Baikal-GVD muon track results

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The Baikal-GVD detector

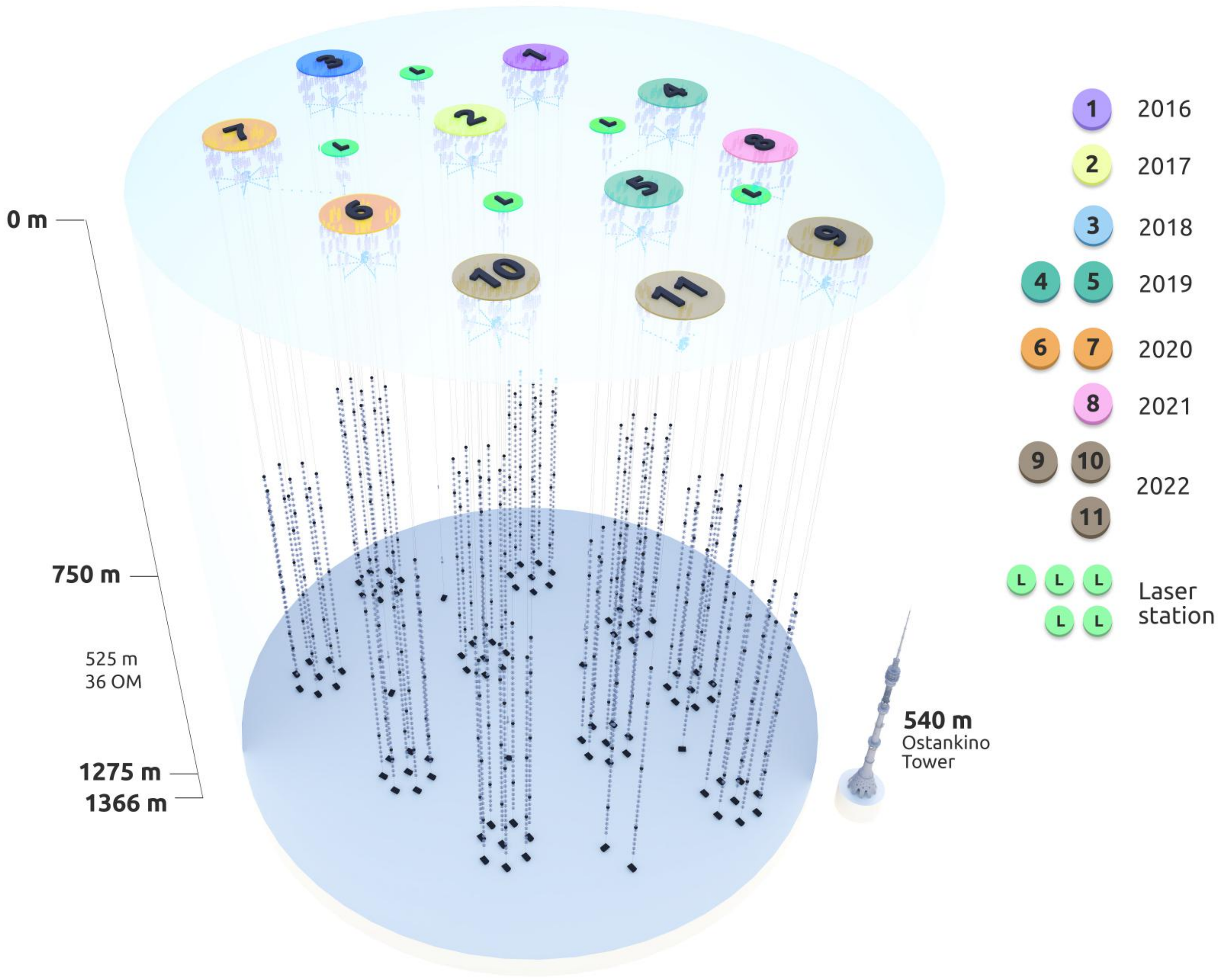
3D array of PMTs submerged into the Lake Baikal waters

