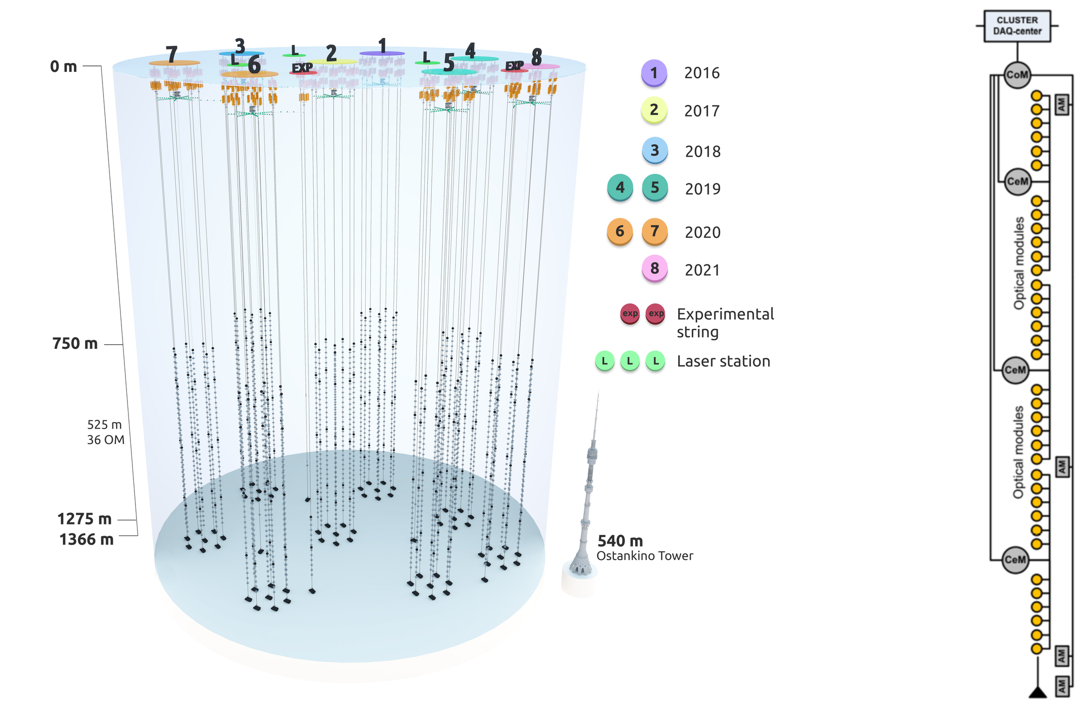
Development of the Double Cascade Reconstruction Techniques in the Baikal-GVD Neutrino Telescope

{ E. Eckerová* on behalf of the Baikal-GVD Collaboration }

* Faculty of Mathematics, Physics and Informatics, Comenius University in Bratislava

Neutrino Telescope GVD

The Baikal Gigaton Volume Detector (Baikal-GVD) [1] is a neutrino telescope installed in the deepest freshwater lake in the world - Lake Baikal. The main goal of this telescope is to observe neutrinos via detecting the Cherenkov radiation of the secondary charged particles originating in the interactions of neutrinos. It is a three dimensional array of photomultiplier tubes installed approximately 3.6 km from shore, at the depth of ~ 1.3 km. The basic independently working unit of the Baikal-GVD is called cluster. The cluster consists of 8 strings, on every string there are 36 Optical Modules (OM). In 2021, 8 clusters are installed resulting in 2304 OM deployed and effective volume ~ 0.4 km^3



