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# Selection techniques of neutrino-induced cascades in the Baikal-GVD neutrino telescope

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One of the light signatures in the Baikal-GVD neutrino telescope consists of hadronic and electromagnetic cascades produced by charged interactions of electron and tau neutrinos. In the case of neutral current interactions, all flavors yield cascades. The background in the neutrino cascade channel arises mainly due to discrete stochastic energy losses produced along atmospheric muon tracks. In this contribution, a developed algorithm for the cascade event selection is presented.

*XVIII International Conference on Topics in Astroparticle and Underground Physics (TAUP2023)*
*28.08-01.09.2023*
*University of Vienna*

[*] Speaker



https://pos.sissa.it/

PoS(TAUP2023)248

## 1. Introduction

A cubic kilometer scale neutrino observatory Baikal-GVD (Gigaton Volume Detector) is located in the southern part of Lake Baikal in Siberia. As of 2023, it comprises 3456 light sensors (optical modules - OMs) designed for detecting Cherenkov light produced by secondary charged particles resulting from neutrino interactions in the Baikal water. The primary purpose of the Baikal-GVD is to search for high-energy neutrinos that originate from the same cosmic particle accelerators which produce very high energy cosmic rays.

Thirty-six OMs are placed on each of the 96 vertical strings with an equal distance of 15 m between two adjacent OMs, from depths of 750 m to 1275 m below the lake surface. Each OM contains a 10-inch photomultiplier tube (PMT) Hamamatsu R7081-100 housed in a 17-inch glass sphere. Most of the strings are arranged into independently operated units - clusters, while each cluster is composed of 8 strings (distance of 7 peripheral strings to the central one is 60 meters) [1].

There are two topologically distinct classes of events observed in Baikal-GVD: tracks and cascades. The charged current interaction of a muon neutrino ($\nu_\mu$) with matter results in an outgoing muon, which travels a long distance in water and leaves an elongated track signature. The cascade events arise from the interactions of all three neutrino flavours. The charged current (CC) electron neutrino ($\nu_e$) interaction and the neutral current (NC) electron, muon, and tau neutrino ($\nu_e$, $\nu_\mu$, $\nu_\tau$) interactions produce detectable cascade light signatures.

There is an overwhelming amount of muons produced in air showers when cosmic rays enter the Earth's atmosphere. Muons from the air showers are propagating downwards in bundles containing up to hundreds of muons or even more. In the cascade channel, the main background originates from the discrete stochastic processes along the muon track as a result of bremsstrahlung, photonuclear processes or direct electron-positron pair production. Key feature of a common rejection strategy is to select upgoing events only, however, some cascade events may be wrongly reconstructed as upgoing, while they were truly downgoing muons. A reliable search for the neutrino cascades is, therefore, challenging due to the high atmospheric muon flux.

In this contribution, developed and optimized techniques allowing to distinguish between the neutrino-induced cascades from the falsely identified ones originating from atmospheric muon bundles are discussed. The main difference between signal and the background cascades is the presence of a muon track in the latter ones. For the development of the selection methods Monte Carlo (MC) simulations for the part of the 2019 season from April to June (a configuration of 5 clusters operating independently) were used. Each selection method provides an output variable that serves as an input for the Boosted Decision Tree (BDT) package [2]. The selection algorithm was optimized with single-cluster data only. A selected experimental neutrino cascade candidate was searched for among the multicluster events to find an indication of a muon track.

## 2. Neutrino Cascade Events Selection Algorithm

For the development of the techniques for the selection between signal and background cascades MC data sets were generated for each of 5 clusters individually. Between April 1 and June 30 of year 2019 the optical activity (luminescence) of the lake was relatively low and the noise rates fluctuated from $\approx$ 15 kHz (for the bottom OMs) to $\approx$ 50 kHz (for the OMs located at the uppermost sections)

[3]. The experimental data of this period add up to a single-cluster equivalent livetime of 353 days (combined for all 5 clusters). In MC data samples, the atmospheric $\nu^{\mathrm{atm}}$ and astrophysical $\nu^{\mathrm{astro}}$ neutrino events (only electron and muon flavors for both fluxes) were considered as signal events. Neutrino energies range from 1 TeV to 400 TeV and from 1 TeV to 400 PeV for atmospheric and astrophysical neutrinos, respectively. The energy interval of cosmic ray protons in the background MC sample is from 240 GeV to 100 PeV. In the following analysis, a simple containment cut was applied: the horizontal distance from the vertex to the cluster center must be less than 100 meters.

Within this context, a presented selection technique that implements various selection methods for neutrino cascade events with multicluster search represents an improved version of the cascade selection algorithm [4]. The optimization was performed on the simulated data of background cascades from atmospheric muons $\mu_{\mathrm{atm}}$ and on signal cascades from $\nu^{\mathrm{atm}}$ and $\nu^{\mathrm{astro}}$ interactions. Signal cascades from both datasets ($\nu^{\mathrm{atm}}$ and $\nu^{\mathrm{astro}}$) were merged into one for the selection analysis to properly include the weights of both neutrino fluxes and also to include higher energies.

