PROCEEDINGS OF SCIENCE

Gamma-hadron separation approach to point-like source observations in the TAIGA-IACT experiment in stereo observation mode

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This paper is devoted to the analysis of simulation results of TAIGA-IACT in stereo mode of observations and describes the technique of gamma-ray detection with energies higher than several TeV.

TAIGA-IACT is part of the TAIGA astrophysics complex. Installation currently consists of three operating telescopes located 300-500 m apart. Two additional telescopes will begin operation in the next two years. We describe a new gamma-hadron separation technique for point-like source observations.

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1. Introduction

Generation of gamma-rays with energies above 100 TeV in some sources of Galaxy have now obtained experimental confirmation[1–3]. This may indicate that in such objects cosmic rays are accelerated to PeV energies, but it is still unclear what mechanism of hadronic or lepton nature is responsible for the generation of such gamma-rays. In this regard, the search for and study of the so-called Pevatrons is one of the most urgent tasks of high-energy astrophysics.

The TAIGA Astrophysical complex (Tunka Advanced Instrument for cosmic ray and Gamma Astronomy)[4] is designed to study gamma radiation and charged cosmic rays in the energy range of 10^{13} – 10^{18} eV. The complex includes installations aimed both at studying charged cosmic rays: Tunka-133[5], Tunka-Grande[6], and for gamma-ray astronomy in the TeV-PeV energy range: TAIGA-Muon[6], TAIGA-HiSCORE[7] and TAIGA-IACT[8]. The TAIGA-IACT installation consists of three atmospheric Cherenkov telescopes (IACTs) with a mirror diameter of 4 m, their energy threshold is 2-3 TeV. In the next two years, two more telescopes of the installation will start working (Fig. 1).

The analysis of the Crab Nebula observations by TAIGA-IACT01 was carried out independently by the Moscow and German groups. Both of them obtained source spectrum consistent with observations from other high-energy observatories, and the significance of the gamma-ray excess was 12σ[9] and 8.5σ[10], respectively. TAIGA-IACT01 data also obtained a gamma-ray signal from MRK421 at the 5σ level[11].

The data from TAIGA-IACT can be analyzed in stereo mode - that is, when one event is detected by at least two telescopes. This approach is widely used in most IACT observatories. When extensive air shower (EAS) is detected jointly by two or more telescopes, the accuracy of the reconstructed parameters of the primary particle increases significantly. For example, in stereo mode observations it is possible to achieve an energy resolution of 15% for the recorded gamma-rays, while in stand-alone observations it is 30%. The energy threshold for this approach is 8 TeV. According to the joint work of the two telescopes, the energy spectrum of gamma-rays from the Crab Nebula in the range of 8 - 70 TeV was reconstructed[12].

Further in this paper we evaluate the possibility of gamma-ray detection from a point-like source by the TAIGA-IACT with 5 telescopes in the stereo observing mode with new approach.

2. TAIGA-IACT

According to the CTA[13] classification, the telescopes of the TAIGA-IACT installation are small size telescopes (SST). The reflector diameter is 4.3 meters and the viewing angle is 9.6 degrees[14] The size of a single pixel is 0.36 degrees. The final configuration of the installation will include 5 telescopes: one in the center and 4 at a distance of 250 meters from the central telescope. The telescopes' detecting cameras include 600 PMT XP1911 grouped into 22 clusters, each of which is controlled by a specialized MAROC3 integrated circuit. Trigger generation occurs when the amplitude of 10 p.e. is exceeded by two neighboring PMTs of the same cluster.

