PROCEEDINGS OF SCIENCE

The Baikal-GVD telescope follow-up analysis of the IceCube neutrino alerts

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The Baikal Gigaton Volume Detector is a neutrino telescope of a km^3 scale currently under construction in lake Baikal. Baikal-GVD participates in the international multi-messenger program at earlier stages of its construction. Since autumn 2020 Baikal-GVD follows up of the IceCube neutrino astrotracks. Recent results of fast follow-up searches for time-and-direction correlation of Baikal-GVD high-energy cascades with IceCube GCN messages are presented.

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1. Introduction

Baikal Gigaton Volume Detector (Baikal-GVD) aims at observations of high-energy neutrinos. Identification of their astrophysical origin could indicate cosmic Tevatrons and Pevatrons. Twenty five high-energy neutrino events as the first astrophysical event candidates have been observed by Baikal-GVD in the period from April 2018 to March 2022, as was recently presented in Ref. [1], [2]. Among them, it was found that the most energetic upward-going cascade-like event (above 200 TeV) arrived from a direction near the radio blazar TXS0506+056 with a probability of the association of $7.4 \cdot 10^{-3}$ [3]. Multi-wave activity of this blazar has been indicated earlier in 2017 by an IceCube muon neutrino alert [4]. This is a promising example of a search for astrophysical neutrino sources.

Baikal-GVD is a deep-water neutrino telescope which detects neutrinos through Cherenkov light from secondary particles produced in neutrino interactions in water. Baikal-GVD reconstructs events in two modes, track-like and cascade-like. This depends on a neutrino flavor, a type of interaction and produced outgoing particles i.e. a long-lived muon or particles of electromagnetic or hadronic showers. With large volume detectors like Baikal-GVD and IceCube, the accuracy of muon direction reconstruction is better than 1° [7], [8]. As far as cascade events produce quasi-isotropic light, the average angular resolution of their reconstruction is more dependent on optical parameters of the environment. It is 2–4° for Baikal-GVD [9] and 10–15° for IceCube [10]. The benefit of cascade reconstruction is a good energy resolution: 10 – 30% [9] for Baikal-GVD and about 15% for IceCube [11]. Also known that an energy estimate of neutrino-induced muons contains a large uncertainty, while one can study a probable energy value with Monte-Carlo simulations.

Since autumn 2020 Baikal-GVD followed up IceCube alerts on the base of preliminary quasi-online and offline reconstructed data. In the absence of significant correlations with IceCube alerts in the season 2020, the upper limits at 90% c.l. on the neutrino fluence in each alert arrival direction for the E^{-2} spectrum in the source have been obtained [12]. At the beginning of 2021, the Baikal-GVD own alert system was launched, that allows monitoring of the celestial sphere in real time. The neutrino alerts are formed in two ranks as "a muon neutrino" in long length upward-going track-like events and "all flavor neutrinos" in high-energy cascades. The system is able to get a preliminary response on external alerts with a delay of ~ 3-10 minutes. Offline performance of the data to search for coincidences includes determination of a half-open cone around the sources and time windows of ± 1 h and ± 12 h. The description of Baikal-GVD data processing and results of the follow-up procedure are presented below.

2. Baikal-GVD data processing in the follow-up regime

The Baikal-GVD telescope has a modular structure, in 2022 it consists of 10 clusters of 8 strings each. Every cluster works as a separate detector and consists of 288 optical modules (OMs) with photodetectors to register Cherenkov light. The telescope is located at depths from 750 to 1275 meters as shown in Figure 1. A total number of deployed OMs is 2196.