Consists of “clusters”

Each cluster works as an independent detector

- Includes 8 strings
- 36 optical modules (OM) at each string

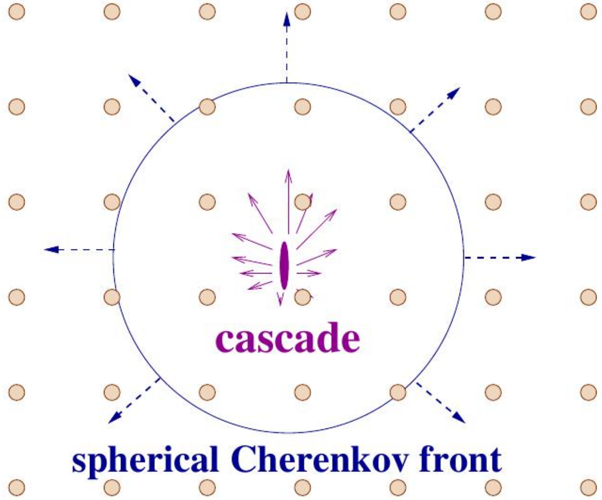
After 2022 deployment campaign the detector includes 10 standard clusters (1-10) and one incomplete cluster with new DAQ (11)



Neutrino telescope event types

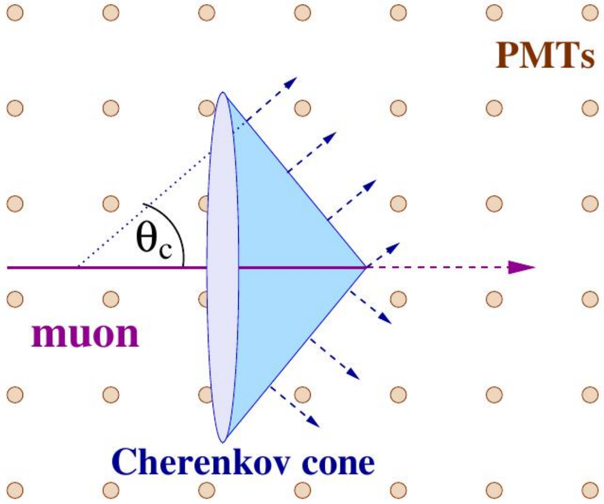
Cascades (ν_e ν_μ ν_τ)

- NC and CC ν interactions
- Cerenkov light from the cascade of charged particles from electron, hadron or nucleus remnants
- Localised energy deposition: R < ~ 100 m
- Moderate angular resolution: 3° - 10°
- Good energy resolution: 5 - 30%



Tracks (ν_μ ν_τ)

- CC ν interactions
- Cerenkov light emitted along the muon path
- Large extension of Cerenkov signal (up to ~ 1 km)
- Good angular resolution: ~0.3° - 0.5°
- Poor energy resolution: 200 - 300%
- Large detector effective volume