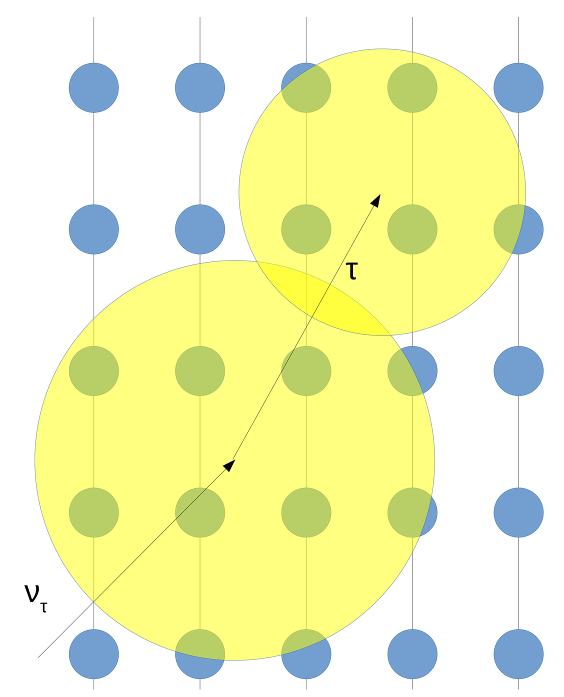
The main component of the OM is a photomultiplier tube with hemispherical photocatode enclosed in pressure-resistant glass sphere with diameter 42 cm. In OM, there is also a controller, a two channel amplifier, two LEDs for time and charge calibrations, and a high-voltage supply.

Tau Neutrino Interaction

One of the methods for astrophysical neutrino detection is an observation of high-energy ν_τ, because the rate of ν_τ produced in the atmosphere is almost negligible [2].

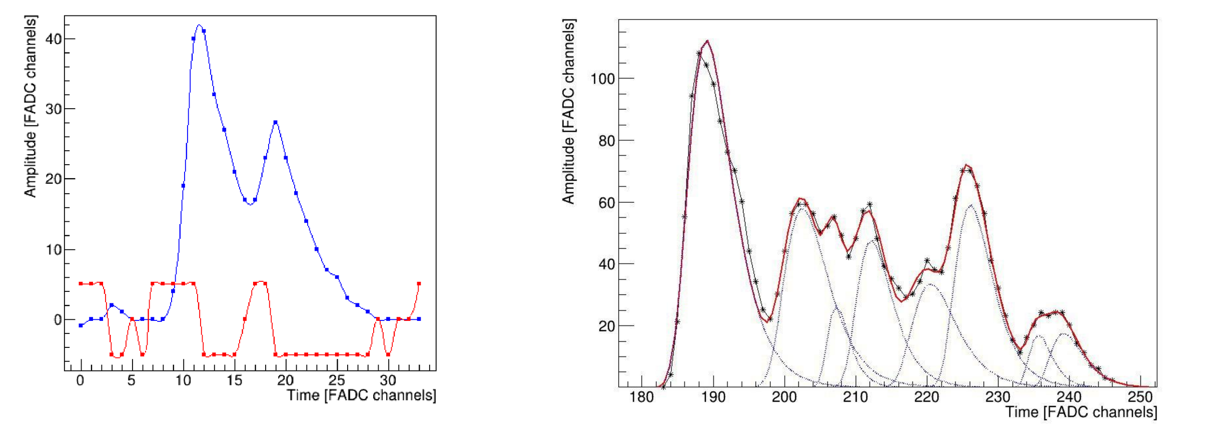
In general, there are two types of signatures of charged current ν_τ interaction according to τ decay mode:

- decay to muon $\rightarrow$ single cascade signature, branching ratio $\sim 17\%$
- **decay to electron/hadrons $\rightarrow$ double cascade signature, branching ratio $\sim 83\%$**

