PROCEEDINGS OF SCIENCE

Hybrid method for study multi TeV gamma rays in the TAIGA astrophysical complex: methodics and results.

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The TAIGA astrophysical complex includes now 3 IACTs at the distance 300-500 m between each other and 1 km^2 area wide-angle timing array TAIGA-HiSCORE. At energies above 40 TeV, a hybrid approach to the detection of gamma-rays becomes possible - the detection of EAS by both IACTs and the TAIGA-HiSCORE installation. The main advantage of the joint operation of the IACTs and timing array HiSCORE is a good gamma/hadron separation by image parameters information, and core position, direction and energy reconstruction by the timing array data. In this paper the following topics of a hybrid method are discussed: data processing and analysis, a comparison experimental results with Monte-Carlo simulations, selection of the first events with the energy more than 100 TeV from Crab Nebula in 250 hours of observation. The data were taken during the period of installation deployment, with one IACT in operation and half of the area of TAIGA-HiSCORE installation.

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1. Introduction

Gamma-ray astronomy is a promising field of research of galactic and extragalactic sources of gamma radiation. Modern studies show that galactic objects, such as the Crab Nebula, are capable of generating radiation with energies above 100 TeV (HAWC [1], LHAASO [2]). But the origin of radiation (electromagnetic or hadronic) is not understood yet. Until now, most of gamma-rays with energies above 100 TeV are detected only by ground-based observatories that register the charged component of the EAS. This is due to the fact that such instruments are capable of conducting observations regardless of weather conditions and seasons. Observatories that register Cherenkov radiation of the EAS are able to work only on clear moonless nights and it is necessary to have a high effective area to accumulate significant statistics. One of the aims of TAIGA gamma-ray observatory is to detect gamma-rays with energy more than 100 TeV by Cherenkov light EAS installation with 1 km^2 size effective area [3, 4].

2. TAIGA gamma-ray astrophysical complex

Currently, on an area of ~1 km^2, the TAIGA Astrophysical complex [5] (Fig. 1) includes three atmospheric Cherenkov telescopes of the TAIGA-IACT installation [6], wide-angle Cherenkov detectors of the TAIGA-HiSCORE installation [7, 8] (High Sensitivity COsmic Rays and gamma Explorer) and other installations.

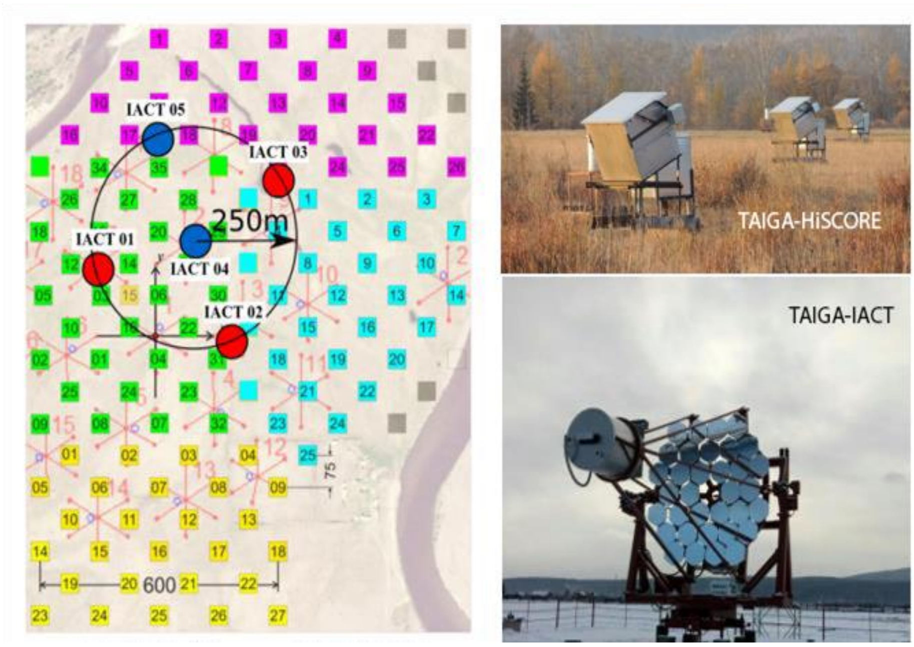

Fig. 1. TAIGA gamma-ray observatory

To cover the entire energy range available for observation, the TAIGA experiment uses three modes of detecting of Cherenkov radiation of EAS: standalone mode, stereo and hybrid mode (Fig. 2). The standalone mode is used to detect gamma-rays with energies of more than 3-4 TeV with only one IACT. To detect gamma-rays with energies above 10 TeV, it is possible to use a stereoscopic approach – the EAS is detected by two or more IACTs.

