METHODS FOR THE SUPPRESSION OF BACKGROUND CASCADES PRODUCED ALONG ATMOSPHERIC MUON TRACKS IN BAIKAL-GVD

Zuzana Bardačová
on behalf of the Baikal Collaboration

Comenius University in Bratislava

BAIKAL GVD

The Baikal Gigaton Volume Detector (GVD) is placed 1366 meters deep in Lake Baikal and 3.6 km from the shore [1]. The major benefit of Lake Baikal is that its surface freezes during the winter, which enables easier and cheaper installation of the detector. Moreover, its very clear water provides low absorption and scaterring of light.
Currently (year 2021) the detector consists of 8 clusters with a total instrumented volume of 0.4 km^3, see Fig. 1. The cluster comprises 288 Optical Modules (OMs) arranged on 8 strings. Especially, 7 peripheral strings are located around a central string at a radius of 60 m. The basic detection component is the OM, which registers Cherenkov radiation produced by charged particles coming from neutrino interactions. The OM includes a pressure-resistant glass sphere, which contains a PMT R7081-100, a LED calibration unit, a controller, an amplifier, and HV converter.

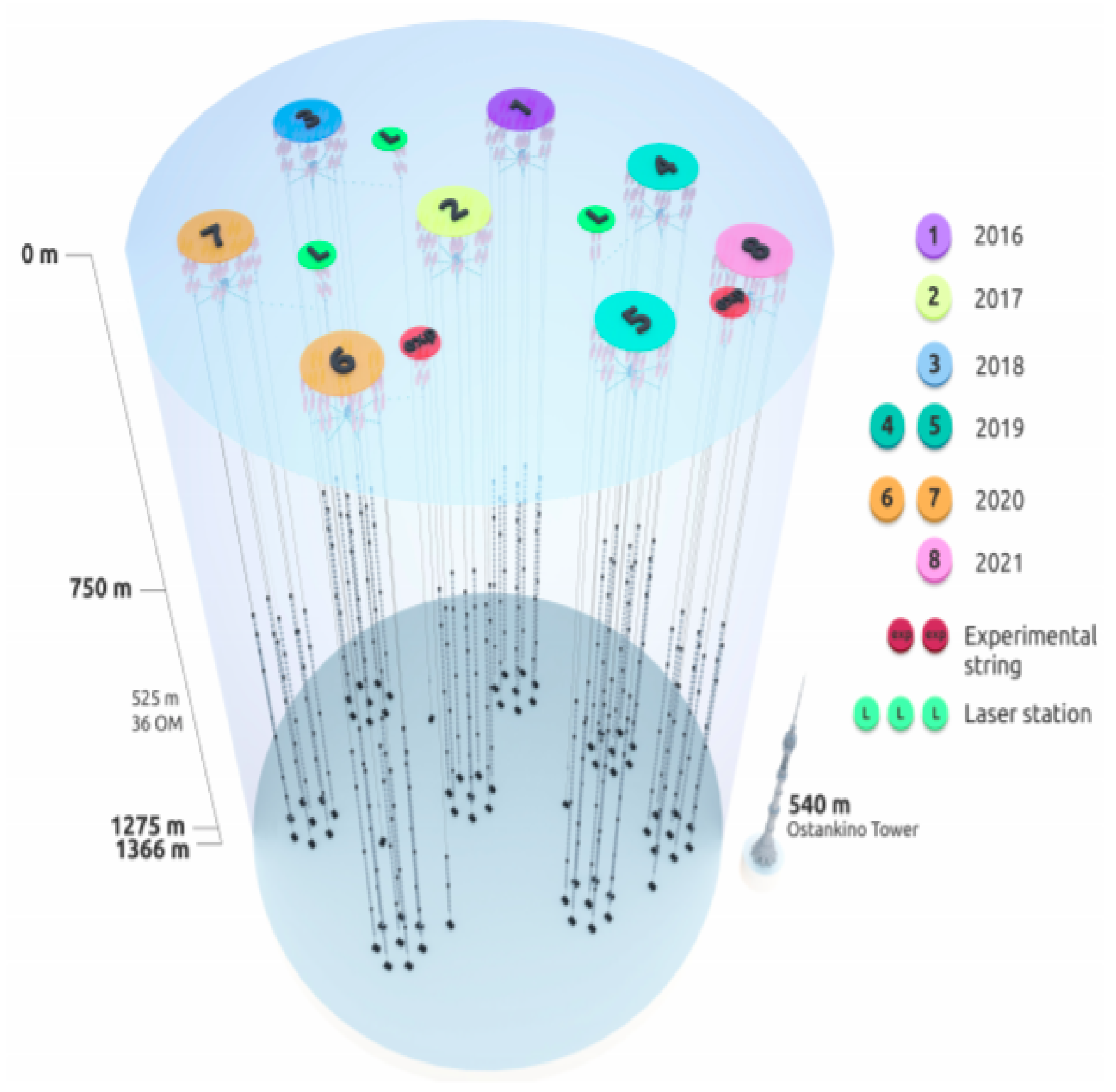

Figure 1: Illustration of the Baikal-GVD detector.

LIGHT TOPOLOGIES

According to the event topology, it is possible to distinguish between different types of the neutrino interactions. The signature of charge-current ν_μ interaction (see Eq. 1) gives rise to the track-like events.