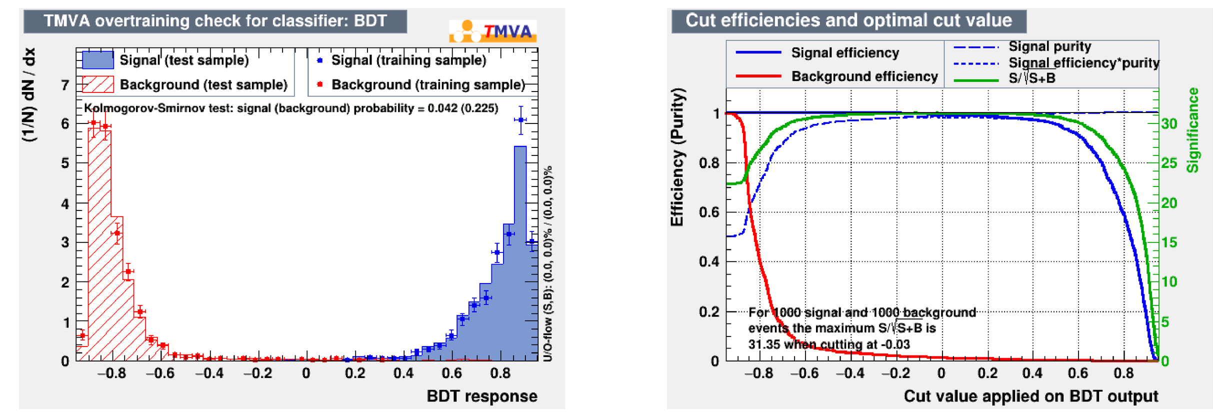


Search for Double Cascades with Double Pulses

For the reconstruction of double cascade events with small distance between cascade vertices, double pulse detection method was developed. Potential double pulses (DPs) are selected by differentiation method. If the sign of the first derivative is changed from negative to positive value, potential DP is tagged.



However, many fake DPs created by pedestal oscillations are selected with the differentiation method. To be able to supress them, multivariate technique based on machine learning - Boosted Decision Trees (BDTs) from the ROOT TMVA package [3] was trained. The signal and background datasets contain 12 parameters of approximately 3000 waveforms for training and testing of BDTs. The signal efficiency gained is 99.6%, the background efficiency is 1.4% [4].



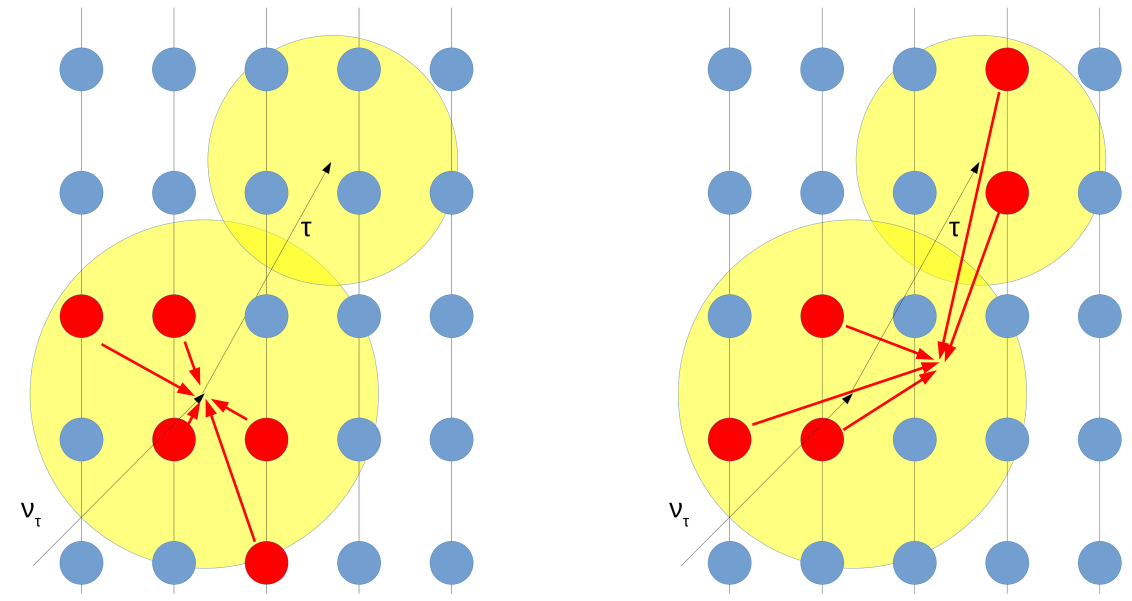
Double pulse detection method can also be used for multiple pulses identification. Subsequently, multiple pulses can be separated and attributes of individual pulses can be determined.