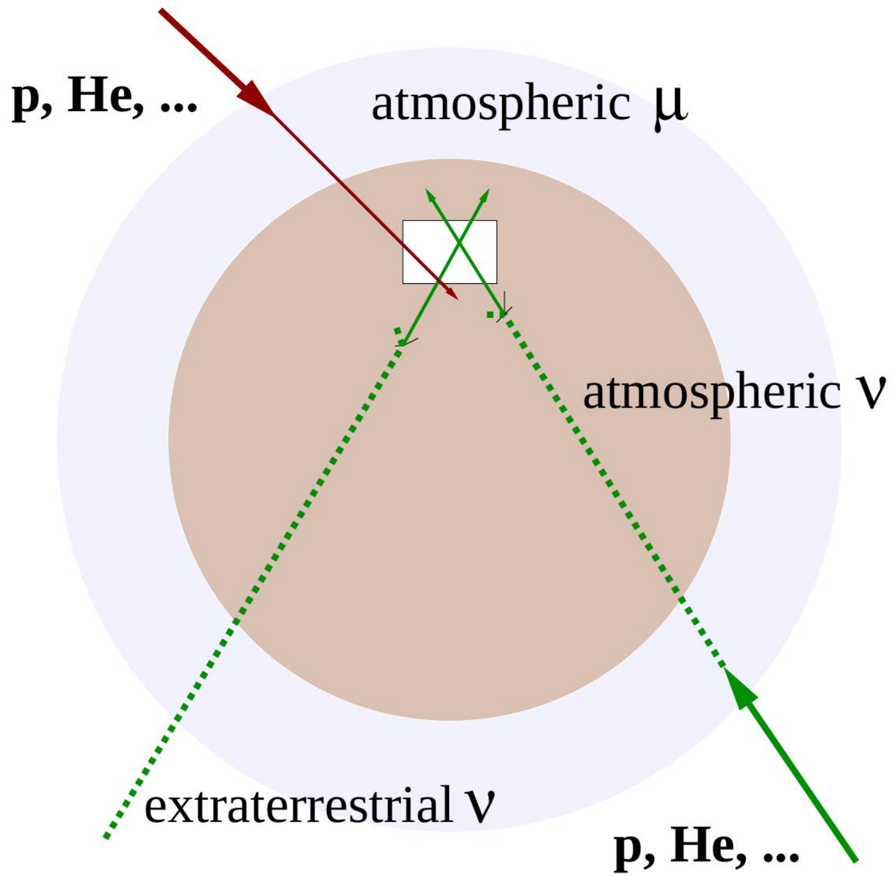


Sources of track-like events

Atmospheric muons: bundle of downgoing muons from CR interaction
- Background to neutrino events

Atmospheric neutrino: neutrino from CR interaction
- Selected as upgoing events
- E > ~ 100 GeV, steeply falling spectrum
- Background to astrophysical neutrino events
- “Standard candle” for neutrino telescope performance

Astrophysical neutrino: Multi-TeV - ~PeV neutrino from remote cosmic accelerators
- Main purpose of the experiment