Raw triggered data from OMs are transferred to the shore by optical fibre cabling and to Baikalsk town by radio waves. Finally, the data are sent to the Computer Center of Joint Insti-

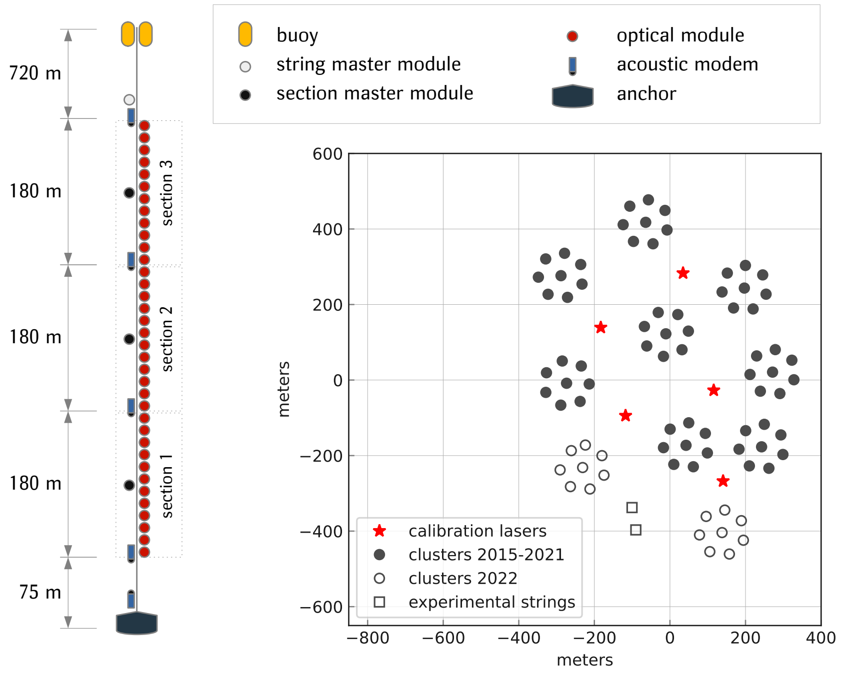

Figure 1: The scheme of Baikal-GVD. Left: a string structure (side view). OMs are installed on flexible cables and grouped in sections, digitization of photodetectors' signals is carried out in a master module of a section. Sections are organized in strings, the top of a string is mounted on buoys, the bottom of it is fixed with an anchor. To determine OM positions, GVD is equipped with acoustic modems located on the strings. Right: cluster arrangement (top view) and planar coordinates of Baikal-GVD system in 2022. Five strings of lasers between clusters are used for intercluster calibration. Additionally, two experimental strings also were installed to test telescope upgrade options.

tute for Nuclear Research in Dubna via the Internet, where they are stored, processed and reconstructed. The Baikal Analysis and Reconstruction Software (BARS) filtering system is able to select cascade-like or track-like alert events that pass quality, multiplicity, energy and various other criteria [9]. Alert messages about these events are issued to the Baikal-GVD analysis group members immediately and stored in the database. Every signal message corresponds to the generally accepted format of astronomical alerts. It contains full information about an event, including date and time of a discovery, horizontal, equatorial, galactic and elliptical coordinates, the moon and the sun positions, energy value and preliminary calculations of a background events' number per year (false alarm rate) and statistical significance. Additionally, cascade-like and track-like events are subdivided into high-energy and low-energy classes.

Baikal-GVD data are separated into runs, each run contains hundreds of files. In average, a run consists of data from 24 h one cluster's life time. When all files from one run sequentially arrive to the store, the offline processing is started. The processing time is proportional to the noise level in the lake and takes approximately 3–5 h [13]. In order to reduce the delay between a neutrino-candidate event and an alert message about it, in 2020 the initiation of fast processing has been started. It is carried out in parallel with the offline processing and contains data from one file.

Therefore, currently Baikal-GVD follows IceCube alerts using two processing systems: fast and offline. Both of them result in reconstruction of track-like and cascade-like events. The fast lightweight processing chain handles individual run files and outputs the results in few minutes in real time. It does not include data quality monitoring (DQM) (since this process is too slow) and the dynamic geometry of optical modules, the static geometry is used instead. It is deployed on the Dubna server and tested on real data. The future plans include the installation of the server on the shore to reduce the delay. The full automatic system of the follow-up reply is currently under development. The offline full data processing chain runs on Dubna servers too. Usually an offline-search for coincidences is carried out in time windows of ±500 sec, ±12 h, ± 1 day and within a half open cone ψ = 5.5° towards each alert's direction that covers angular resolutions of both telescopes. The full real-time automatic processing of external alerts with the higher precision of reconstructed events' parameters is in progress and will be the next improvement of the Baikal-GVD telescope.

