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Towards neutrino astronomy with tracks in Baikal-GVD

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Baikal-GVD is a gigaton-scale neutrino telescope being constructed in Lake Baikal. The detector presently includes 14 independent detector sub-arrays (clusters), each consisting of 8 or 9 strings, each of which holds 36 optical modules. High-energy muon neutrino interaction through the W-boson exchange results in the production of muons with range of propagation reaching many kilometers. Reconstructing the neutrino-induced muon tracks in the detector provides a measurement of the neutrino direction with precision up to 0.2° and beyond, enabling the use of the neutrino data for astronomy. The Baikal-GVD data from data-taking seasons 2019-2023 have been processed with a dedicated track reconstruction algorithm, yielding a sample of few thousand neutrino candidate events. The data sample have been employed to search for astrophysical neutrino diffuse flux and for neutrino emission from point-like sources. In this report we briefly discuss the data reduction algorithms and present the preliminary analysis results.

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1. Introduction

The main purpose of the large-volume neutrino telescopes such as Baikal-GVD is the study of TeV - PeV cosmic neutrino flux. The Baikal-GVD telescope presently consists of 14 independent sub-detectors (clusters) comprising 117 vertical strings carrying in total 4212 optical modules. In the next few years it is planned to expand the detector up to ∼ 6000 optical modules, reaching a sensitive volume of ∼1 km^3. The detector collects data in partial configurations since 2016 and the data from 2018 onwards have been used to obtain the number of physical results such as observation of atmospheric neutrino flux using tracks [1] or observation of diffuse astrophysical neutrino flux in cascade channel with the significance above 5σ [2]. While the cascade detection channel provides precise neutrino energy reconstruction and is good for spectrum measurements, the muon track channel is optimal for the purpose of the astrophysical point source searches due to better direction reconstruction. The median agular resolution reaches $\sim 0.2°$ and better for tracks of length ∼500 m and beyond. The Baikal-GVD data taken between April 2019 and March 2024 have been processed with the track reconstruction algorithms and used for astrophysics measurements. In this report we review the muon reconstruction methods adopted by the experiment and discuss the astrophysical neutrino diffuse flux measurements and point source search using track-like events.

2. The Baikal-GVD detector

The Baikal-GVD detector [3] is located in Southern part of Lake Baikal 4 km from the shore. The lake depth at the telescope location is about 1366 meters, water light absorption length reaches 22 m [4]. The detector consists of 14 independent clusters and each cluster includes 8 or 9 strings instrumented with 36 optical modules (OM) at depths between 750 and 1275 meters with a vertical spacing of 15 m. Each OM is instrumented with single high-quantum-efficiency 10-inch PMT HAMAMATSU R7081-100 and various sensors. Each string is subdivided onto three elementary units of the data readout - sections. Each section consists of 12 OMs each connected via coaxial cable to the section central module (CM). CM receives analog signal from OMs, digitizes it and performs triggering. Once the trigger condition is satisfied [3] full waveforms within 5 μs time window around the trigger signal are sent to the shore.

The data accumulated at the shore station is transmitted to JINR, Dubna. At JINR the primary raw data processing is performed during which independent readout windows from the CMs are merged into the cluster-wide events [5]. Further processing is performed via two pipelines: multi-cluster and single-cluster. In the multi-cluster pipeline common events between clusters are found. Single-cluster events are merged into the multi-cluster events based on the requirement that time of the triggers in different clusters is consistent with the response from the same particles. In further processing, time and charge calibrations are applied to single-cluster or multi-cluster events [6, 7]. OM coordinates, as reconstructed in quasi-online manner from regular acoustic modem polls [8], are available from the online database.

3. Track-like event reconstruction and neutrino event selection

PMT pulses in the telescope data are dominated by those due to ambient optical background of the Lake Baikal waters. The background is caused by luminiscense of sinking remains of living

