The Baikal-GVD Neutrino Telescope: Muon Track Events Reconstruction

Lukáš Fajt
on behalf of Baikal-GVD collaboration

IEAP CTU PRAGUE & FMPI CU BRATISLAVA

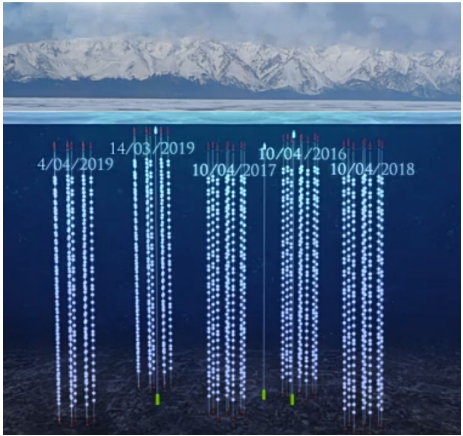
36^{th} International Cosmic Ray Conference, Madison, Wisconsin
July 31, 2019

Author G. B. Safronov

Author G. B. Safronov

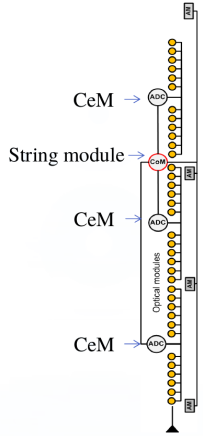
Introduction

- First full-scale cluster “Dubna” was commissioned and taking data since 2016
- In 2019, 5 clusters working = 40 strings = 1440 OMs = 0.25 km^3
- Charge and Time calibrations performed and applied
- Real position of every OM measured with Acoustic Positioning System
- Lake and PMT noise studied in detail.
- Data quality monitoring
- Muon track reconstruction developed using 2016 data

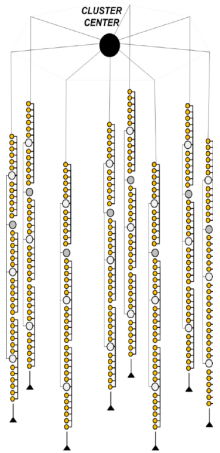


Baikal-GVD

Optical Module (OM)
PMT: Hamamatsu R7081-100



String: 3 sections, 12 OMs/section
Instrumented depth: 750 -1250 m



Cluster: 8 strings, 288 OMs
Radius 60 m, Clusters distance 300 m

Track Reconstruction Procedure

Track Parametrization: At least 6 hits at 3 strings are required, simple χ^2-like fit is used so far

$$\vec{R}(t) = \vec{R_0} + c\,(t - t_0)\,\vec{V} \tag{1}$$

where $\vec{V}$ is a unit vector and $\vec{R}_0$ and t_0 are taken in plane $z = 0$.

Initial Track Approximation:

$$\vec{V}_{init} = \frac{1}{\sum\limits_{t_i < t_j} |\vec{R}_{ij}|} \sum_{t_i < t_j} \vec{R}_{ij} \tag{2}$$

where i and j are ordered in time and belong to different strings.

Minimization function (quality):

$$Q = \sum_{i=1}^{N_{hit}} \left[\frac{(t_i^{est} - t_i)^2}{\sigma^2} + \frac{A(a_i)D(d_i)}{d_0} \right] \tag{3}$$

where A and D are amplitude and distance functions and $\sigma_t = 3\,\text{ns}$. Inspired by ANTARES arxiv:1105.4116.

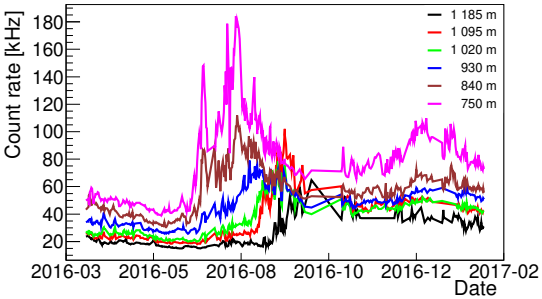
Muon prompt Cherenkov radiation approximation is used for the time estimation

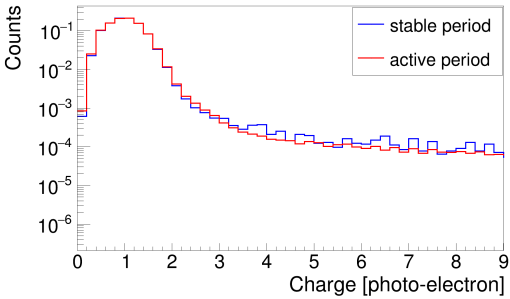
Lake and Detector Noise

OM pulses due to PMT dark current and lake fauna must be rejected before reconstruction

