewhere.

4. Conclusions and outlook

This work reports preliminary results on the search of very-high-energy cosmic gamma rays with *Carpet-2*, a EAS detector at the Baksan Neutrino Observatory. Thanks to a 175 m^2 muon detector, separation of photon-induced showers from the bulk of cosmic-ray induced events becomes possible. We consider two datasets, Dataset I with large exposure and trigger conditions allowing for the search of $E_\gamma > 1$ PeV photons and Dataset II with smaller exposure but lower gamma-ray energy threshold, $E_\gamma > 0.3$ PeV. We present upper limits on the photon fluxes from a set of four predefined point sources. One of the sources, Mrk 421, demonstrates a weak excess in both independent data sets; its origin remains to be understood. Crab nebula demonstrates an insignificant excess at lower energies, Dataset II, and will be monitored. More results will be discussed at the conference.

The installation is being upgraded to *Carpet–3*, with the extended 410 m^2 muon detector. The new muon detector is already installed and it is planned to start data taking in the new configuration this fall, which should result in a crucial improvement in the gamma-hadron separation. Additional surface-detector stations will be installed to increase the collecting area. Preliminary simulations [15] allow to hope that one year of *Carpet–3* live data taking might probe Galactic models of IceCube neutrinos [17] with the diffuse photon flux at $E_\gamma > 100$ TeV.

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References

[1] P. Lipari and S. Vernetto, *Diffuse Galactic gamma ray flux at very high energy*, *Phys. Rev. D* **98** (2018) no.4, 043003 [arXiv:1804.10116 [astro-ph.HE]].

[2] S. Gabici *et al.*, *The origin of Galactic cosmic rays: challenges to the standard paradigm*, arXiv:1903.11584 [astro-ph.HE].

[3] M. Ahlers and K. Murase, *Probing the Galactic Origin of the IceCube Excess with Gamma-Rays, Phys. Rev. D* **90** (2014) 023010 [arXiv:1309.4077].

[4] O. E. Kalashev and S. V. Troitsky, *IceCube astrophysical neutrinos without a spectral cutoff and* 10^{15}-10^{17} *eV cosmic gamma radiation*, *JETP Lett.* **100** (2015) 761 [arXiv:1410.2600].

[5] M. G. Aartsen *et al. First observation of PeV-energy neutrinos with IceCube*, *Phys. Rev. Lett.* **111** (2013) 021103 [arXiv:1304.5356].

[6] A. D. Avrorin *et al.*, *Baikal-GVD: first results and prospects*, *EPJ Web Conf.* **209** (2019) 01015.

[7] S. V. Troitsky, *Axion-like particles and the propagation of gamma rays over astronomical distances*, *JETP Lett.* **105** (2017) 55 [arXiv:1612.01864].

[8] G. Galanti and M. Roncadelli, *Extragalactic photon-axion-like particle oscillations up to 1000 TeV*, *JHEAp* **20** (2018) 1 [arXiv:1805.12055 [astro-ph.HE]].

[9] J. Szabelski *et al.*, *Carpet-3 - a new experiment to study primary composition around the knee*, *Nucl. Phys. Proc. Suppl.* **196** (2009) 371 [arXiv:0902.0252].

[10] D. D. Dzhappuev *et al.*, *Search for cosmic gamma rays with the Carpet-2 extensive air shower array*, arXiv:1511.09397.

[11] D. Heck *et al.*, *CORSIKA: A Monte Carlo code to simulate extensive air showers*, Tech. Rep. 6019, FZKA (1998)

[12] S. Ostapchenko, *Monte Carlo treatment of hadronic interactions in enhanced Pomeron scheme: I. QGSJET-II model*, *Phys. Rev. D* **83** (2011) 014018 [arXiv:1010.1869 [hep-ph]].

[13] G. Battistoni *et al.*, *The FLUKA code: Description and benchmarking*, *AIP Conf. Proc.* **896** (2007) 31.

[14] D. D. Dzhappuev *et al.*, *Carpet-2 search for PeV gamma rays associated with IceCube high-energy neutrino events*, *JETP Lett.* **109** (2019) 226 [arXiv:1812.02662 [astro-ph.HE]].

[15] D. D. Dzhappuev *et al.*, *Search for astrophysical PeV gamma rays from point sources with Carpet-2, EPJ Web Conf.* **207** (2019) 03004 [arXiv:1812.02663 [astro-ph.HE]].

[16] A.I. Nikishov, *Absorption of high-energy photons in the Universe*, *Sov. Phys. JETP* **14** (1962) 393. [*ZhETF* **41** (1962) 549].

[17] A. Neronov, M. Kachelrieß and D. Semikoz, *Multimessenger gamma-ray counterpart of the IceCube neutrino signal*, *Phys. Rev. D* **98** (2018) 023004 [arXiv:1802.09983].

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