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# Baikal-GVD: cascades

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**Abstract.** Baikal-GVD is a next generation, kilometer-scale neutrino telescope currently under construction in Lake Baikal. GVD is formed by multi-megaton subarrays (clusters) and is designed for the detection of astrophysical neutrino fluxes at energies from a few TeV up to 100 PeV. The design of Baikal-GVD allows one to search for astrophysical neutrinos with flux values measured by IceCube already at early phases of the array construction. We present here preliminary results of the search for high-energy neutrinos via the cascade mode obtained in 2015 and 2016.

## 1 Introduction

The deep underwater neutrino telescope Baikal-GVD (Gigaton Volume Detector) is currently under construction in Lake Baikal [1]. Baikal-GVD is formed by a three-dimensional lattice of optical modules, which consist of photomultiplier tubes housed in transparent pressure spheres. They are arranged at vertical load-carrying cables to form strings. The telescope has a modular structure and consists of functionally independent clusters - sub-arrays comprising 8 strings. Each cluster is connected to the shore station by

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an individual electro-optical cable. The first with reduced sided, named “Dubna”, was deployed and operated in 2015. In April 2016, this array has been upgraded to the baseline configuration of a GVD-cluster, which comprises 288 optical modules attached along 8 strings at depths from 750 m to 1275 m. In 2017 and 2018, the second and third GVD-clusters were commissioned, increasing the total number of optical modules up to 864 OMs. As Part of phase 1 of the Baikal-GVD construction, an array of eight clusters will be deployed until 2021.

IceCube has discovered a diffuse flux of high-energy astrophysical neutrinos in 2013 [2]. The 7.5 year data sample of high-energy starting events (HESE) comprises 103 events, 77 of which are identified as cascades and 26 as track events [3]. The Baikal Collaboration has long-term experience with the NT200 array to search for diffuse neutrino fluxes via the cascade mode [4,5]. Baikal-GVD has the potential to record already at early phases of construction astrophysical neutrinos with a flux measured by IceCube [6]. One search strategy for high-energy neutrinos with Baikal-GVD is based on the selection of cascade events generated by neutrino interactions in the sensitive volume of the array [7]. Here we discuss the first preliminary results based on data accumulated in 2015-2016.

## 2 Cascade detection by GVD

The search for high-energy astrophysical neutrinos is based on data collected from 24 October till 17 December 2015. A data sample of $4.4 \times 10^8$ events formed after the array trigger was accumulated. This corresponds to 41.64 array live days. Causality cuts and the requirement of $N \geq 3$ hit OMs left about $1.8 \times 10^7$ events for the subsequent analysis. After applying an iterative procedure of cascade vertex reconstruction for hits with charge higher 1.5 photoelectrons, followed on each iteration stage by the rejection of hits contradicting the cascade hypothesis, 316229 events survived as cascade-like events. After cascade energy reconstruction and quality cuts, 12931 cascade-like events remained. 1192 of these events were reconstructed with energies above 100 TeV. The multiplicity distribution of hit OMs for these events is shown in Figure 1 (left). Also shown are the expected event distributions from an astrophysical flux with an $E^{-2.46}$ spectrum and the IceCube normalization, as well as the expected distributions from atmospheric muons and atmospheric neutrinos. The statistics of the generated atmospheric muon sample corresponds to 72 live days of data taking. All experimental events but one have less than

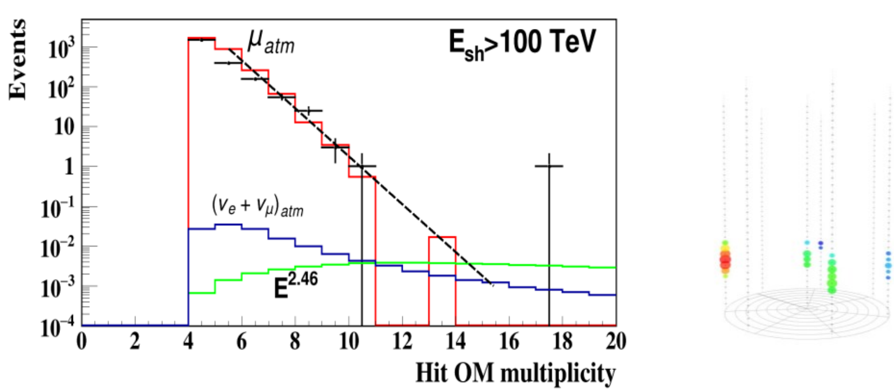


**Fig. 1.** Left: Multiplicity distribution of hit OMs for experimental events with reconstructed energy $E_{rec}$ > 100 TeV (dots). Also shown are the distributions of expected events from astrophysical neutrinos with an $E^{-2.46}$ spectrum and of background events from atmospheric muons and neutrinos. Right: The event with a hit multiplicity of 17 was observed on October 2015.

10 hit OMs and are consistent with the expected number of background events from atmospheric muons. One event with 17 hit OMs was reconstructed as a downward moving cascade. For a more precise reconstruction of cascade parameters, this event was retested including hits with charges below 1.5 photoelectrons. In this case, 24 hits are consistent with the cascade hypothesis. The reconstructed cascade parameters are: cascade energy $E$ = 107 TeV, zenith angle $\theta = 57^{\circ}$, azimuthal angle $\varphi = 131^{\circ}$, distance from the array axis $\rho$ = 68 m. The event is shown in Figure 1 (right panel).