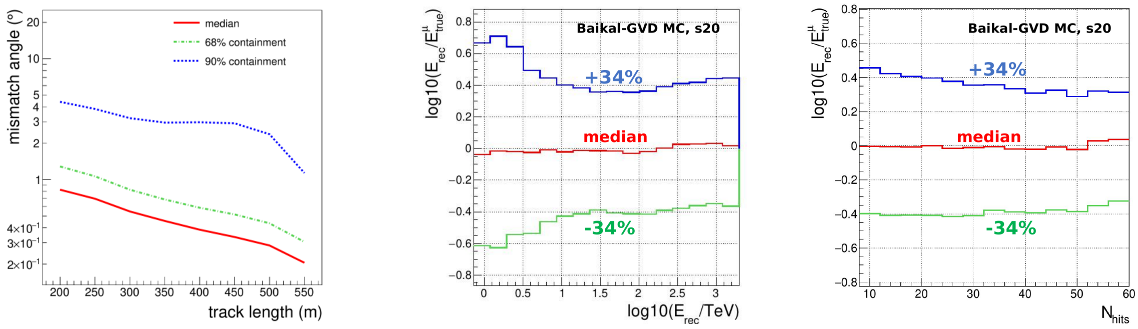

Figure 1: Angular resolution of the muon direction reconstruction as a function of track length (left). The muon energy reconstruction precision defined as 68% containment in $log_{10}(E_{rec}/E^{\mu}_{true})$ as a function of muon energy (center) and N_{hits} (right).

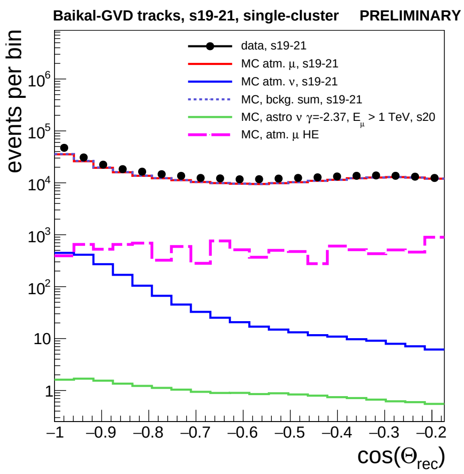

Figure 2: Distribution of the reconstructed cosine of the zenith angle for upgoing tracks reconstructed in seasons 2019-2021 before the neutrino selection cuts (see text). The distribution is dominated by misreconstructed tracks produced by atmospheric muon bundles. Data (black points) is compared to the expectation from CORSIKA7.741 MC sample (see text). Contribution from high-energy muon bundles for the presented livetime is shown with magenta. Plot is taken from [11].

organisms and/or algae. The PMT signal due to background is at the 1 photoelectron level. The noise pulse rate depends on the depth and season reaching up to hundreds of kHz at top OM layers in mid-summer while in general being few 10's of kHz per detection channel [9].

The event reconstruction uses the 5μs event time frame filled with pulses which are characterized by their time of arrival, defined by the front of pulse onset, and calibrated deposited charge. The challenging part of the reconstruction procedure is to suppress pulses from lake water optical background to acceptable level, while keeping the efficiency of pulses from Cerenkov light detection high. This is performed by applying two-stage selection procedure employing Cerenkov pulses correlation in time first developed in [10]. Both stages of the procedure use graph theory methods

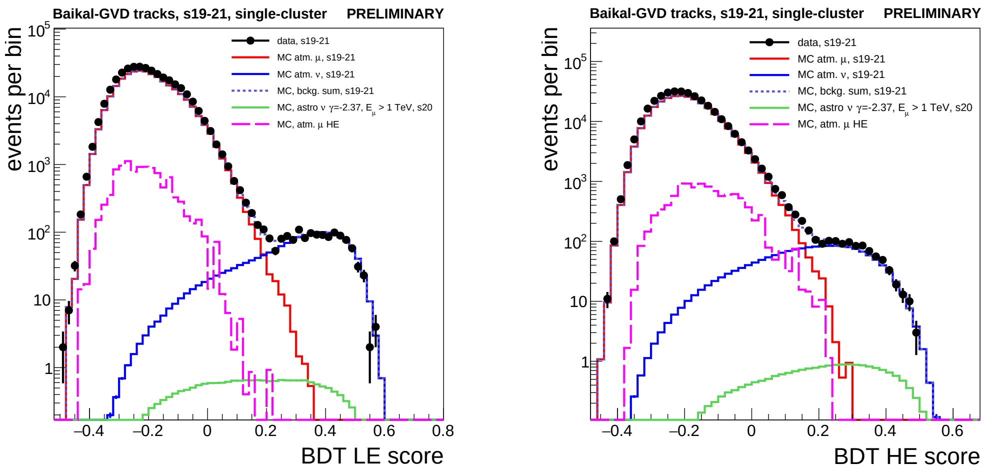

Figure 3: Boosted decision tree classifiers BDT_{LE} (left) and BDT_{HE} (right) evaluated for upgoing event sample presented in Figure 2. Atmospheric neutrino spectrum used here is Bartol flux [13] rescaled by a factor of 1.32 to match the data normalisation. Plots are taken from [11].

to find the largest clique of connected pulses. At the first stage pulses are connected by common causality criterium used in e.g. [1]. At the second stage more complex directional causality criteria are used explained in [10] and the scan over the grid of directions around the preliminary track direction estimation using the flat wavefront approximation is performed. The described procedure suppresses the average number of noise pulses per event down to 5% keeping the Cerenkov pulse detection efficiency at 95% for the atmospheric neutrino spectrum [10].