$$\nu_\mu\,(\bar{\nu_\mu}) + N \xrightarrow{W^\pm} \mu^-\,(\mu^+) + X \qquad (CC). \tag{1}$$

For all neutral-current interactions, a cascade of hadrons is produced at the interaction vertex along with the outgoing neutrino (see Eq. 2).

$$\nu_l\,(\bar{\nu_l}) + N \xrightarrow{Z^0} \nu_l\,(\bar{\nu_l}) + X \qquad (NC). \tag{2}$$

The cascade is also produced by the CC interaction of ν_e where the outgoing electron produces an electromagnetic shower. In comparison with the muon tracks, cascades provide a relatively precise energy measurement, but they have worse angular resolution. The irreducible background from atmospheric ν_e is smaller than in the muon channel from the atmospheric ν_μ . A large part of the most energetic events detected by neutrino telescopes were cascades. All these traits make cascades promising detection channel for the identification of extraterrestrial neutrinos of high energies.

BACKGROUND CASCADES

The classification of detected events in the reconstruction procedure may not always be clear. Atmospheric muons produce cascade-like events along their tracks via stochastic energy losses. These events create background in the search of the high-energy signal neutrino cascades. These background cascades constitute a major part of reconstructed cascade events from experimental data (season 2019), see Fig. 2.