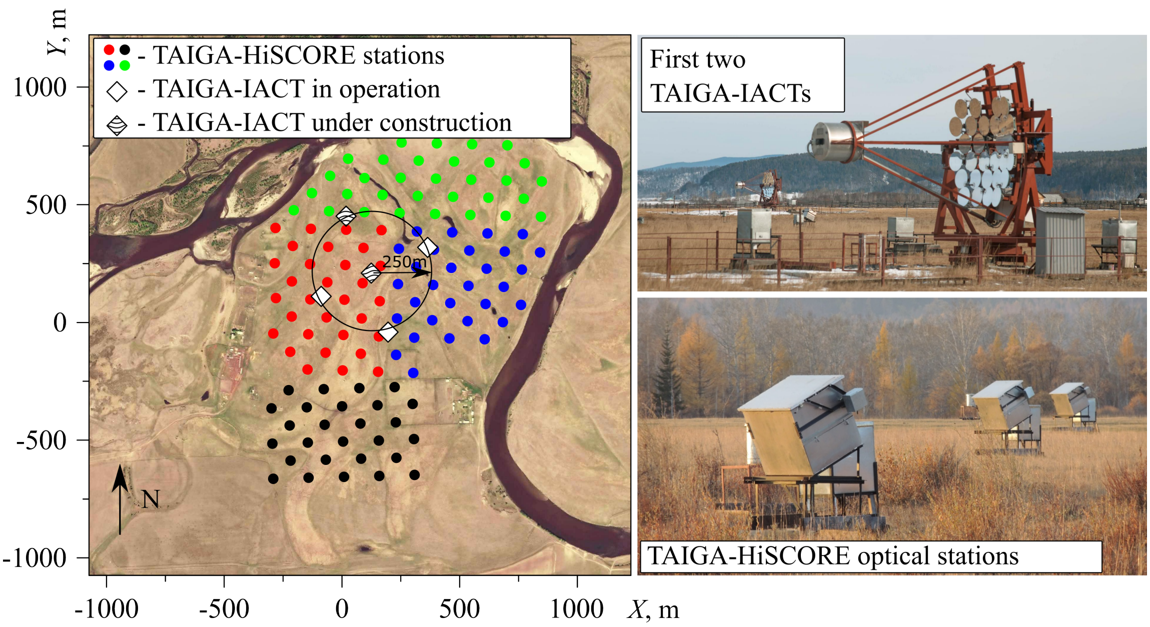

Figure 1: TAIGA astrophysical complex setup

3. Monte-Carlo simulation

To develop a new gamma-ray extraction technique, gamma-rays with energies from 2 to 200 TeV and protons with energies from 1 to 400 TeV were simulated with CORSIKA [15] version 7.35 using the QGSJET-II-04 [16] model for high-energy interactions and GHEISHA-2002d [17] for low-energy interactions. The particles were thrown over an area of 3 km^2 over a range of zenith angles of 30-40 degrees, which corresponds to the observation angles of the Crab Nebula at the Tunka valley site. The slope of the spectrum of the modeled events was mostly -1 (Fig. 2a), and therefore a weighting procedure was performed for further analysis: for gamma-rays, the modeled energy spectrum was fit to the Crab Nebula spectrum obtained by HAWC [18], for protons the spectrum was fit to DAMPE [19] observations (Fig. 2b).

The simulated events were passed through the TAIGA-IACT optical properties simulation program (TAIGA_OPTICS[20]), and then through the telescope trigger simulation program (Fig. 2c). The PMT amplitudes are chosen randomly based on the single-photoelectron distribution obtained for XP1911 in [21], where afterpulses are taken into account. The night sky background(NSB) level was estimated from experimental data and was $\sigma_{NSB} = 2.5 p.e.$, which was accounted for in the simulated events as the additional random amplitude of the NSB of each pixel, from a Gaussian distribution.