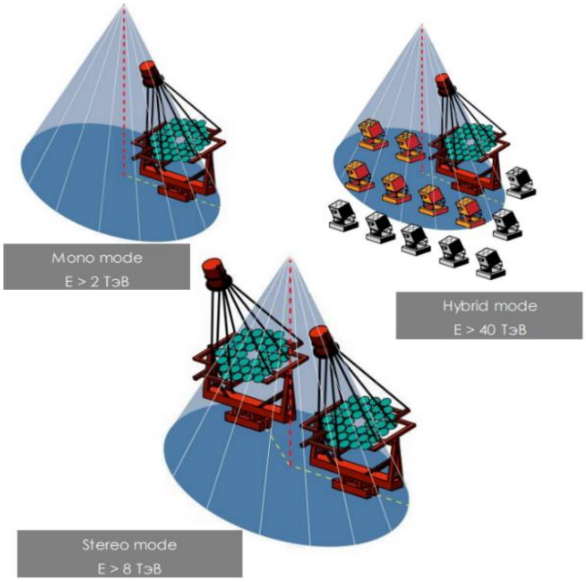

Fig. 2. Modes of registration of EAS in the TAIGA experiment

The hybrid approach combines data obtained by TAIGA-IACT and TAIGA-HiSCORE installations. This method is unique for modern gamma experiments and is aimed to register gamma quanta with energies of more than 40 TeV. An energy, an arrival direction and the position of the axis of the EAS are reconstructed by analyzing the data of the TAIGA-HiSCORE installation. A type of primary particle is determined by the image parameters detected by the IACTs [5].

2.1 TAIGA-HiSCORE

The TAIGA-HiSCORE installation is a network of 120 wide–angle Cherenkov detectors (stations) located on an area of 1.1 km^2, grouped into 4 clusters and designed to detect Cherenkov light of EAS. The distance between the detectors is 106 m. Every i - station measures a signal amplitude A(i), Cherenkov light flux Q(i), and time T(i) with 1 ns accuracy. Primary reconstruction of the EAS zenith (θ) and azimuth angle (φ) is done by fitting time T(i), with plane model of the shower front. Reconstruction of the shower core position is done by fitting A(i) of the data with the amplitude distance function (ADF) [6]. Final reconstruction of (θ,φ) with known core position X0, Y0 is done by fitting T(i) with the curved model of shower front [6]. This step results to significant improvement of angular resolution. Fitting Cerenkov light Q(i) by lateral distribution function [6] one can measure energy of EAS. The accuracy of arriving direction reconstruction is estimated as 0.1°-0.4°, of core position as 10-40 m, of energy estimation as 0.05-0.2 (in log scale) in dependence on number of hit stations [6].

2.2 TAIGA-IACT

The methods of identification of primary high-energy gamma-rays from hadron background in ground-based gamma astronomy have been developed during last two decades and reach very high level of efficiency. In experiment TAIGA every telescope has an alt-azimuth mount, a 4.3 m diameter reflector and a recording camera in focus. The reflector consists of separate spherical mirrors of the Davis –Cotton system with an area of ∼10 m^2 and a focal length of 4.75 m [10, 11]. The cameras of the telescopes provide an angular view of 9.6° and include matrices consisting of 600 PMT (pixels) with a photocathode diameter of 2 cm each (XP1911). Each pixel has an angular size of 0.36° [11].

2.2.1 Reconstruction of TAIGA-IACT events

Data processing of the TAIGA-IACT installation consists of the following steps:

1. Reconstruction of the amplitude matrix Am (Xi, Yi) (Xi, Yi – pixel coordinates): subtraction of the pedestal values in each pixel, recalculation of the amplitude values of the currents into photoelectrons, introduction of corrections for the sensitivity of the PMT.