Single Cluster Double Cascade Reconstruction

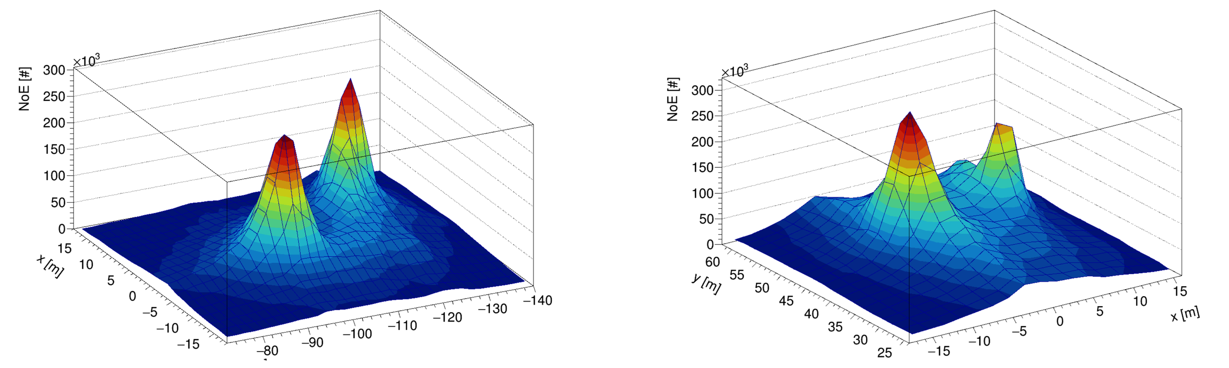
The first step in the single cluster double cascade reconstruction algorithm is to separate signal and noise pulses. The signal pulses are selected according to the causality criterion:

$$| t - t_i | < d_i/v + \delta t. \tag{1}$$

The efficiency of signal pulse selection is $\sim 80\%$ and purity is $\sim 99\%$.
The second step is dividing signal pulses into two subsets for two independent single cascade reconstructions. Firstly, set of five pulses is selected. They are used for estimation of cascade position and time. If they correspond to one cascade only, position and time should be estimated accurately.



Accurate estimation of position and time of cascade allows effective selection of pulses corresponding to particular cascade.



In the next step, selected subsets of pulses are processed with single cascade reconstruction separately [5]. In the single cascade reconstruction, position and time of cascade are estimated via minimizing of χ^2 distribution:

$$\chi^2 = \frac{1}{N_{hit} - 4} \sum_{i=0}^{N_{hit}} \frac{(T_i^{meas} - T_i^{exp}(\vec{R}, T))^2}{\sigma_t^2}. \tag{2}$$

Energy and direction are determined by minimizing of likelihood function:

$$L = - \sum_{i=0}^{hitOM} log(P_i(q_i \mid Q_i)) - \sum_{i=0}^{unhitOM} log(P_i(q_i = 0 \mid Q_i)). \tag{3}$$

where P_i is the Poisson probability of detecting charge q_i on i^{th} OM, while detection of charge Q_i is expected.