3. The results of the search for correlations

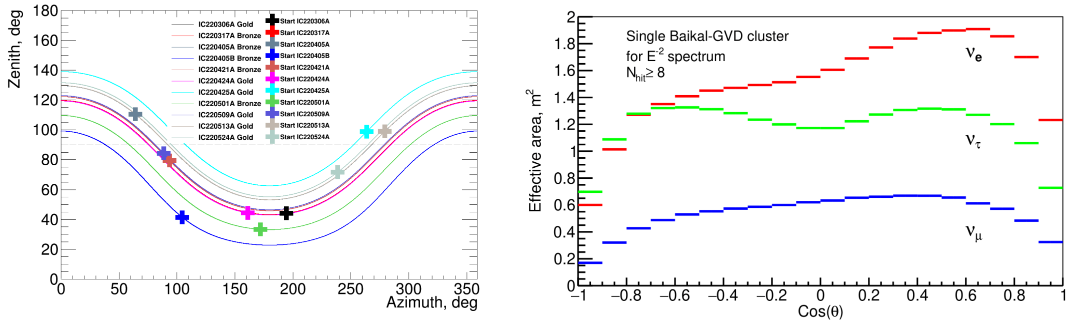

Figure 2: Left: The visibility of IceCube alerts of 2022 in horizontal coordinates system of Baikal-GVD. Right: The effective area values for three flavor neutrinos with E^{-2} spectrum in the source and for single-cluster reconstruction of cascade-like events for energies 1 TeV – 10 PeV.

The average rate of IceCube neutrino alerts is about 20 events per year. They are classified as astrotracks i.e. muon track-like events with an energy estimate above 100 TeV and with defined signalness more than 30%. The most part of the IceCube astrotracks is visible for Baikal-GVD as down-going events. In the task of tracking the source during a time window of ± 12 h they are usually seen near the Baikal-GVD horizon, not above 120°. For example, Figure 2 (left) shows the visibility of incoming alerts of 2022 in the local horizontal coordinates of Baikal-GVD. Here the downward-going events have zenith angle less than 90° (i.e. events below dashed line). It is well known that the background for down-going events is very high due to atmospheric muon groups, however the background becomes relatively less important with increasing energy due to the softer spectrum of atmospheric muons compared to that of astrophysical neutrinos. Selection criteria for triggered upward- and downward-going events in single-cluster reconstruction are different in energy values and number of hits (N_{hit}). However, for the follow-up regime these selection conditions are softer by separating cascade-like events in two categories: low energy (between 5 and 40 TeV) and high-energy (> 40 TeV) for $N_{hit} > 10$, i.e. LE and HE ranks. For upward-going muon tracks the criteria for the selection are E > 500 GeV and $N_{hit} > 7$. Whereas Baikal-GVD track reconstruction has not yet been optimized for high-energy events and near horizontal events either [14], we present the results of a search for coincidences between Baikal-GVD cascade-like events and IceCube signal track-like events during two years of Baikal-GVD observations. Nevertheless, a preliminary search in Baikal-GVD track-like events did not discover a statistically significant detection of a signal.