4. Reconstruction of EAS parameters

Procedure for preprocessing and geometric parameter reconstruction such as EAS core position and arrival direction has been described in [22]. The X_{max} is reconstructed on the basis of simulation. It is taken into account that the observed $X_{max}^{cherenkov}$ should be corrected depending on the distance to the EAS core position to match $X_{max}^{charged}$[23]. The energy of the primary particle

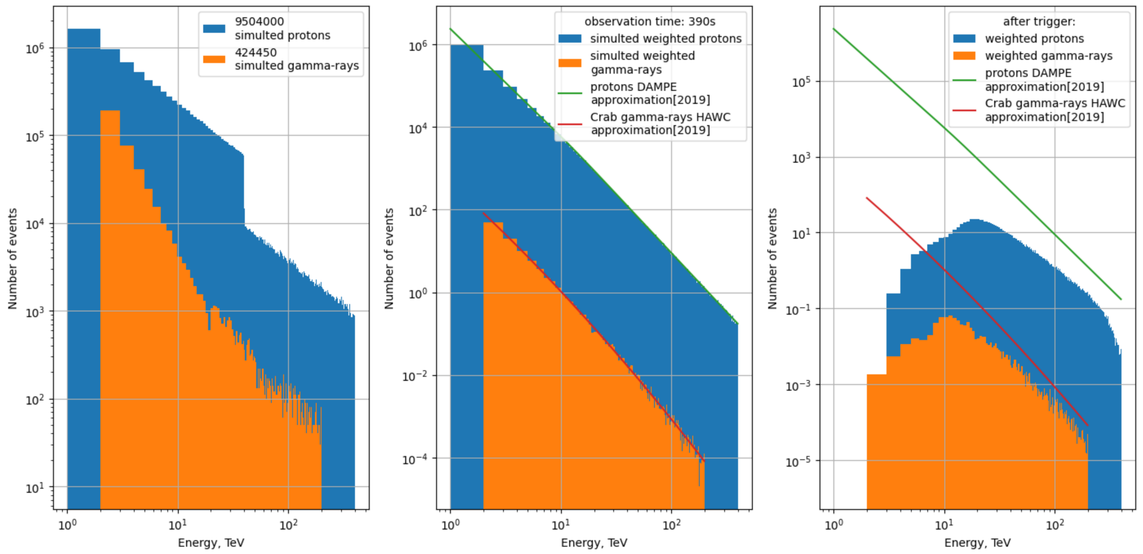

Figure 2: a) simulated spectra of hadrons and gamma-rays; b) simulated spectra after weighting procedure; c) spectra of simulated protons and gamma-rays after passing events through the telescopes trigger

is reconstructed on the basis of a lookup table, where the energy value is related to the previously reconstructed X_{max}, distance to the EAS core, and full number of photoelectrons of image ($size$). Both X_{max} and energy are reconstructed individually for each triggered telescope. The parameter value averaged over the number of triggered telescopes characterizes the stereo event. As a result, the accuracy of X_{max} reconstruction in the energy region above 50 TeV reaches 28 g/cm^2, and the energy resolution is $\sim$ 15% (Fig. 3). The standard deviations of these parameters in each event are used for gamma-hadron separation.

5. Gamma-hadron separation

The gamma-hadron separation used in this work is based on the calculation of normalized parameters [24]. However, in contrast to [24], in addition to the normalized width, a number of other normalized parameters such as length, ellipticity, concentration, number of pixels, 3rd and 4th order momentum along the major and minor axes of the ellipse are calculated. Another distinctive feature is that this approach involves normalization not only as a function of the distance to the EAS axis position, but also as a function of the reconstructed X_{max} value and the zenith angle of the observation. In addition to the normalized parameters, standard deviation of the reconstructed energy and X_{max} are also used for classification.

Thus, 9 parameters are used to perform gamma-hadron separation. As a classifier we use LightGBM - gradient boosting framework that uses tree based learning algorithms[25]. Preliminarily, the parameters of all events are scaled so that all values lie in the range from 0 to 1. This procedure is necessary to correctly perform back propagation of the error at the model training step. Since the number of simulated protons is much larger than gamma-rays, weights are assigned to the events of the training sample so that the distribution of events by the reconstructed energy is uniform and the sum of gamma-ray and proton weights is equal.

