PROCEEDINGS OF SCIENCE

Large neutrino telescope Baikal-GVD: status 2023

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The status of the Baikal-GVD neutrino telescope after the winter 2023 deployment campaign that results in 3 456 optical modules installed on 96 vertical strings is reviewed. The Baikal-GVD data collected in 2018-2022 show the presence of cosmic neutrino flux in high-energy cascade events consistent with observations by the IceCube neutrino telescope. An identification of the first high-energy muon neutrino candidate is presented as a result of analysis of track-like events.

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1. Introduction

Registration of high-energy neutrinos of astrophysical origin has been achieved thanks to the construction of large volume neutrino telescopes installed in ice or under water both the Southern (IceCube) and Northern (Baikal-GVD, ANTARES, and KM3NeT) Hemispheres. The main aim is to reveal the astrophysical sources of the most energetic particles in the Universe which still remain unknown. Neutrinos are not deflected by intergalactic magnetic fields or influenced by the cosmic microwave background radiation. This feature makes them perfect tool for identification of remote high-energy particle sources. The IceCube neutrino observatory has reported on detection of a diffuse neutrino flux [1]. In recent times, first hints of sources established with radio, optical, x-ray and gamma-astronomy observations to high-energy neutrino have been obtained [2, 3].

A recent progress on the construction of the Baikal-GVD neutrino telescope is reported in this review. Developments in track-like and cascade-like event analyses are presented. Difuse neutrino flux results obtained in cascade channel are shown.

2. Baikal-GVD experiment 2023 status

The Baikal-GVD is a water Cherenkov neutrino telescope under construction in the southern part of Lake Baikal since 2016 [4]. It is located approximately 3.6 km offshore at 51° 46'N and 104° 24'E coordinates, where lakebed is nearly flat at a constant depth of 1 366 m. The detector layout has been established for optimal measurement of astrophysical neutrinos in the TeV-PeV energy range. There are two neutrino event classes: tracks and cascades. Events resulting from charged current (CC) interactions of muon (anti-)neutrinos posses a track-like topology, while the CC interactions of the other neutrino flavors and neutral current (NC) interactions of all flavors typically mimic nearly point-like events. The Baikal-GVD telescope is indeed a 3-dimensional array of photo-sensors: optical modules (OMs). 36 OMs are vertically arranged with 15 m spacing on load-carrying cables - strings - that are anchored to the bottom of the lake and kept straight by a

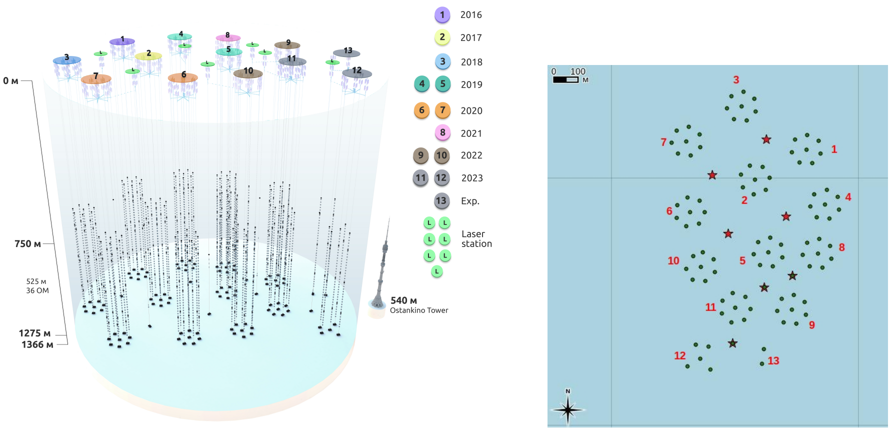

Figure 1: Left panel: Schematic view of the Baikal-GVD detector. The legend shows annual progress in the deployment. Right panel: Schematic top view of the Baikal-GVD detector in the year 2023.