The Baikal-GVD follow-up procedure apart from Baikal-GVD event reconstruction includes time-directional analysis of real data, estimations of atmospheric background and probability of belonging to it and calculations of upper limits on the number of expected signal events s_{up} at 90% confidence. We also obtain constraints at 90% confidence on the energy-dependent neutrino fluence of one type $\Phi_\nu(E)$ in units (TeV cm^{-2}) with the E^{-2} spectrum for the energy range 1 TeV – 10 PeV under the assumption of equal fractions of neutrino types in the total fluence:

$$\Phi_\nu^{up} = \frac{s_{up}}{\overline{S}_{eff} \cdot T}; \overline{S}_{eff} = \frac{\int S_{eff}(E) \cdot \Phi_\nu(E) dE}{\Phi_\nu(E)}, \tag{1}$$

where T is time of observation and $\overline{S}_{eff}(E)$ is neutrinos effective area in single Baikal-GVD cluster reconstruction of cascade-like events, which is averaged over neutrino spectrum in the source, as shown in Figure 2 (right) for three flavor neutrinos with E^{-2} spectrum [16]. Only preliminary selected reconstructed cascade-like events are considered in the follow-up analysis. The selection cuts for rejection of poorly reconstructed events were optimized on Monte Carlo simulations and adjusted using previous years' data set [16]. The values of χ_t^2 and maximum likelihood functions, OMs hit multiplicity etc. are restricted, this allows to consider only well-reconstructed cascade-like events [16], [9]. Since the majority of Baikal-GVD real data are events from atmospheric background, with a goal to estimate a probability not to be an astrophysical event, we used mixed real data samples of 2018-2019 years as the background [12]. The prompt search of Baikal-GVD towards directions of all received IceCube alerts within a time window ±500 seconds did not reveal any associations with them. Further in this paper, we report on the offline analysis results within the ±12 h time window and within $\psi = 5.5°$ in each alert's direction.

In the first results of Baikal-GVD follow-up analysis for the IceCube alerts received in autumn 2020 three candidates were found in the direction of IC200926B, IC200929A and IC201014A, all of which were LE cascade-like events. Their probability being of background origin was estimated as 0.32, 0.29, 0.36, respectively [12]. The calculated limits on the neutrino fluence for energies 1 TeV – 10 PeV with spectrum E^{-2} assuming equal fluence in all flavors for each considered alert were in the range of 1 – 2.5 GeV/cm^2 [12], [15].

In 2021 data two cascade-like events passed all selection criteria for HE events. One of them was observed 3.95 h after the announced alert IceCube211208A (GCN 31191), which energy was 172 TeV and signalness 50.2%. This cascade-like event [17] was reconstructed with an energy value of 43 TeV. The event arrived from the direction (RA=119.44°, DEC=18.00°) that is 4.68° from PKS 0735+17 and 5.30° from the best-fit direction of IceCube-211208A. The Baikal-GVD PSF, estimated by Monte-Carlo simulations for the conditions of this cascade event, has a 50% (68%) containment radius of 5.5° (8.1°). One expects only 0.0044 events per 24 h in the 5.5°

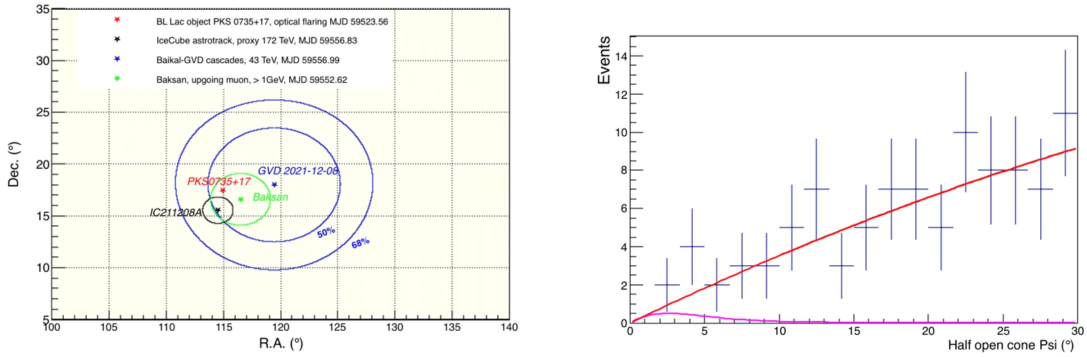

Figure 3: Left: Arrival directions of the IceCube astrotrack and the Baikal-GVD cascade with their directional uncertainties of 50% observed on December 8, 2021, when PKS0735+17 was in a flaring state. Right: The distribution of angular distance to PKS0735+17 for the observed events (points in bins with error bars), background events (red) and expected signal events of the best-fit spectrum.