The search for cascades from astrophysical neutrinos has been continued with the data sample collected between April 2016 and January 2017, corresponding to an effective live time of 182 days. A data sample of $3.3 \times 10^{8}$ events passed the causality cuts and the requirement of N $\geq 3$ hit OMs on $\geq 3$ strings with hit charges $\geq 1.5$ photoelectrons. At the

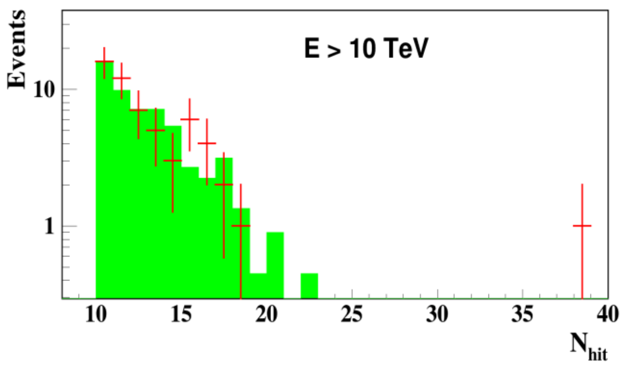


**Fig. 2.** Multiplicity distribution of hit OMs for data (points) and atmospheric muons (histogram), for events with reconstructed energies $E_{sh}$ > 10 TeV.

next stage of analysis, a cascade reconstruction procedure and a set of quality cuts have been applied to the data. 57 events with $E_{sh}$ > 10 TeV and 5 events with $E_{sh}$ >100 TeV passed all procedures. Figure 2 shows the hit multiplicity of events with $E_{sh}$ > 10 TeV and the expected distribution of background events from atmospheric muons. Four of five

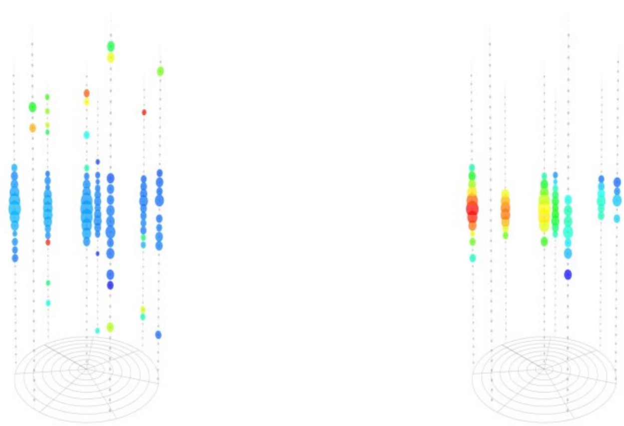

**Fig. 3.** The event with multiplicity 38 was observed on April 2016. The left plot shows all hits; the right plots shows the hits, which survived all cuts. Note that the color scale that indicates the relative times is different.

events with energies higher than 100 TeV have hit multiplicities consistent with the expected distribution of background events from atmospheric muons. One event with 38 hit OMs was reconstructed as downward moving contained cascade. Again, for a more precise reconstruction of the cascade parameters, this event was re-analyzed including hits with charges lower 1.5 photoelectrons. 53 hits are consistent with a cascade hypothesis. The reconstructed cascade parameters are: cascade energy $E$ = 155 TeV, zenith angle $\theta = 57^{\circ}$ azimuthal angle $\varphi = 249^{\circ}$, distance from array axis $\rho$ = 45 m. Accuracy of cascade energy reconstruction is about 30%, the accuracy of direction reconstruction is about 4.5° degree (median value) and vertex resolution is about 1.5 m. The event is shown in Figure 3. The left and right panels show the hit OMs before and after noise hit rejection, respectively. The calculations of the probabilities to obtain such high multiplicity events from atmospheric muons and neutrinos are in progress.

In summary, two high-energy cascade events have been selected from GVD data recorded during 2015-2016. The equatorial coordinates of their potential sources are: right ascension (RA) $139^{\circ}$ and declination (Dec) $6^{\circ}$ for the first (2015) event, and right ascension (RA) $173^{\circ}$ and declination (Dec) $14^{\circ}$ for the second (2016) event.

## 3 Conclusion

The ultimate goal of the Baikal-GVD project is the construction of a $km^3$-scale neutrino telescope with the implementation of about ten thousand photo-detectors. The array construction was started by the deployment of a reduced-size demonstration cluster named "Dubna" in 2015, which comprises 192 optical modules. The first cluster in its baseline configuration was deployed in 2016 and the second one in 2017. With the deployment of the third GVD-cluster in April 2018, Baikal-GVD comprises a total of 864 OMs arranged in 24 strings. It is, at present, the largest underwater neutrino telescope. The modular structure of Baikal-GVD design allows for studies of neutrinos of different origin at early stages of construction. The analysis of data collected in 2015-2017 allows for selection of the first two promising high-energy cascade events - candidates for events from astrophysical neutrinos. The commissioning of the first stage of the Baikal neutrino telescope GVD-1 with an effective volume 0.4 $km^3$ is envisaged for 2020-2021.

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