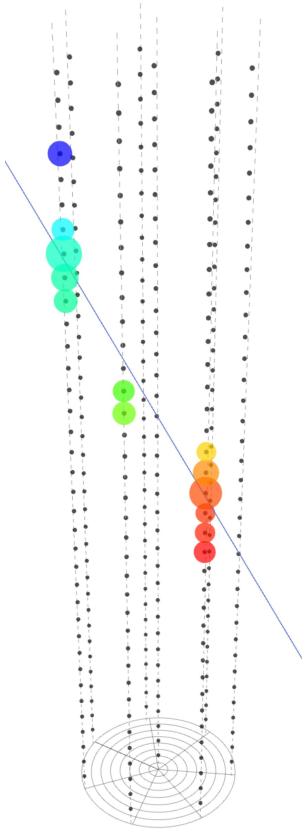


Focus on atmospheric neutrino in this talk

Track-like events

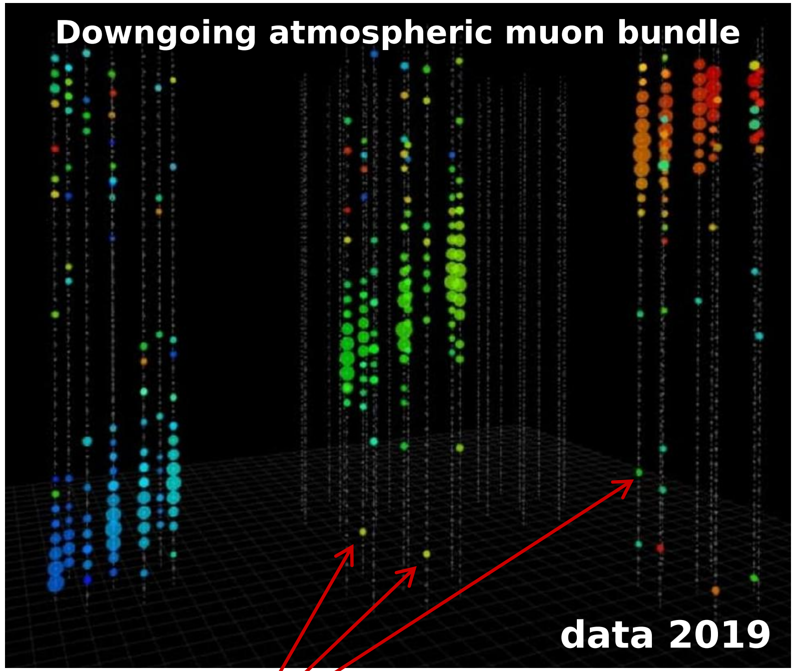
Two modes of analysis
- Single-cluster: each cluster is treated as an independent detector
- Multi-cluster: common reconstruction for simultateously triggered single-cluster events (in development)

Single-cluster upgoing event:

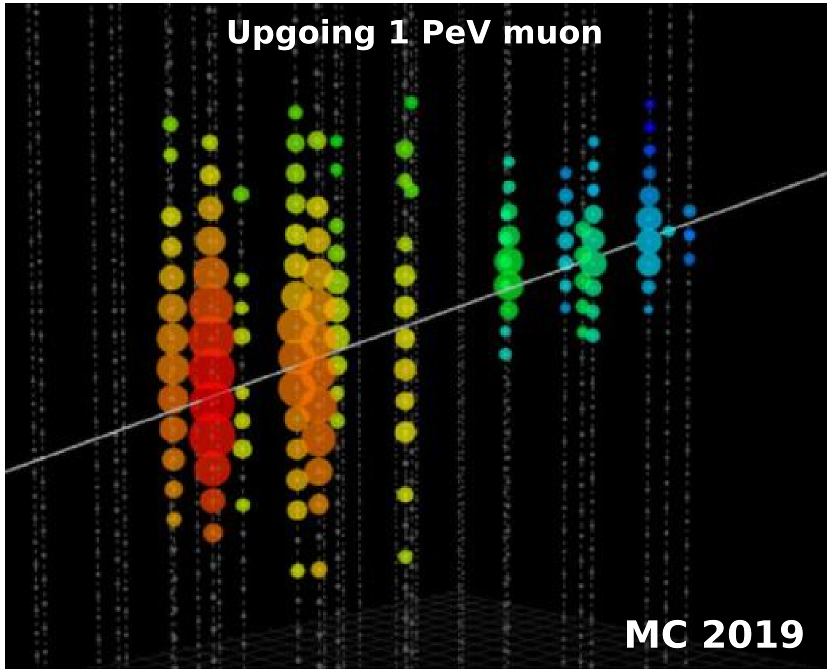


data 2019

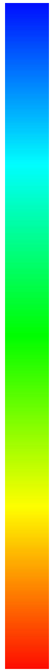
Multi-cluster events:



Lake and PMT noise hits



late



early

Reconstruction algorithms

Track direction, position and energy are reconstructed using PMT hit time, position and charge deposition information