system of buoys at the top. Each OM comprises a 10-inch high-quantum-efficiency photo-multiplier tube (Hamamatsu R7081-100 PMT) oriented downwards and electronics for the measurement of pressure, humidity, tilt, etc. A basic element of the detector readout in the Baikal-GVD is a section consisting of 12 OMs on one string and a control module (CM). The CM controls the OM status, converts the analog signals of the PMT into the digital form by a 12-channel ADC with a sampling frequency of 200 MHz, and forms local triggers of the section. The standard trigger condition requires a registration of two pulses on two neighboring OMs within the same section in a 100 ns time window with integrated charges exceeding channel-dependent thresholds. The string control module (SM) controls the 3 sections of the strings, acoustic beacons for acoustic monitoring of the PMT positions and LED beacons for the detector time calibration [5, 6]. Cluster is a fully functionally independent unit consisting of 7 peripheral strings surrounding a central one at a 60 m distance. Once the trigger condition is fulfilled for any of the CMs, a 5 μs event time frame is read out from all the CMs of the cluster and send to the shore station by a dedicated electro-optical cable. The clusters are arranged on the lakebed in a hexagonal pattern, with a distance of 300 m approximately between the cluster centers. Timeline of the deployment that started in 2016 is shown in Fig.(1). Recently, 3 456 OMs are deployed in total attached to 96 strings. There are special additional inter-cluster strings (ICS) equipped with high-power pulsed lasers (red and black stars in Fig.(1) right panel) dedicated for the inter-cluster time calibration and the light propagation studies. The first ICS was installed in 2022 and two more were commissioned in the expedition of 2023. They are placed approximately in the geometric centers of each three clusters of the detector. Like in regular string, there are 36 OMs arranged vertically in 3 sections. In addition, the acoustic modems (providing the positioning of the ICS) and a laser source with different levels of intensity and attenuation (providing inter-cluster time calibration and charge calibration of OMs) are attached to the string (see [7]). Installation of additional ICS is the most effective way to increase the Baikal-GVD telescope sensitivity of cascade-like neutrino events. MC simulations show that for cascades with an energy higher than 100 TeV the increase in the number of events is 24% for the distance between clusters being 250 m.

3. Recent development in the track-like events analysis

Muons originating in charged current (CC) interactions of muon (anti-)neutrinos and tau (anti-)neutrino CC interactions, in case when tau decays into a muon, leave track-like events topology in the Baikal-GVD detector. Muon track reconstruction is a consecutive two step process. In the first step, registered pulses originating in emission of Cherenkov light by muon are selected while the background noise pulses are eliminated (see [8]). In the second step, the track direction, energy, and some quality paramaters (e.g. fit convergence, value of minimisation function) are obtained by means of algorithm based on the directional causality criterion and fast track reconstruction algorithm [9]. The directional resolution varies from $\sim 1.5^\circ$ for short tracks to below 0.5° for long tracks. A simple cut-based analysis (see [10]) allowed to select 44 neutrino candidate events from data collected in April–June 2019. The neutrino candidate event rate roughly agrees with the MC expectation for atmospheric neutrino flux (Fig.(2) left and middle). Applying the selection to the full year 2019 dataset results in finding an upgoing muon with median estimate of energy corresponding to 103.4 TeV. The reconstructed zenith angle θ is 153.4° and visible track length is

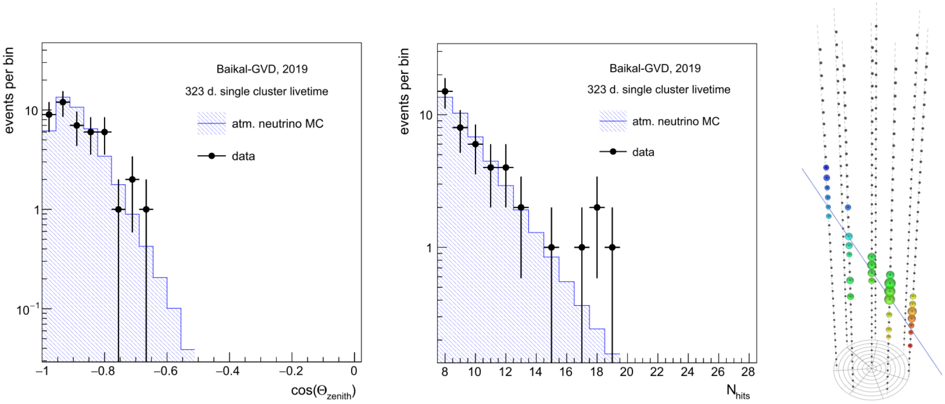

Figure 2: A sample of upgoing track-like neutrino events as a result of the analysis of a 2019 data sample [10]. Left panel: Zenith angle distribution. Middle panel: Distribution of number of hits used in the reconstruction. The black points are the Baikal-GVD data. Blue filled area stands for the MC prediction for atmospheric neutrinos. Right panel: Visualization of a 100 TeV upgoing muon neutrino candidate selected by the current analysis. Estimated signalness > 90 % indicates high probability of astrophysical origin of this event.

332.4 m (see Fig.(2)). By considering atmospheric muon bundles, atmospheric neutrino including prompt neutrino contribution, and by using astrophysical neutrino spectrum index γ_{astro} ~-2.36, the estimation of probability (signalness) of this event is larger than 90%.