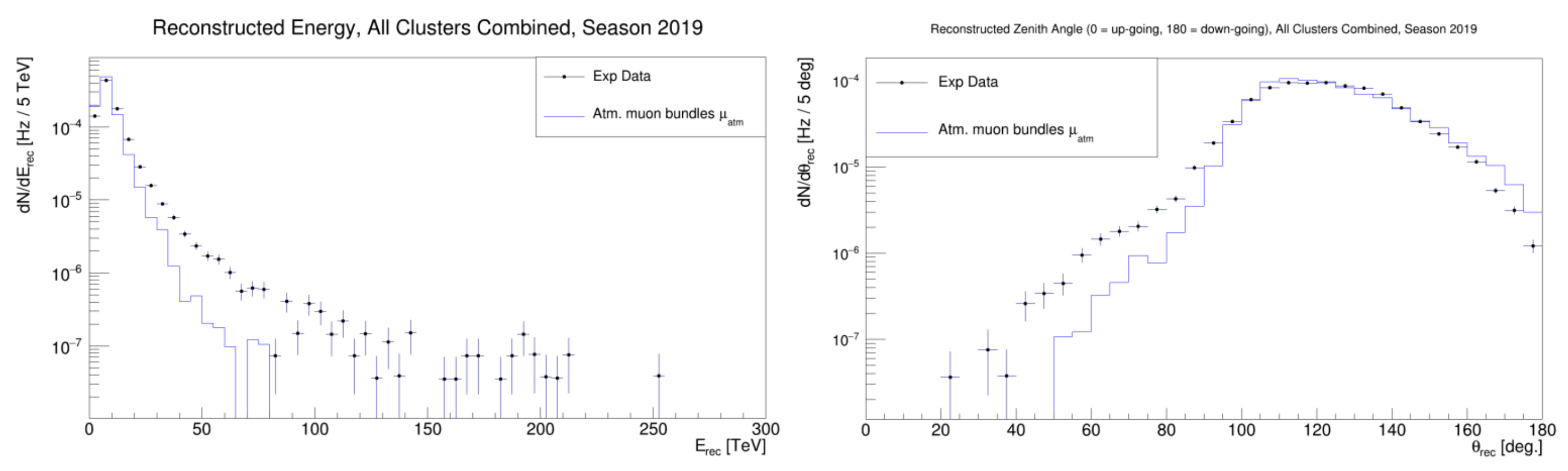

Figure 2: Left: Reconstructed energy distribution of well-reconstructed contained cascades. Right: Zenith angle distribution.

For that reason, different analysis methods for the suppression of such events have been developed, tested, and optimized with MC datasets: atmospheric muon bundles sample (μ_{atm}), atmospheric upgoing muon neutrinos (ν_μ^{atm}) and atmospheric electron neutrinos (ν_e^{atm}). One of such methods is a nTrackHits function, which is supposed to find most of the muon track hits (referred to as $nTrackHits$) in the μ_{atm} event. It is based on calculation of track expected time T_i on a given OM according to equation, see Fig. 3 (left):

$$T_i = t_{\text{recoCascade}} + (\text{sLong} - \text{lLong}) \cdot \frac{1}{\text{c}} + \sqrt{\text{sPerp}^2 + \text{lLong}^2} \cdot \frac{1}{\text{c}_{\text{water}}} \tag{3}$$

The next applied method, called BranchRatio filter is used to reduce down-going μ_{atm} events. The BranchRatio is defined as follows: $BR = \frac{\text{nHitsOMs}_{\text{upper}}}{\text{nHitsOMs}_{\text{lower}}}$
In Fig. 4 (left) the dependence of the detected hit time on the OM z coordinate, which detected a given hit within one cluster string is displayed. The graph is shown for the MC μ_{atm} simulated event, where different origins of hits are differentiated in color. Fig. 4 (right) shows the BR distribution for MC datasets. Some other suppression methods have also been developed and implemented.

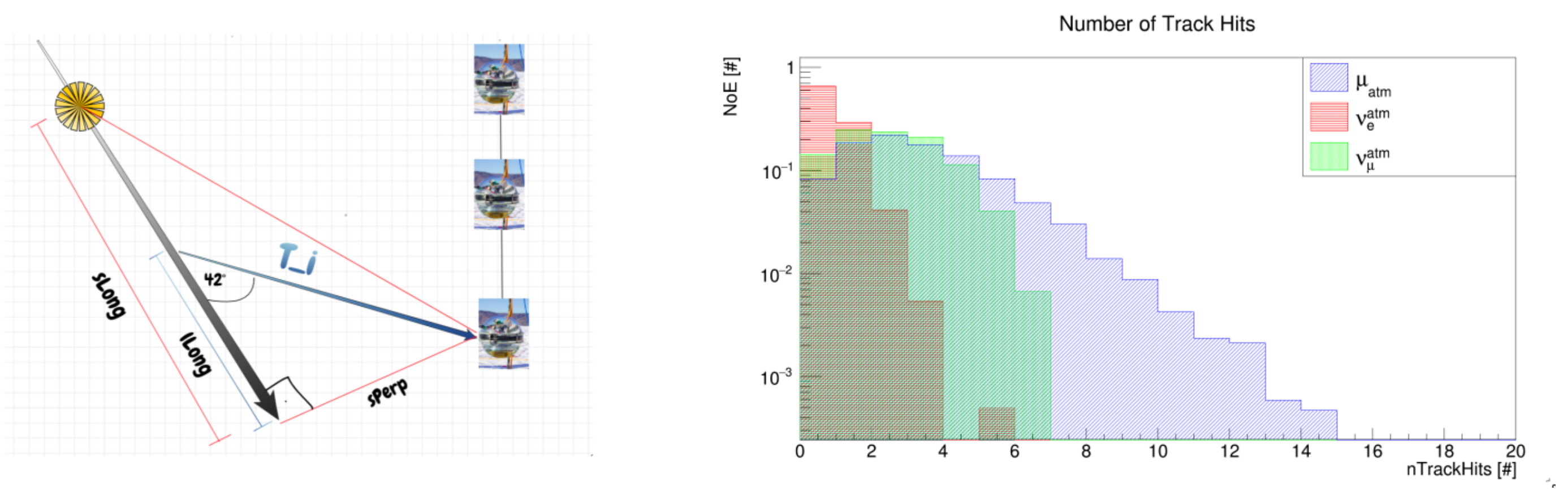

Figure 3: Left: Illustration of the background cascade geometry used for the T_i calculation. Right: Distribution of found nTrackHits for MC datasets. distribution.