The track direction, position, and time are found by minimising the two-term loss function consisting of a $\chi^2(t)$ term and a term proportional to the sum of products of pulse charge and the distance from the track [11]. For each of the few biggest hit collections found by the hit selection procedure the minimisation of the loss function with successive variations of hit collections to account for possible remaining noise hits is performed. The hit configuration giving the best loss function value is used for the final track fit, muon energy estimation and calculation of variety of track quality parameters to be used at the stage of the event selection. The median angular resolution of 0.2° is achieved for sufficiently long tracks for the described track reconstruction procedure (Fig.1, left).

The energy of the muon is reconstructed using the energy loss rate estimate. Indeed starting from ~1 TeV the rate of muon energy losses is caused mainly by bremsstrahlung and pair production and is proportinal to the muon energy. To estimate the energy loss the amount of light emitted by the muon is estimated for each OM within 40 m from the track based on the measured hit charge and taking into account light absorption, geometric factor and OM angular acceptance. Such elementary energy losses are ordered by their magnitude and the median value is taken as a proxy. The proxy is further mapped to the median muon energy in the plane containing the center of the detector based on the MC simulation of muon neutrinos with power-law spectrum with index $\gamma = 2$. The energy resolution of factor 2.5 is attained for muons of energy above ~10 TeV (Fig.1, center, right). More details on the track reconstruction procedure can be found in [11].

The described track reconstruction procedure was applied to data-taking seasons 2019-2023 that correspond to runs recorded between April 2019 and March 2024. The detector performance during this period was simulated with realistic Monte Carlo simulation passed through the similar event reconstruction procedure. The detector simulation for each season included realistic channel-by-channel trigger thresholds, noise rates, missing channels due to hardware failures and other detector-related parameters. The atmospheric muon bundle MC employs CORSIKA 7.741 [12] to simulate the extensive atmospheric showers and record secondary muons at the lake surface level. Further simulation is performed with a custom-build software [1]. Atmospheric neutrino flux was simulated according the DAEMONFLUX code for conventional and prompt atmospheric neutrino [14]. The astrophysical neutrino flux was simulated with the spectral fit reported for the 9.5 years of IceCube northern tracks data [15]. This is given by $\Phi = \phi_0(E/100TeV)^{-\gamma}$, with spectrum index $\gamma = 2.37^{+0.09}_{-0.09}$ and normalisation $\phi_0 = 1.44^{+0.25}_{-0.26}\ 10^{-18}$ GeV^{-1}cm^{-2}s^{-1}sr^{-1} [15]. The neutrino flux simulation takes into account the attenuation in the Earth evaluated with nuFATE program [16]. In addition a dedicated bank of CORSIKA events with the energy of leading muon > 100 TeV was used to enrich the background MC simulation with rare very-high-energy muon bundle events which were used in neutrino selection optimisation procedure.

The muon bundles are dominating in the reconstructed data and the total rate of events passing the reconstruction procedure is ~3 Hz per cluster. A tiny fraction of atmospheric muon bundle events is misreconstructed as upgoing, that forms the background to neutrino events exceeding the signal by 100-1000 times depending on zenith angle (Fig.2). The suppression of the misreconstructed muon background is performed with boosted decision trees (BDT) employing ~ 20 reconstructed muon track variables characterizing the quality of the fit and event topology. Two BDTs were trained using different signal event spectrums for the reconstructed zenith angle region $\theta > 100°$. The low-energy BDT (BDT_{LE}) was trained on atmospheric neutrino spectrum with cutoff of $E_\mu < 10$ TeV. The high-energy BDT (BDT_{HE}) was trained on hard power-law spectrum $\Phi \sim E^{-2}$ with an energy cut $E_\mu > 10$ TeV. Two CORSIKA -based muon bundle samples were used as a background. One of them contains events with regular spectrum, another sample - events with leading muons with $E > 100$ TeV - was used to ensure good suppression of bright muon bundle -induced event with large hit multiplicity. The TMVA framework was used for the BDT construction and training [17]. The BDT response distributions are shown at Fig.3. The cut on the classifier response of ($BDT_{LE} > 0.25$ or $BDT_{HE} > 0.25$) often used for performance studies provides the sample of events with misreconstructed muon bundle contribution estimated as ~3% and neutrino event selection efficiency being of order of 70%.