4. Cascade events in Baikal-GVD

The key role in the search for high-energy astrophysical neutrinos is a reliable reconstruction of high-energy neutrino induced cascades. An improvement is achieved by setting cuts on quality variables by means of Monte Carlo simulations according to the data sample accumulated in 2016 – 2017, e.g. pulses with charge Q higher than 1.5 p.e. are considered only. A criterium of selecting events with a large multiplicity of hit OMs $N_{hit} > 7$ at least on three strings supports further improvement. High-energy cascade energy, direction, and vertex reconstruction is a two step process [11]. At the first stage, vertex coordinates $\vec{r}_{sh}$ are found by minimization of χ^2_t function with use of time information of pulses on OMs. At this procedure level cascade is treated as a point-like souce of light. The obtained cascade vertex coordinates serve as input for the second step which reconstructs the cascade energy and direction by use of the maximum-likelihood method. The achieved precision of energy and direction of the cascade varies typically between 10% – 30% and 2° – 4°, respectively. Data analysis described in our previous studies [12] was used in search of astrophysical neutrinos on data colected by Baikal-GVD in 2018-2021. The result is a set of 11 high-energy cascade events with cuts on OM hit multiplicity $N_{hit} > 11$, reconstructed energy $E_{sh} > 15$ TeV, and reconstructed zenith angle cos$\theta < $ -0.25. These are considered as astrophysical neutrino candidates.

The energy and zenith angle distributions of these 11 events also with MC simulation distributions are shown in Fig.(3). Based on this dataset characterization of the diffuse neutrino flux under

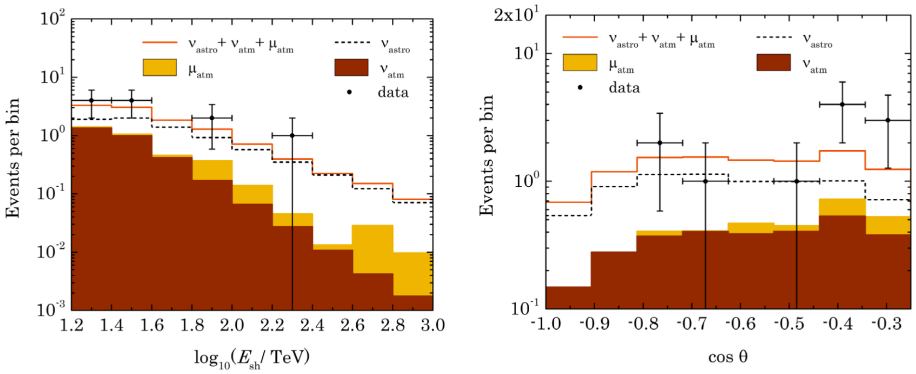

Figure 3: Left panel: Reconstructed cascade energy distributions of the dataset consisting of 11 selected events. The best-fit distribution of astrophysical neutrinos (dashed line), expected distributions from atmospheric muons (yellow) and atmospheric neutrinos (brown) and the sum of the expected signal and background distributions (orange line) are also shown. The atmospheric background histograms are stacked (filled colors). Right panel: The same for the reconstructed zenith angle distribution.

the assumption of single power law model

$$\Phi^{\nu+\bar{\nu}}_{astro} = 3 \times 10^{-18} \Phi_0 \, (E_\nu/E_0)^{-\gamma_{astro}} \; [\text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}] \tag{1}$$

with $E_0 = 100$ TeV, one neutrino flavor flux normalization Φ_0, and a spectral index γ_{astro} was performed. By means of a binned likelihood approach the best fit parameters are found to be $\Phi_0 = 3.04$ and $\gamma_{astro} = 2.58$ [13]. The background-only hypothesis is excluded at the level of 3.05σ. The achieved Baikal-GVD results of cosmic neutrino diffuse flux measurements are consistent with measurements of IceCube and ANTARES (all-neutrino flavor).

In search for neutrino induced cascade events, the main background originates from the discrete stochastic processes along the muon track. There is an ongoing development of a selection technique that reliably distinguishes between the neutrino-induced cascades and the cascade-like background events (mainly from atmospheric muon bundles) that represents an additional step in the cascade selection algorithm described in [14]. Several variables were selected for the training and testing of a Boosted Decision Tree within the TMVA package of the CERN ROOT framework that significantly help to reduce the background (see [14]).

An identification of double cascade events among the cascade-like events implies a very high chance for the registration of astrophysical neutrino. This can be achieved using a two-step reconstruction algorithm. Firstly, a selection of pulses from cascades is perfomed with suppression of noise pulses. Secondly, a step of categorizing the signal pulses to the cascade created in the ν_τ interaction vertex and the second one that consists of pulses from τ-lepton decay cascade. Subsequently, vertices coordinates, direction, and energies of both cascades are obtained by means of minimization of χ^2 function with use of time information of pulses on OMs and the maximum-likelihood method. For the detailed description and evaluation of the performance of the algorithm for search of double cascade events see [15].

5. Conclusion

A report on the construction progress of the Baikal-GVD neutrino telescope that now comprises 3 456 optical modules on 96 vertical strings has been presented. Low-energy neutrino event rate in track-like channel is in a fair agreement with the MC expectation for atmospheric neutrino flux. A track-like event that is highly probable of astropysical origin has been selected for the first time. A selected sample of high-energy cascades is consistent with the astrophysical neutrino flux at the level of 3.05 σ.

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