For the analysis we considered only contained cascade-like events reconstructed as upgoing. The *nTrackHits* method is described here in detail among other methods like e.g. *BranchRatio* or

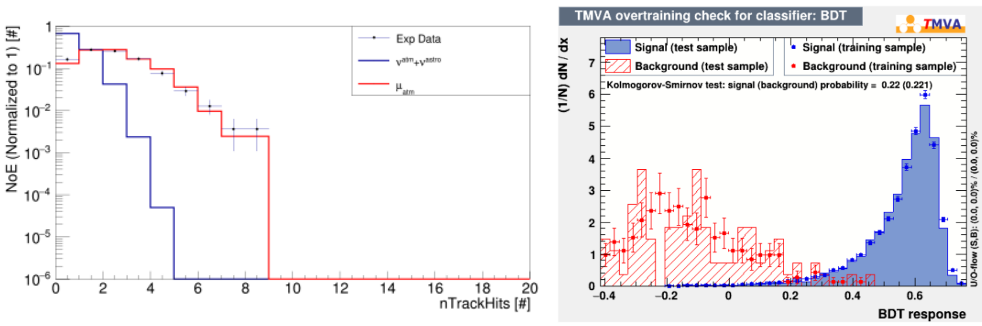


**Figure 1:** *nTrackHits* (left) distribution for the signal cascades (blue line), background cascades (red line), and experimental data (black dots). BDT response score (right) for background cascades (red histogram) and signal cascades (blue histogram).

*QEarly* (see ref. [4] for more details) for the sake of illustration. It relies on the existence of a muon track within the atmospheric muon bundle and its absence in the neutrino cascade events. The *nTrackHits* method selects hits with time residuals in the interval: $t_1 < t_i - T_i^{\mathrm{track}} < t_2$, where $t_i$ is the OM hit time, $t_1 = -100$ ns, $t_2 = 25$ ns. The expected time $T_i^{\mathrm{track}}$, when the OM is supposed to detect a hit from the muon track [4]. This method identifies the hits per event that fulfill the criteria for the muon track. In the background cascade event, track hits occur earlier at a given OM than the cascade hits are expected to. In Fig. 1 (left) the distribution of such *nTrackHits* for neutrino-induced cascade-like events (combined MC datasets $\nu_{e,\mu}^{\mathrm{atm}}$ and $\nu_{e,\mu}^{\mathrm{astro}}$ shown by blue line), background cascades (red line), and experimental data (black points) is displayed.

**Table 1:** Reconstructed parameters of the most energetic event found in data of year 2019 for Cluster1: energy, zenith angle, azimuth angle, distance from the cluster center, likelihood, total charge, total number of hits, number of hits used in the reconstruction, and number of hits identified as track hits.

| $E_{\mathrm{rec}}$ [TeV] | $\theta$ [°] | $\phi$ [°] | $\rho$ [m] | L | Q [p.e.] | nHits | nRecoHits | nTrackHits |
|---|---|---|---|---|---|---|---|---|
| 83.3 | 70.9 | 4.96 | 47.65 | 1.01 | 1665 | 106 | 44 | 1 |

In total, there are five output variables from the cascade reconstruction of signal and background simulated datasets for the multivariate event classifier BDT within the TMVA package [2]. In particular, these are *nTrackHits*, *BranchRatio*, *QEarly*, the Chi-Square after cascade position reconstruction [5], and the reconstructed zenith angle. The BDT response value for signal and background cascades is shown in Fig. 1 (right) while a cut on the BDT response score 0.48 has been chosen according to maximum significance. In addition, a minimal energy cut of 50 TeV was introduced. Applying this analysis to the April-June 2019 dataset yields one upgoing event, which is detected in Cluster 1 with zenith angle $\theta = 70.9°$ and reconstructed energy E = 83.3 TeV. A search for simultaneous events in the other detector clusters has been performed. The multicluster event detection can be very useful as a veto for the background cascades produced along muon tracks due to the fact that long-range muon track can often be detected in more than one cluster. The event presented in Tab.1 was not found among multicluster events, providing additional support to its cascade-like origin. Given the relatively high energy of this event, it is likely of astrophysical origin.

## 3. Conclusion

Several selection methods for the selection of neutrino induced cascades have been developed. The methods have been optimized using Monte Carlo simulations for a part of season 2019 exhibiting relatively calm ambient lake background. Selected background rejection variables were used for training and testing of BDT with the contained upgoing neutrino and background cascades. In search for the neutrino cascade candidates with higher energy in experimental data we applied cuts on the BDT output value and the reconstructed energy. As a result, a contained upgoing event was reconstructed with 83.3 TeV energy. A multicluster analysis of this experimental event found no muon counterparts in the multicluster data. Most likely this event is of neutrino origin.

## 4. Acknowledgements

The author (Z. Bardačová) is supported by Slovak Research and Development Agency (Contract No. APVV-22-0413). We acknowledge support by the MEYS of the Czech Republic (Contract Number LM2023063).

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