circle around this source, and the Poisson probability of the chance coincidence is 0.0044 (2.85σ significance). The sky part, where the source PKS 0735+17 (red star), the astrotrack IceCube-211208A (black) and the Baikal-GVD cascade-like event (blue) are located, is shown in Figure 3 (left). The discovery time as the MJD of events is also shown. At the time of both events registration, active state of the source was observed in optical (MASTER), HE gamma-rays (Fermi LAT), X-rays (Swift XRT) and radio instruments [18]. Respectively to the Baikal-GVD horizon, the alert was found as downward-going. Two other neutrino telescopes in the Northern Hemisphere with smaller effective areas as the Baksan underground scintillator neutrino telescope and the KM3Net deep-sea underwater telescope (under construction) reported observations of upward-going muon neutrino events possibly associated with PKS0735+17, while they had a few days difference relatively the time of IC211208A. The Baksan collaboration estimated the statistical significance of the association with the flaring source as about 3σ [19] (shown in Figure 3 (left) as green star), while for KM3Net211215 the reported significance was 1.1σ [20]. The neutrino flux implied by these observations appears to be inconsistent with one-zone lepto-hadronic models constrained by the multiwavelength data, which tend to predict a much smaller neutrino flux for this source [18]. As a follow-up study, of the flaring source PKS0735+17, we analise the Baikal-GVD data set collected between April 2018 and November 2021 using the unbinned likelihood method. For this, the mismatch angle distribution (Figure 3, right) is fitted using the following likelihood function:

$$L = \prod^{N_{obs}} Poisson(n^i_{obs}; (\alpha S_i + (1-\alpha)B_i)), \tag{2}$$

where the free parameter is the relative signal fraction α, constrained to values between 0 and 1, while B_i and S_i are the expected background and signal distribution functions, respectively. Here we used ON/OFF areas around the source as 10°/30° and also scrambling of RA to estimate background events B_i. Observed events (points), background events (red line) and expected contribution of signal events S_i (pink) from the best-fit procedure around the PKS 0735+17 direction are shown in Figure 3 (right). In the results, the post-trial probability being of background origin is found to be 1.13 σ, that is not very significant for the association. Baikal-GVD will continue the follow-up observation of such potential source of neutrino, especially when an electro-magnetic conterpart appears and produces an alert.

Preliminary searches for coincidences in Baikal-GVD 2022 year's data towards IceCube alerts do not indicate any significant Baikal-GVD cascade events, we continue to carry out the research. The upper limit values on the neutrino fluence $E^2 \cdot \Phi_\nu(E)$ in the energy range 1 TeV – 10 PeV for the spectrum E^{-2} assuming equal fluence in all flavors towards IceCube alerts within a time window of ± 12 h were calculated for two years of observations at 90% c.l. and does not excess 3 GeV/cm^2. Further extension of the Baikal-GVD telescope's volume and the potential of law latency multimessenger searches provide great advantages for the cooperation of the IceCube, the KM3NeT and the future P-One neutrino detectors.

4. Conclusion

In summary, since 2020 the Baikal-GVD alert system has been successfully operating both in triggering high-energy events and in the follow-up regime. Based on cascade-like events reconstruction Baikal-GVD detects three-flavors neutrinos in 4π steradian field of view and fullfills the complementary part of the sky observation. This makes Baikal-GVD an important instrument of multi-messenger astronomy. Two years of IceCube follow-up analysis did not reveal any significant correlations between Baikal-GVD cascade-like events and IceCube track-like alerts. Presently, the Baikal-GVD neutrino telescope contains 10 large-volume Cherenkov detectors (clusters), each of them has about 0.04 km^3 of effective volume for electron neutrinos detection in the energy range above hundreds of TeV. In a few years, it is planned to increase the volume of detection of Baikal-GVD to the scale of 1 km^3.

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