2. Cleaning procedure – cleaning the Cherenkov image of the EAS in the telescope camera from pixels, the amplitude of the signal in which is associated with fluctuations in the light background.

3. Calculation of the Hillas parameters.

The selection of events generated by high-energy gamma quanta is carried out on the basis of the analysis of the shape of the Cherenkov image of the EAS according to the method proposed by Hillas [12]. Depending on the type of primary particle, the images obtained in the telescope camera have a different shape, which allows using simulation to isolate gamma quanta on a hadron background.

4. The hybrid events are formed as events detected by both the IACT and by 3 or more HiSCORE stations in 3 mks time window.

3. Data processing and analysis

In TAIGA experiment observations of the Crab Nebula source were carried out from October to February every year in three seasons from 2019 to 2022. The total good observation time was of about 250 hours. The total number of selected hybrid events detected by the first IACT and half of HiSCORE staions (58 station) and coin cided in time window of 3 mks is 0.9 mln events. The data were taken during the period of installation deployment, so only data obtained by one IACT and 58 stations of HiSCORE were included in analysis.

The accuracy of arriving direction reconstruction is estimated as 0.1°-0.4°, and of energy estimation as 0.05-0.2 (in log scale) in dependence on number of hit stations [6]. To increase the accuracy of arrival direction measurements, only events with number of hit stations more than 5 were included inanalysis. For such events accuracy of dgam reconstruction is 0.025 degrees and parameter dgam (angular distance to direction to Crab Nebula) we use as a final parameters for gamma excess search.

The essential problem for gamma quanta selection is a choice of background («OFF») points of measurements for increase the statistical significance of the observed signal. We use the reflected-region-background model [14] which was developed earlier for wobble observations. In TAIGA experiment the observations were carried out in wobble mode, using alternating offsets of the pointing positions of ±1.2° to the position of the Crab Nebula. The wobble direction changes every 20 minutes from +1.2° to -1.2°. For each trial source position «ON» a ring of 9 «OFF» regions we used, where every «OFF» region has equal offset to observation position. Each «OFF» point in the telescope camera was recalculated into celestial coordinates (Fig. 3), that allows to use the same 9 «OFF» position for two installations IACT and HiSCORE and recalculate dgam value for 9 background points. The statistical significance of the signal is calculated by the formula Li&Ma [15].

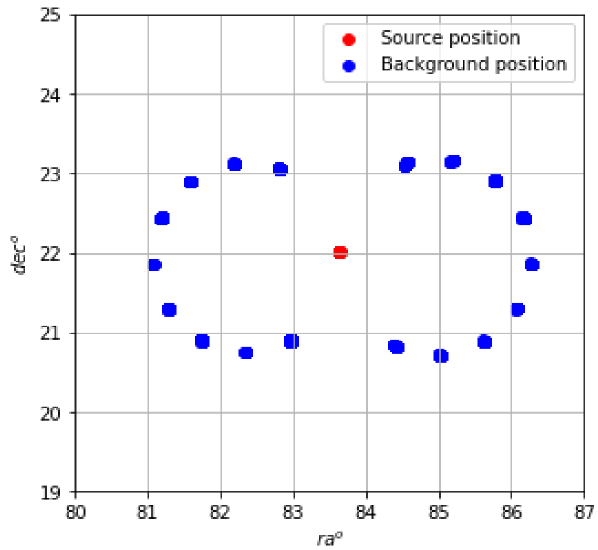

Fig. 3. Distribution of source and background positions in celestial coordinates

3.1. Monte Carlo simulation

Extensive and detailed MC simulation for both installation, HiSCORE timing array and IACT, have been made and tested. For identification of gamma-like events there were elaborated cuts, based on MC simulation of both types of detectors: HiSCORE timing array and IACT. The simulations performed in 4 steps. On the first step a shower development in the atmosphere was simulated by CORSIKA; on the second step Cherenkov photons of the shower were traced through the optical system of the IACT and optical system of the every station of HiSCORE, by program TAIGA OPTICA [16], including many details of Cherenkov light tracing in Optic system and registration; on the third step the trigger conditions were included in simulations, on the forth step methods of shower arrival direction, energy and core position reconstruction, used in experiments, were implemented in program. The threshold region of shower detection is most complicated for reproduction in simulation. To adjust little- known parameters we have achieved a satisfactory description of the most important parameters such as a counting rate of 4 and more hit stations, energy and size spectra of different samples of events. Using Monte Carlo simulation, optimal cuts for the different parameters of hybrid events were obtained, when the maximum number of suppressions of the hadron background is reached ~10^{-4}, but a suppression of gamma quanta not exceed 50% (Fig. 5). The most effective two cuts are presented in Fig 5. The effective area (Fig. 4) was calculated for these optimal criteria on MC events as ~0.25 km^2 in the region exceeding 100 TeV.