Noise rate 20-60 kHz for "low noise period" $\rightarrow$ Signal at photoelectron level

Event frame: 5 μs : 60 noise pulses per event





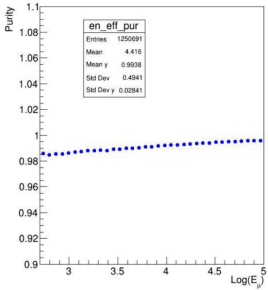
Noise Suppression

Pulses are clustered around "seed": $Q > 2$ p.e.
Each causally-connected pulse with $Q > 0.5$ p.e. is clustered

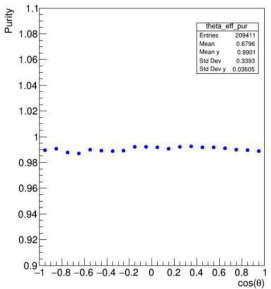
Causality

$$|t_i - t_j| \leq \frac{\Delta R_{ij}}{c_w} + t_s, \; t_s = 10\,\text{ns} \tag{4}$$

Initial track approximation is calculated, ouliers are removed iteratively in tightening set of cuts
Cluster of pulses with the best quality is selected

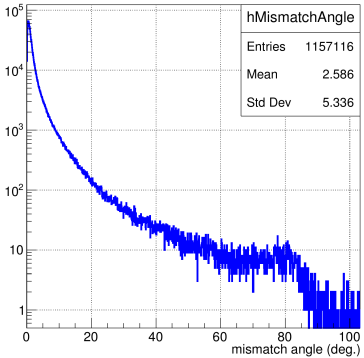


Purity of selected group of pulses $\sim 99\%$
weakly depends on muon incident angle and energy

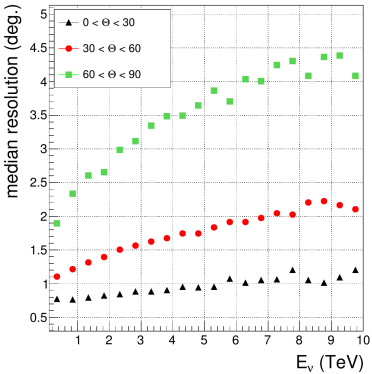


Reconstruction Performance

Reconstruction performance is evaluated on atmospheric neutrino sample, $E > 100\,\mathrm{GeV}$



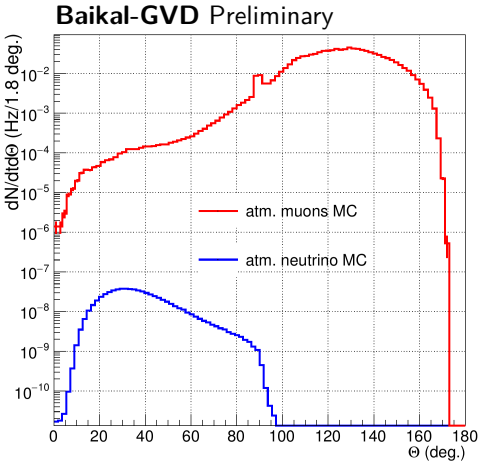
median: $\sim 1.2\,deg$
tail > 10 deg: 4.4 %
tail > 20 deg: 1.4 %



Degrades with energy
Worse for horizontal events

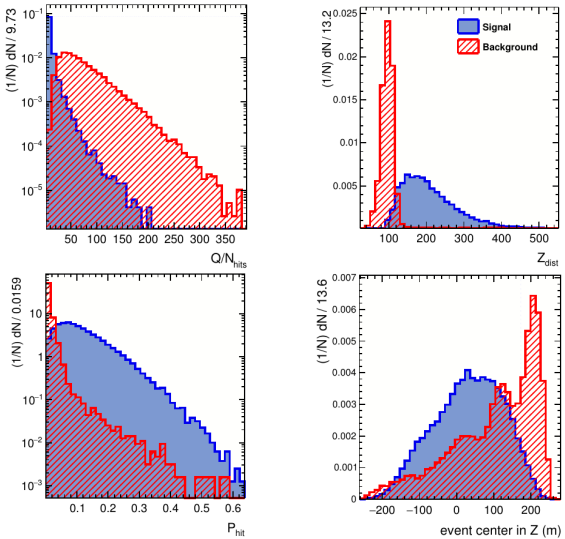
Atmospheric Muon Flux

- Large tail of atmospheric muons misreconstructed as up-going events ($\sim$3 %)
- $\sim$ 4-5 orders of magnitude larger than expected up-going neutrino flux
- Technique to reject misreconstructed muon groups is needed
- Simplest: track quality variable cuts, but rejects a lot of signal
- Boosted decision trees: acceptable signal efficiency

