

Track-Like Event Analysis at the Baikal-GVD Neutrino Telescope

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Reconstructed tracks of muons produced in neutrino interactions provide precise information about the neutrino direction. Therefore, track-like events are a powerful tool to search for neutrino point-like sources. Recently, Baikal-GVD has demonstrated the first sample of low-energy neutrino candidate events extracted from the data of the season 2019 in a so-called single-cluster analysis — treating each cluster as an independent detector. In this paper, the extension of the track-like event analysis to a wider data set is discussed and the first high-energy track-like events are demonstrated. The status of multi-cluster track reconstruction and that of the event analysis are also discussed.

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1. Introduction

Baikal-GVD [1] is the experiment in a construction phase located in the southern part of Lake Baikal. The depth of the lake in the installation area is approximately constant and is about 1366 m. The telescope has a modular structure and consists of independent detectors, so-called clusters. After the deployment campaign in winter 2023, the detector includes 12 standard clusters and one cluster with the experimental high-bandwidth DAQ. Each cluster has its own independent trigger and readout system and comprises 8 strings carrying optical modules (OMs) equipped with photomultipliers or control and readout electronics. The total number of deployed OMs with PMTs is 3456. A specialized module 30 m below the water surface controls the cluster readout system and is connected to the shore station by a hybrid electro-optical cable which provides electric power to the installation and enables data transmission. The data from the shore station are transferred to JINR (Dubna) where they are processed and stored. The stored data are divided into a single-cluster event set (individual events for each cluster) and a multi-cluster event set (combined events in which the coincidence of triggers on different clusters was found — in a time window defined by the maximum muon propagation time between these clusters).

The main goal of the experiment is to study the astrophysical neutrino flux. Neutrino interaction with matter in the vicinity of the detector is accompanied by a cascade of charged particles and/or a muon that propagates over large distances keeping the direction of the neutrino with a good accuracy (which improves with increasing energy). The direction and energy of the muon can be estimated using the times and integrated charges of the pulses registered in the PMTs along the track. The angular resolution for track events is at the level of 0.5° for muons with a sufficiently long track in the sensitive detector volume, which is substantially better than the typical resolution for cascades. At the same time, the energy resolution is much worse than that for cascade events [2]. A good directional resolution makes the track analysis especially important for the search for neutrino point-like sources.

The majority of neutrinos reconstructed by the detector are produced in the Earth's atmosphere. The spectrum of atmospheric neutrinos decays rapidly as energy increases. At particle energies of above several tens of TeV, the flux of astrophysical neutrinos starts to dominate. Both single-cluster and multi-cluster events generated by the data processing system are important for the track analysis. Single-cluster events ensure the sensitivity of the telescope to ascending neutrinos with zenith angles greater than 120° . Multi-cluster events provide the sensitivity to nearly horizontal events which are important at high energies ($> O(500 \text{ TeV})$) since the Earth loses transparency to neutrinos in this energy range. The analysis of track-like events is aimed at an efficient and precise neutrino reconstruction in the 100 GeV—multi-PeV energy range. In this paper, the recent developments in the track-like event analysis are discussed.

2. Muon track reconstruction algorithm and its performance

Muon tracks are reconstructed in two stages: at the first stage, the PMT pulses (hits) generated by the Cherenkov light emitted by the muon are selected while the noise pulses from the luminiscense of the lake water or PMT dark current or afterpulses are suppressed; at the second stage, the direction, energy, and various quality parameters of the track (e.g. fit convergence, value of minimisation

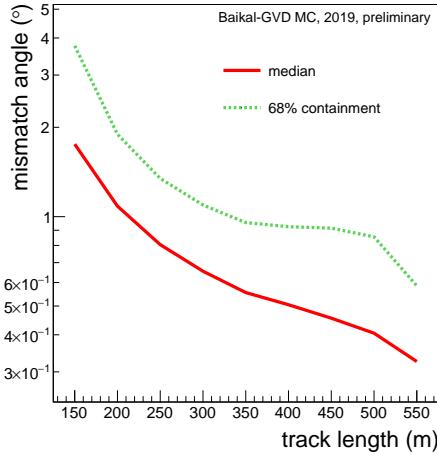


Figure 1: Angular resolution for single-cluster reconstruction of muons with energy in the center of the detector between 10 TeV and 1000 TeV.

function) are reconstructed. Noise suppression for single-cluster reconstruction is performed with the effective algorithm based on the directional causality criterion and fast causally-connected pulse search algorithm [3]. The celestial sphere is scanned with an adjustable step ($5\text{--}10^\circ$). For each direction, a clique of pulses that fall within a direction-dependent time window is identified. The direction with a sufficiently large number of selected pulses and the minimum value of the quality function is chosen as a preliminary one, and the corresponding set of pulses is used to accurately reconstruct the track parameters. This approach retains a large fraction of the signal pulses in large energy range keeping the contamination with noise pulses at the level of few %. The multi-cluster reconstruction has a dedicated noise suppression algorithm. The track is approximated using two pairs of pulses identified by the trigger system [1] in different clusters and other pulses are collected using time window with respect to this approximation. Track fit procedure is similar to single-cluster analysis. The track fit is performed using pulse collection and preliminary track direction as found by the noise suppression algorithm. Track direction, position and time are found by minimising the quality function consisting of a $\chi^2(t)$ term and a term proportional to the sum of products of pulse charge and distance from the track. Tens of track quality parameters and the muon energy are reconstructed at this stage. The energy is reconstructed using mean muon energy loss along the track estimation as a proxy. The track direction measurement precision depends on track length and varies from $\sim 1.5^\circ$ for short tracks to below 0.5° for long nearly vertical tracks (Fig.1). The energy resolution depends on energy and varies between factor 3 and 3.5. The directional resolution for multi-cluster analysis is better due to larger track lengths and approaches 0.2° for longest tracks.