4. Limits on the astrophysical neutrino diffuse flux with track-like events

The total livetime of the data processed with the single-cluster track reconstruction amounts to 30 years of data-taking of one cluster. This event set was used to examine the data on the deviation above the atmospheric background expectation in a simple preliminary cut-based event-counting analysis. To minimize the background from atmospheric muon bundles the analysis was restricted to zenith angles $\theta > 100°$. The main cuts suppressing atmospheric background, namely cuts on BDT and muon energy, were optimised on MC simulation before unblinding the full dataset. For

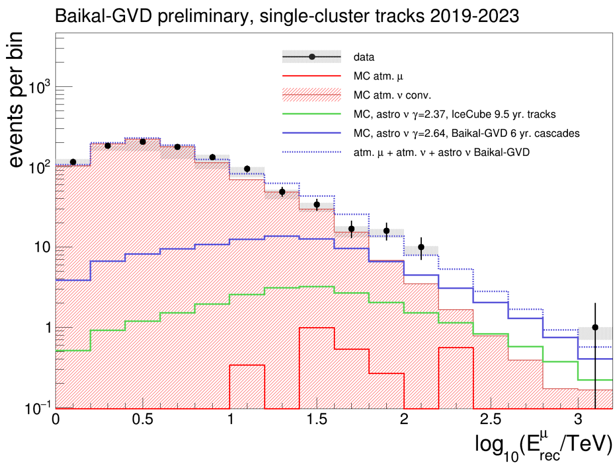

Figure 4: Distribution of the reconstructed muon energy of neutrino candidates in track-like channel for the cut at BDT $BDT_{HE} > 0.26$ obtained in the optimisation. The data are compared to the expectations from the atmospheric backgrounds and recent spectrum fit in cascade channel from Baikal-GVD [2] and IceCube best-fit spectrum using 9.5 years of northern tracks [15]. The 90% CL interval for flux normalisation for spectral index $\gamma = 2.37$ obtained in dedicated analysis (see text) does not contradict neither Baikal-GVD nor IceCube fits. Neutrino MC normalisation was scaled to match the normalisation in data for the atmospheric neutrino spectrum. The energy scale for MC was corrected to match the data in low-energy range by increasing the photoelectron yield in MC by 20%. Shaded area around the data points correspond to the muon energy scale uncertainty derived by varying photoelectron yield in MC by (+20%,-5%).

the cut optimisation and further assesment of data excess over background the atmospheric neutrino MC was scaled to match the normalisation of the data in the low-energy region dominated by atmospheric neutrino. Similar normalisation scaling was applied to the astrophysical spectrum. Further the shape of the reconstructed energy distribution in the atmospheric neutrino MC was varied to obtain the best match to the data in low-energy range (~1-30 TeV) by applying the scaling of the photoelectron yield. The best matching was found for adding 20% to the baseline MC photoelectron yield in the energy estimator. The same scalings were aplied to the atmospheric and astrophysical neutrino MC. The cut optimisation was performed with a two-dimensional scan over the high energy BDT (BDT_{HE}) and the muon energy cut (E^{μ}_{rec}). The cut values giving the best sensitivity to the flux with index $\gamma = 2.37$ [15], without including systematic uncertainties, were found as $BDT_{HE} > 0.26$ and $E^{\mu}_{rec} > 45$ TeV. After MC adjustments and cut optimisation the reconstructed energy distribution for seasons 2019-2023 was unblinded (Fig.4). One can visually identify an excess of events in data at ~ 100 TeV energies and beyond. The MC expectation for the analysis cuts is 23.5 events from atmospheric neutrino and 1.36 events from atmopspheric muon bundles while 38 events are observed in data. Purely statistical significance of the excess corresponds to 2.39σ. The 90% CL flux limits were estimated using only statistical uncertainties and correspond to $0.59 < \phi < 3.95$ (10^{-18} GeV^{-1}cm^{-2}s^{-1}sr^{-1}). The observed excess favours the presence of the astrophysical neutrino flux component in Baikal-GVD track-like event data with the probability of 99.13% (statistical only) and relevant flux constraints do not contradict the IceCube