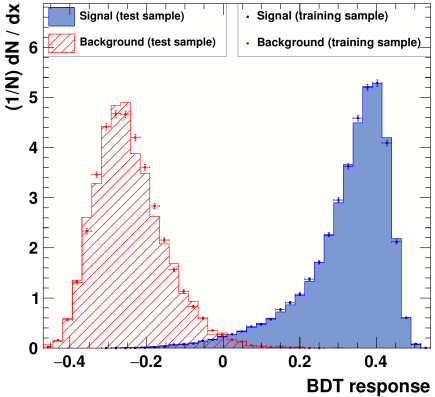


Selection of up-going tracks

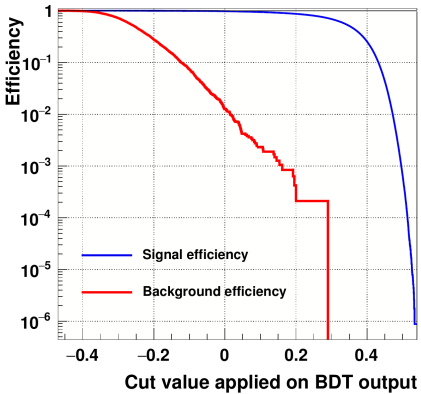
- TMVA framework from ROOT package was used to train the BDT
- A set of 15 quality variables was used at input
- Most significant ones:
  - Quality/N_{hits}
  - P_{hit}: probability of given hit collection
  - Z_{dist}: max distance between OM projections on the track
  - Event center in Z weighted with pulse charge
- **Signal sample: up-going neutrino $E > 100$ GeV**
- **Background sample: misreconstructed down-going muon groups, $\theta_{rec} < 80$ deg**



BDT performance



Cut	S_{eff} [%]
0.25	80
0.3	70
0.35	50
0.4	25



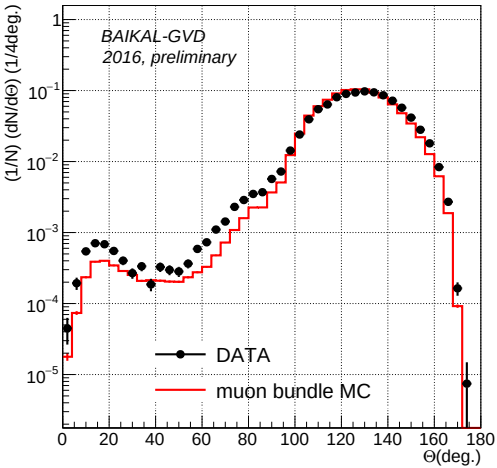
Background is suppressed at the level of $10^4 - 10^5$,
maintaining signal efficiency at the level of $\sim$80 % (cut 0.25)

Data/MC comparison

"Good dataset" (15 days of exposition):

- "Low noise period": runs 90 - 200
- Fixed configuration: 3 sections are off (12.5 % of the cluster off)
- Events with active LED's are rejected

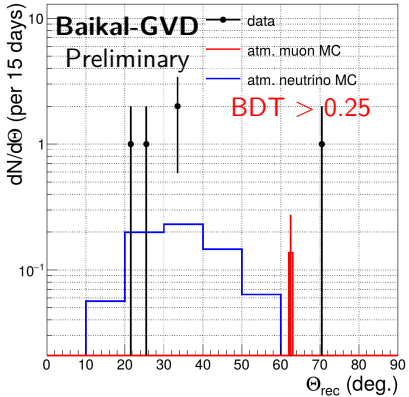
Total 6/3 muon rate in data: 0.22 Hz
Rate in MC is 32 % lower



Results

Good dataset (15 days exposition)