3. Progress in neutrino candidate selection

Most of the events passing through the muon reconstruction are atmospheric muon bundle events. Events from atmospheric muons, incorrectly reconstructed as ascending ones, form the background to atmospheric neutrinos, exceeding the signal by the factor $10^2 - 10^4$ depending on

zenith angle. This background is suppressed by applying cuts on various track parameters or by using the boosted decision tree (BDT) technique.

The first set of candidate events in single-cluster analysis was selected using the so-called fast single-cluster event reconstruction algorithm which was applied to the first three months of 2019 data. As a result, a set of 44 neutrino candidate events was selected in a cut-based analysis [4]. The obtained event set is dominated by atmospheric neutrinos with an average energy of 500 GeV.

An improved method of the hit finding [3] combined with the BDT-based suppression of misreconstructed background allowed to enhance the neutrino yield from the same dataset in single-cluster analysis by a factor of 2 [5].

Single-cluster reprocessing of the full 2019 dataset with improved reconstruction and neutrino selection methods allowed to further increase the low-energy neutrino candidate dataset and also identify first high-energy track-like neutrino candidate events. While analysis is in the development stage in this report we present preliminary characteristics of one of such events (Fig.2, left). An upgoing muon with median estimate of energy corresponding to 103.4 TeV was detected in autumn 2019. Number of hits selected by the hit selection algorithm is 30, the reconstructed zenith angle, θ , of the event is 153.4° and visible track length is 332.4 m. Angular resolution corresponding to 68% containment interval is 0.67°. Probability of the event to be of astrophysical origin (signalness) was estimated taking into account contributions from atmospheric muon bundles, atmospheric neutrino including prompt neutrino contribution and using astrophysical neutrino spectrum with $\gamma_{astro} \sim 2.36$ according to recent IceCube extraction of spectrum for track-like events [6]. The signalness of the event was estimated at >90%.

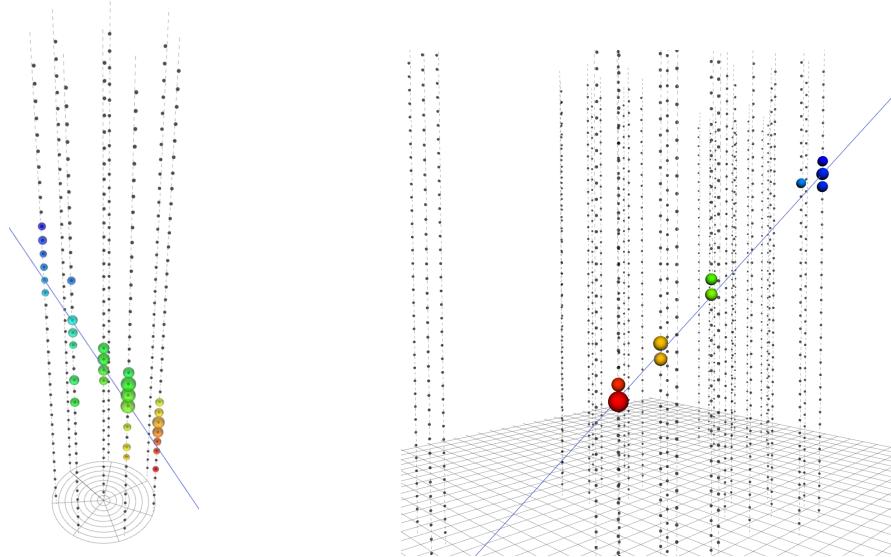


Figure 2: Left: The 100 TeV upgoing muon neutrino candidate selected in single-cluster analysis with high probability of astrophysical origin. Estimated signalness of the event is >90%. Event was registered in autumn 2019. **Right:** The multi-cluster neutrino event candidate registered in summer 2019.

Multi-cluster track-like events allow to fully unlock the potential of the telescope's angular

accuracy. Presently the multi-cluster analysis is in the development stage. The preliminary cut-based analysis optimised on MC and applied to a fraction of 2019 data resulted in the detection of first multi-cluster track-like neutrino candidate (Fig. 2, right). The selected event is a two-cluster event with 10 hits distributed among 5 strings and a track length of 399 m. The reconstructed zenith angle of the track is 125.6° . The event was recorded on July 6, 2019.

4. Conclusions

Baikal-GVD track-like event analysis is progressing towards higher sensitivity and precision. The developed muon reconstruction techniques make it possible to achieve an angular resolution well below 0.5° for sufficiently long tracks. Single-cluster analysis of the full 2019 dataset resulted in detection of the first high-energy muon events; the most spectacular one being the upgoing muon event with energy of 102 TeV and signalness $> 90\%$. Multi-cluster track-like event analysis is in the development stage, and the first multi-cluster neutrino candidate has been registered.

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