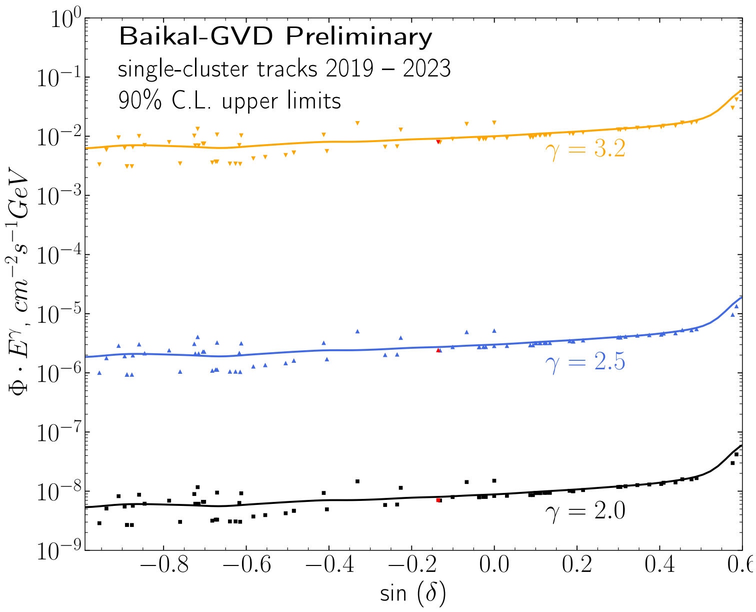

Figure 5: Point source flux limits obtained using track-like event sample from April 2019 to March 2024 for the catalogue of 112 source candidates (see text).

northern track analysis limits [15].

5. Point source flux limits with tracks

A guided search for point-like neutrino sources has been conducted using the same track-like event sample of April 2019 - March 2024. For this, upward-going tracks which pass a BDT-based quality cut, which was optimized using MC simulations to provide the best average 90% C.L. upper limit for an E^{-2} neutrino spectrum ($BDT_{HE} > 0.25$), were used. The analysis used a list of 112 astronomical objects, including the known candidates to neutrino emitters TXS 0506+056 and NGC 1068, the published direction to ultra-high-energy neutrino event from KM3NeT: KM3-230213A, the Galactic center, some objects with claimed associations to IceCube and ANTARES neutrino events and hotspots, and a number of VHE gamma-ray emitters, as well as some X-ray selected Seyfert galaxies and some other notable galactic and extragalactic objects. In the present analysis all objects were assumed to be point-like. The search was conducted in a search cone of a radius of $\alpha = 2°$ around each object. In this simple cut-based analysis the number of events found in the search cone was compared to the estimated background level which was computed by scrambling the data in righ ascension. No statistically significant excess has been found. The 90% C.L. upper limits were calculated following the method of Feldman and Cousins [18] under the assumption of a power law neutrino flux with spectral indices $\gamma = 2; 2.5; 3.2$ (Fig.5). For KM3-230213A, the 90% C.L. flux upper limit is $E^2 dN/dE < 7.05 \times 10^{-9}$ cm^{-2}s^{-1}GeV, assuming E^{-2} spectrum. The upper limits obtained for TXS 0506+056 and NGC 1068 are 9.29×10^{-9} and 1.50×10^{-8} (cm^{-2}s^{-1}GeV), respectively, which does not contradict the IceCube measurements (which rely on a much longer exposure). The object with the largest number of neutrino candidate events falling in the 2° degree cone (three) is Westerlund 1, a young star cluster considered to be a PeVatron candidate. The corresponding pre-trial p-value for the background-only hypothesis is 0.0036, which corresponds to 2.9σ (pre-trial). We note that this analysis does not use the reconstructed muon energy. Therefore we expect the improvement in the analsys sensitivity with inclusion of reconstructed energy variable and using the likelihood technique instead of cut-based.

6. Conclusions

The track-like event reconstruction methods and neutrino selection methods adopted by the Baikal-GVD collaboration have been discussed. Presented methods have been applied to the data taken between April 2019 and March 2024 in single-cluster analysis regime. The total livetime of the selected event sample corresponds to ~30 years of single-cluster data-taking equivalent. The selected data have been used for setting the limits on diffuse astrophysical neutrino flux and point source search. The diffuse astrophysical flux significance and flux limits were estimated in preliminary cut-based analysis using only statistical uncertainties as 2.39σ and $0.59 < \phi < 3.95$ (10^{-18} GeV^{-1}cm^{-2}s^{-1}sr^{-1}) for the spectral index $\gamma = 2.37$ respectively which does not contradict IceCube measurements. The point source search with the selected event sample resulted in no statistically significant excess for the used source catalogue including 112 objects. The 90% CL upper limits on source flux were calculated for a set of single power law spectral indices.

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