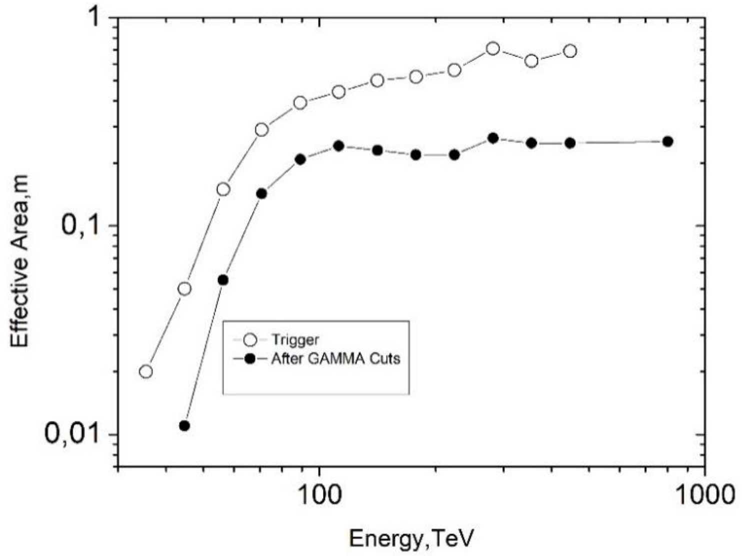

Fig. 4. Dependence of the effective area on the energy of gamma quanta for triggered events and events after gamma cuts (58 HiSCORE stations and one IACT)

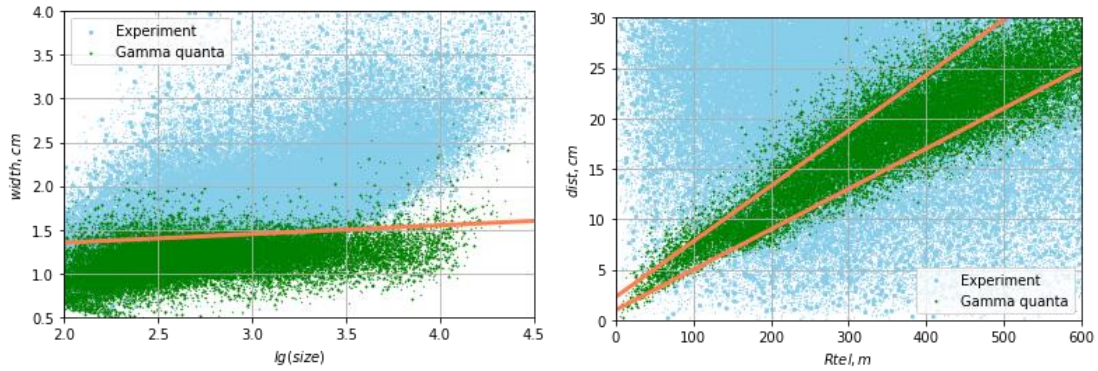

Fig. 5. Dependence of the width parameter on size (left); dependence of the dist parameter on the distance from the EAS axis to the telescope Rtel (right)

4. Results

At the final stage we analyze a distribution by *dgam*^{2} parameter (*dgam* – is the angle between shower axis, reconstructed by HiSCORE data, and direction to Crab Nebula for «ON» events or to direction of background positions for «OFF» events. Two these distributions are presented in Fig. 6. The maximum difference of «ON» and «OFF» events is seen in the range up to 0.25°, where the average number of background events is 79 events, the number of events from the source is 96 events, excess is 17 events.