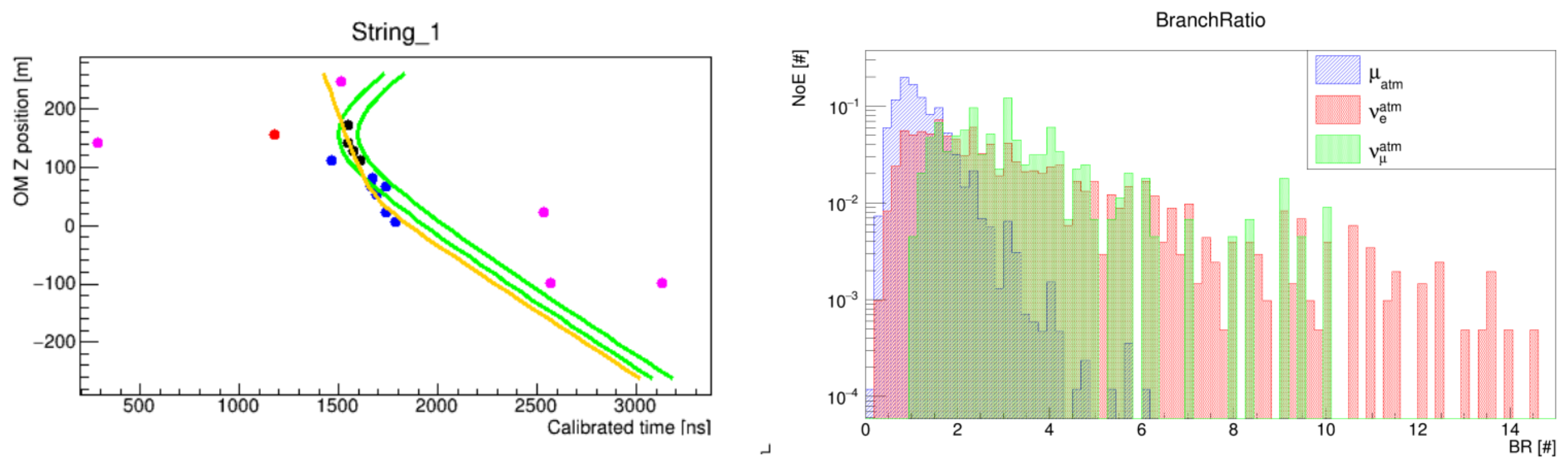

Figure 4: Left: Graph of the hit detection time dependent on the OM z coordinate per one string. Blue point are for track hits, black are for the cascade hits, pink hits belong to the noise, while green band corresponds to the expected time region for cascade hits and orange line is expected time for track hits calculated according to the Eq. 3 Reconstructed cascade is shown by red color. Right: The distributions of BR for three different MC datasets

RESULTS

As any of the developed variables does not provide a clear separation between signal and background cascades, a Boosted Decision Trees (BDTs) were used to obtain the best discriminating power of many variables [2]. After the BDTs are trained, a BDT response of signal and μ_{atm} background event is produced, see. Fig. 5 (left). Agreement of the BDT response for MC μ_{atm} events and experimental data (season 2019) can be seen in Fig. 5 (right). When applying cut on the BDT value, 25 contained and uncontained events satisfy this cut condition. The distribution of reconstructed energies and zenith angles for these experimental signal cascades arse shown in Fig. 6. Most of the events have lower energies (< 20 TeV). Two events have higher energies (see Tab. 1) and were reconstructed as upgoing, which increase the probability they can be produced in the neutrino interaction.