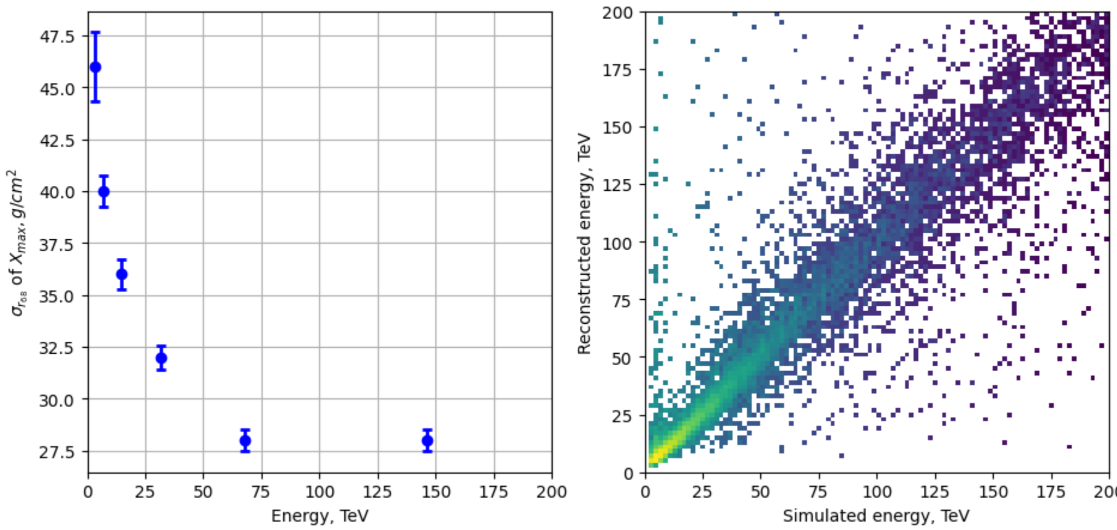

Figure 3: a) The accuracy of X_{max} reconstruction. $\sigma_{r_{68}}$ of X_{max} has the meaning of the value of deviation of X_{max} from the simulated value, within which 68% of events are contained relative to all events in a given energy bin for which X_{max} was reconstructed; b) Event-by-event comparison of the primary true energy and the reconstructed energy for simulated gamma-rays.

To assess the quality of classification we used cross-validation - resampling method that uses different portions of the data to test and train a model on different iterations. This approach allows to use the whole dataset as both test and training samples. The result of the LGBM classifier is a set of values - gammaness - that make sense of the probability that an event is a gamma-ray (Fig. 4a).

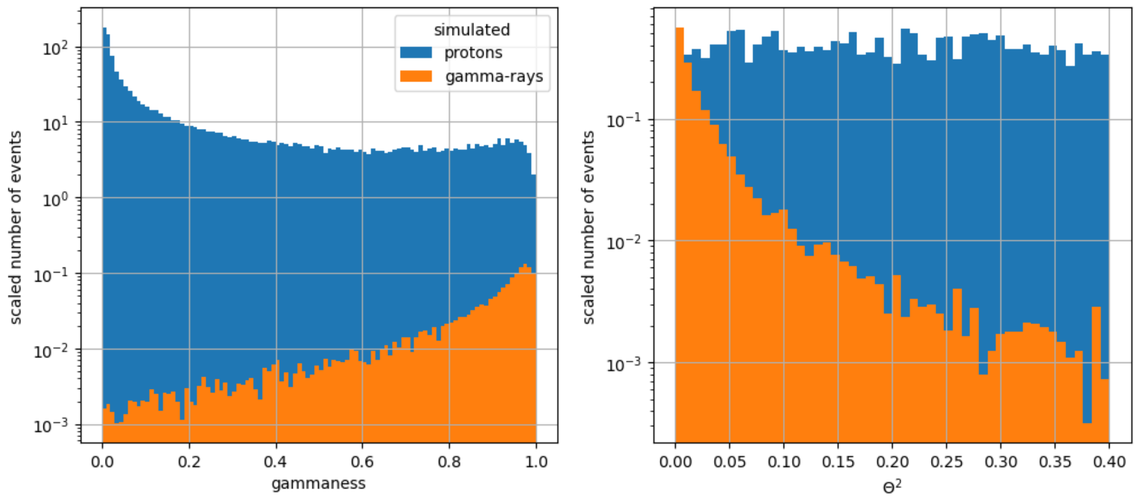

Figure 4: a) Distribution of gammaness - parameter which make sense of the probability that an event is a gamma-ray; b) distribution of θ^2 parameter - square of the angular distance between the direction of event arrival and the position of the source in the IACT's FoV. Both of them are used for gamma-ray selection in different energy bins.