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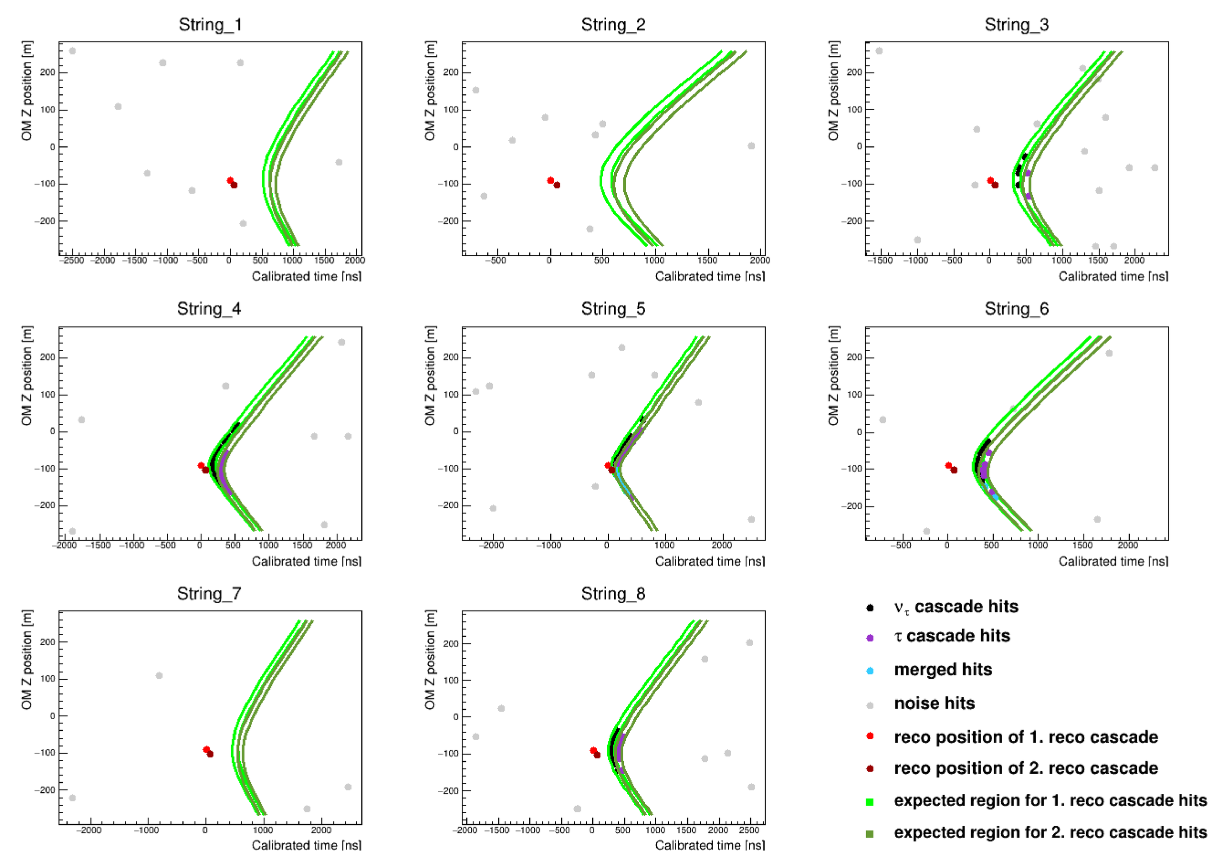
Reconstructed MC ν_τ event



The MC simulated distance between cascades is 18.17 m. The mismatch between simulated and reconstructed position of ν_τ cascade is 1.84 m and 3.27 m for τ cascade.

Multi-cluster Double Cascades

The multi-cluster double cascade identification algorithm combines single cascade reconstruction technique with multi-cluster events. Double cascade event is tagged if two single cascades were reconstructed separately in two different clusters.
Approximately 87 000 cascades were reconstructed by single cascade reconstruction technique in the experimental data collected in year 2019. Same dataset has been processed with multi-cluster double cascade identification algorithm. This method tagged one double cascade event. Reconstructed distance between cascade vertices is ~ 328.75 m.

	θ [rad]	ϕ [rad]	E [TeV]	likelihood
cascade 1	2.20	3.85	8.06	0.92
cascade 2	2.32	3.66	4.72	1.08

According to the analysis of reconstructed parameters of two cascades, the probability of ν_τ origin of this event can be excluded.

References

[1] https://baikalgvd.jinr.ru/

[2] A. Palladino et al., The importance of observing astrophysical tau neutrinos. J. Cosmol. Astropart. P. 8 (2018).

[3] A. Hoecker et al., TMVA 4 - Toolkit for Multivariate Data Analysis with ROOT, Users Guide. ArXiv:physics/0703039 (2017).

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[5] Baikal-GVD Collaboration: A.D. Avrorin et al., Search for cascade events with Baikal-GVD, PoS-ICRC2019-0873, arXiv:1908.05430, doi:10.22323/1.358.0873