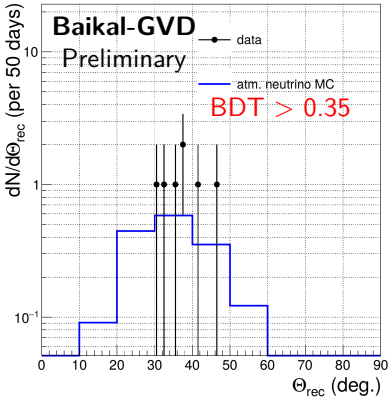
fixed configuration



bckg. expected	0.14
signal expected	0.72
data	5

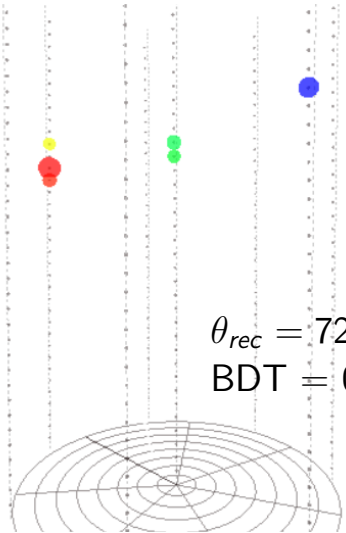
50 days exposition

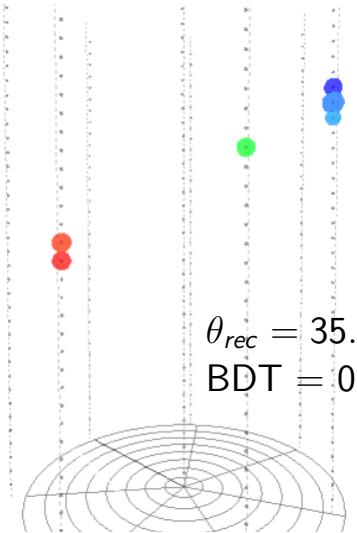
all configurations, noisy runs, hard BDT cut



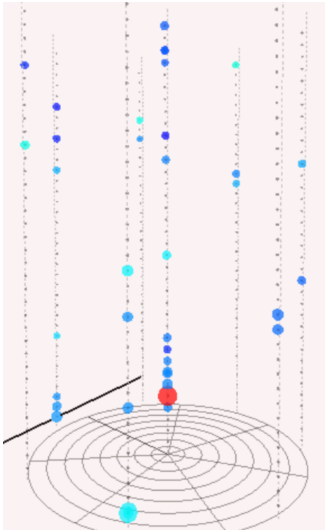
bckg. expected	—
signal expected	1.6
data	7

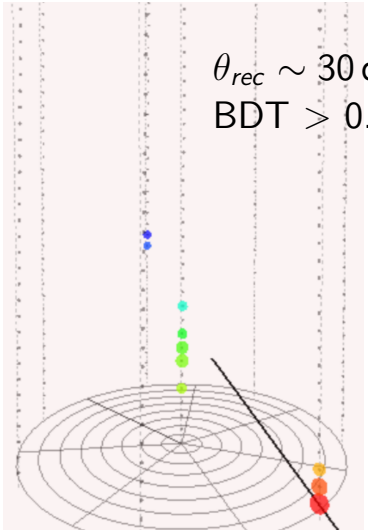
Event Display





Event Display





Summary

Detector properties for 2016 cluster have been studied

We continue to improve MC to match with detector conditions

Procedures to certify good data are being developed

Track reconstruction software has been developed
Simple χ^2-like fit

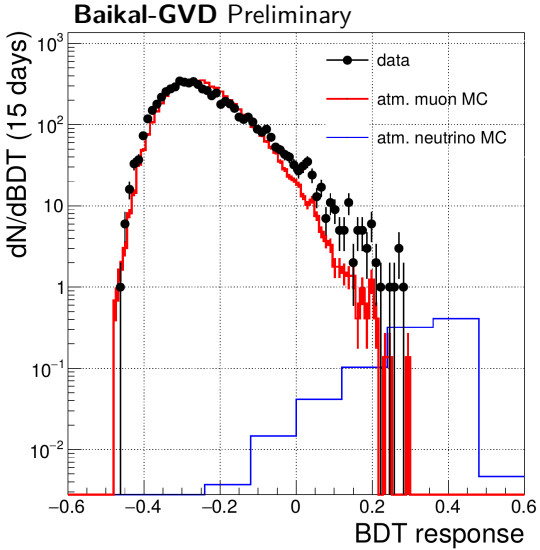
Atmospheric background rejection procedure has been developed
Background rejection at the level of $10^4 - 10^5$

Preliminary results on atmospheric neutrino flux are available
1 neutrino candidate per ~ 3 days per cluster with the current technique

Working hard on the implementation of the likelihood approach


Thank you for your attention.

Results



BDT for "Good dataset":
MC background is scaled by the factor 3.58 to match the data normalization

BDT $>$ 0.25 cut is used for neutrino selection

Detector Effective Areas