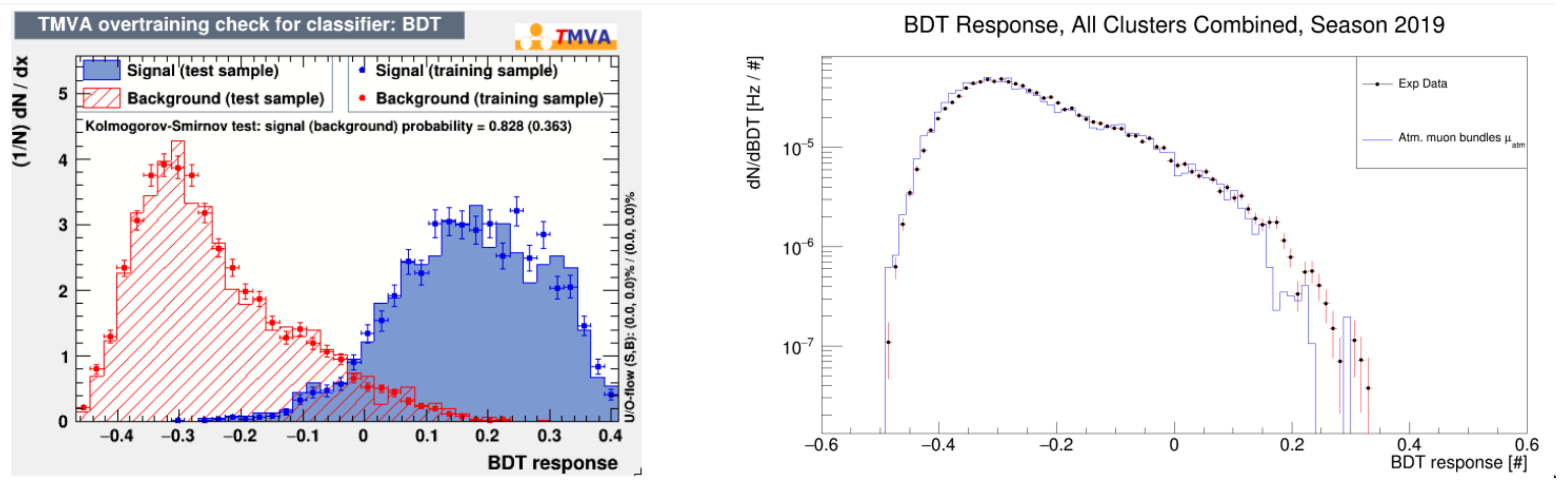

Figure 5: Left: The BDT response distribution for MC signal (blue) and background cascades (red). Right: The BDT value is shown for MC μ_{atm} backgound cascades (blue) and experimental data, season 2019 (black points).