To select the gamma-like sample of events, in addition to gammaness, we also use θ^2 parameter, which determines the square of the angular distance between the direction of event arrival and the position of the source in the IACT's FoV (Fig. 4b). For different energy ranges, the constraints on gammaness and θ^2 were chosen to maximize the Q-factor. As a result, the relative suppression of protons in the energy range from 2 to 200 TeV was 1×10^{-4}. The effective area reaches 0.8 km^2 at an energy of 100 TeV (Fig. 5). The calculation of the differential sensitivity is under development, since the remaining fraction of protons after suppression does not represent significant statistics (0-4 events per energy bin).

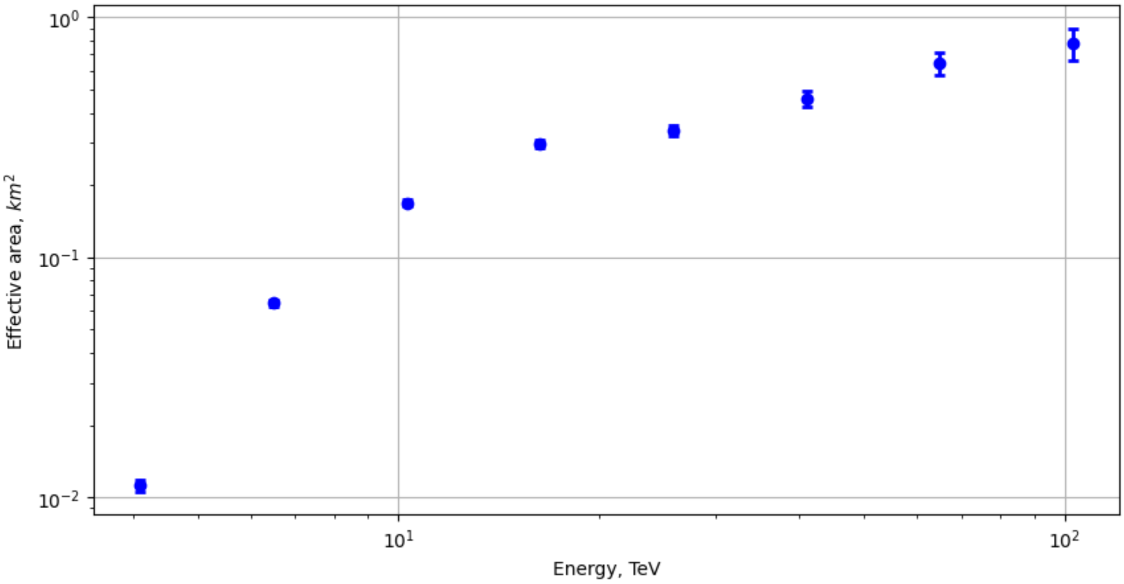

Figure 5: Effective area of the TAIGA-IACT installation

6. Conclusion

In this work, a new technique for detecting gamma-rays from the hadronic background has been developed. The approaches to the reconstruction of the X_{max} parameter and the energy of primary particles were modernized. Thus, at energies above 100 TeV the effective area of TAIGA-IACT reaches 0.8 km^2, the energy resolution is 15% and the accuracy of X_{max} reconstruction is 28 g/cm^2. The methodology will be tested on experimental data of the Crab Nebula observation for 3 seasons of observation by two and three TAIGA-IACTs in the near future.

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