For the selected hybrid events, an energy spectrum (Fig. 7) was constructed as:

$$F(E) = \frac{F_{ON}(E) - \langle F_{OFF}(E) \rangle}{S_{eff}(E) \cdot T}, \quad [TeV^{-1} \cdot cm^{-2} \cdot s^{-1}]$$

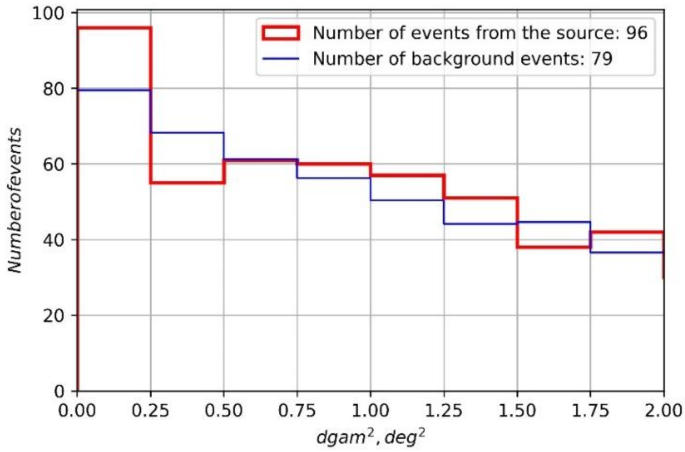

Fig. 6. Distribution by the dgam² parameter after suppression of background events

The resulting number of gamma quanta contains high uncertainty due to high number of background events. The error bars were calculated in according to [15]. The threshold energy estimate for the selected gamma-like events is ~75 TeV.

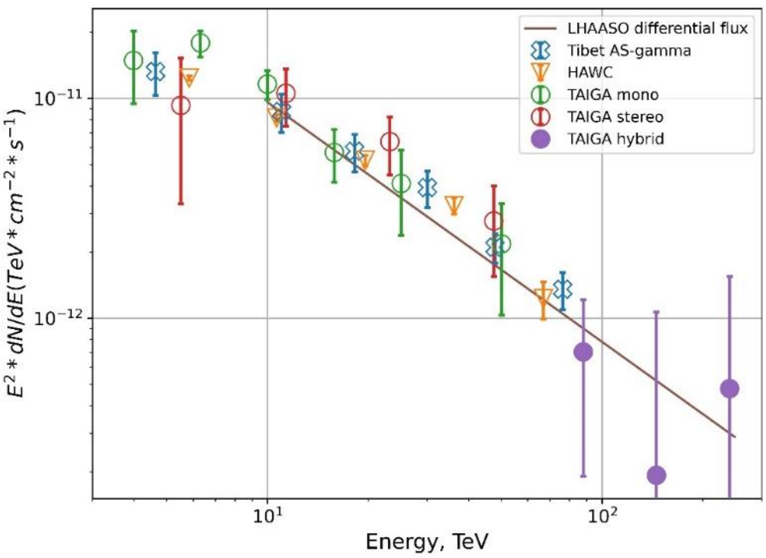

Fig. 7. The measured by different methods spectra from the Crab nebula in TAIGA experiments: in mono, in stereo modes from [17] and in hybrid mode, obtained in this work

Figure 7 shows the energy spectrum of gamma-like events from Crab Nebula, obtained during 250 hours of observation in mono and stereo mode in earlier TAIGA work [17], in comparison with world data, and 3 last points, obtained by hybrid mode in this work, are presented. There is a satisfactory agreement with the spectra measured by the different methods and spectra, obtained in other experiments.

Conclusion

In the course of the work a hybrid method for searching for high-energy gamma quanta from the Crab Nebula source was worked out. An energy spectrum in the region of around 100

TeV was obtained and among them 7 events with energy more then 100 TeV were detected. A preliminary estimate of the threshold energy for the selected gamma-like events is ~75 TeV.

Further work involves carrying out more detailed modeling of hybrid events on full HiSCORE area that will give the basis to refine the Crab spectrum in the region >100 TeV, which is an important result for the method of detecting EAS by Cherenkov radiation.

The effective area for the detecting of gamma-rays by the hybrid method + stereo [18] method at the full HiSCORE area and with five IASTs is expected to be 1.3 km^2 for energy above 100 TeV. In the nearest time, it is planned to introduce machine learning methods for stronger background suppression and to deploy external HiSCORE stations with a large distance between optical stations to increase the effective area at an energy above 200 TeV.

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