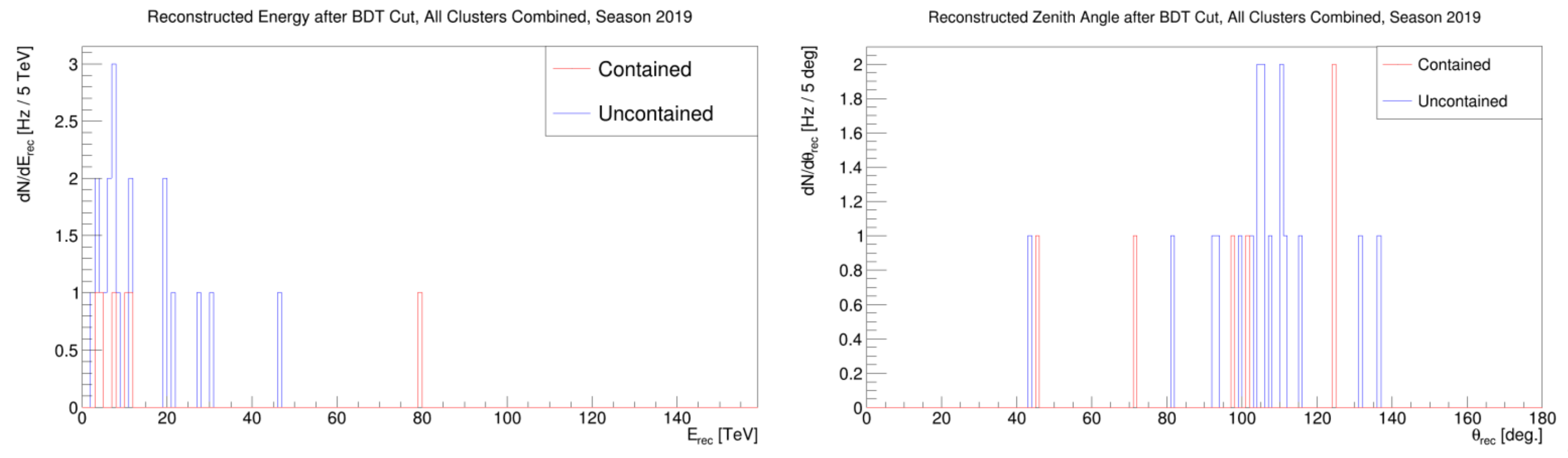

Figure 6: Left: Reconstructed energies for experimental events with applied BDT cut for contained (red) and uncontained events (blue). Right: Reconstructed zenith angle.

Table 1: Reconstructed parameters of two most energetic events: Cluster, Energy, Zenith angle, Azimuth angle, Horizontal distance, Likelihood, Total charge, Total number of hits, Number of hits used in reconstruction, Number of track hits.

Cl	E_{rec} [TeV]	θ [°]	ϕ [°]	ρ [m]	L	Q [p.e.]	nHits	nRecoHits	nTrackHits
0	79.7	71.30	4.96	47.65	1.05	1665.01	106	49	0
4	46.6	43.11	247.31	61.55	1.25	3804.82	69	23	0

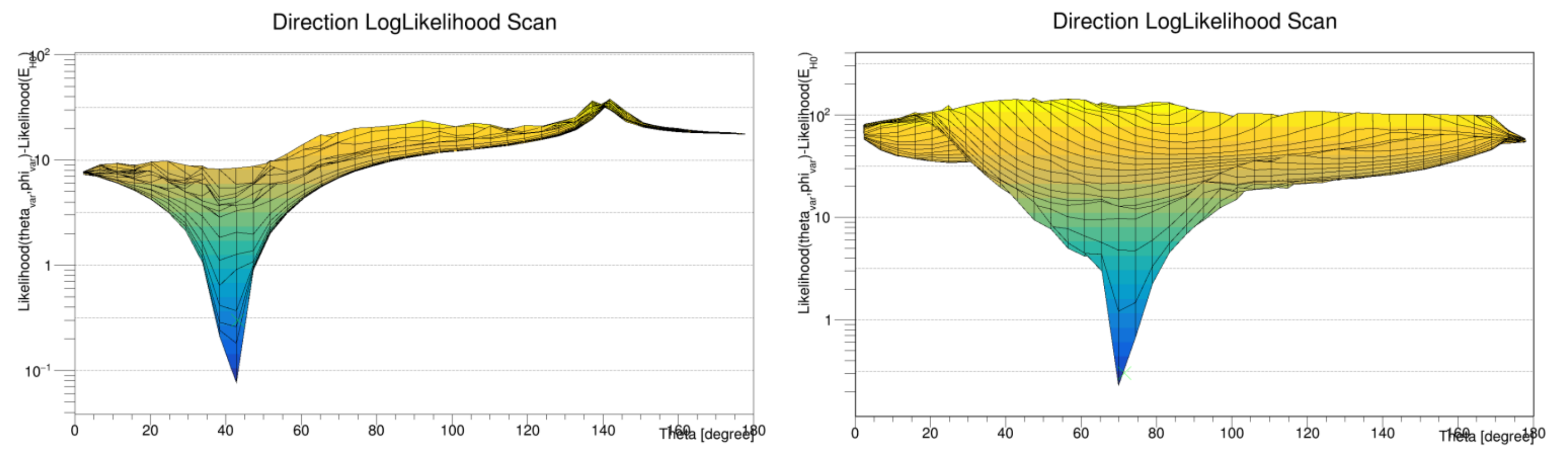

Figure 7: Left: Dependence of the likelihood scan values on the zenith angle for uncontained event with energy 46.6 TeV. The significant minimum of the likeihood values is obtained for the reconstructed zenith angle. Right: Likelihood scan for contained event with energy 79.7 TeV.

REFERENCES

[1] https://baikalgvd.jinr.ru/
[2] A. Hoecker et al., TMVA 4 - Toolkit for Multivariate Data Analysis with ROOT, Users Guide. arXiv:physics/0703039 (2017).