Reconstruction is optimised for single upgoing muons

Hit finder algorithms: select muon-induced hits, reject lake and PMT noise

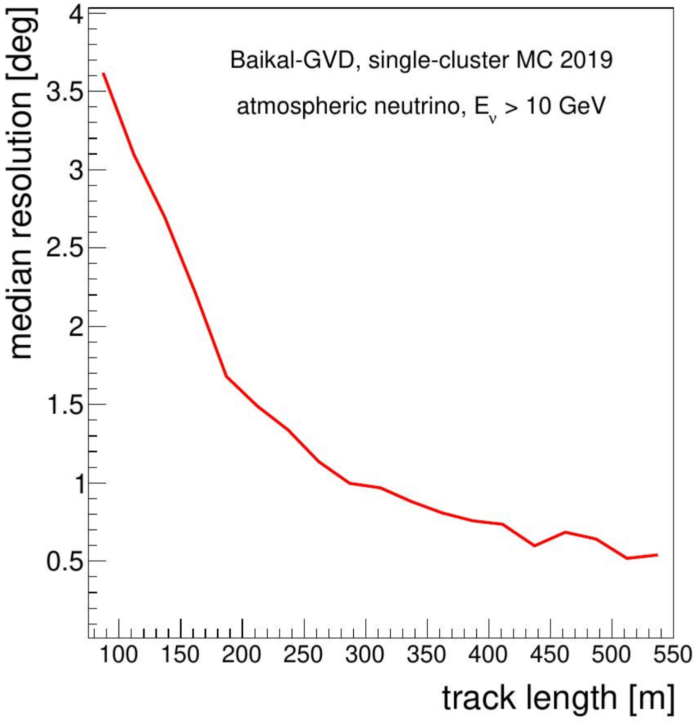
- Fast hit-finder **[Eur. Phys. J. C 81, 1025 (2021)]**
- Efficient scanning algorithm **[PoS(ICRC2021)1063, arXiv:2108.00208]**
- Machine learning: CNN - based hit finder, under development
- Dedicated multi-cluster hit finder

Track reconstruction algorithms: fit the track position and direction

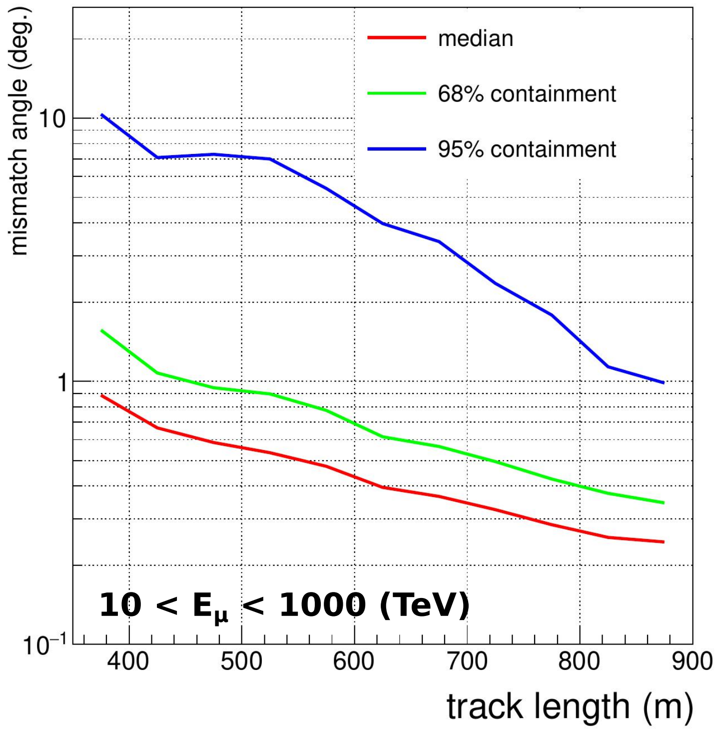
- $\chi^2(t)$ - based minimisation
- Monte Carlo simulation - based likelihood function fit, under development

Reconstruction angular precision

Single-cluster reconstruction



Multi-cluster reconstruction



Better than 0.5° resolution for tacks with length > ~500 m

Reconstruction quality degradation for short tracks

Multi-cluster event reconstruction allows to reach the best angular precision

Energy reconstruction

Linear energy loss dependency on muon energy:

$$-\frac{\mathrm{d}E_\mu}{\mathrm{d}x} = a + b \cdot E_\mu$$

$\mathrm{d}E/\mathrm{d}x$ measurement is an eligible estimator of muon energy:

$$k = \frac{1}{\epsilon L} \sum_{N_{hits}} Q$$

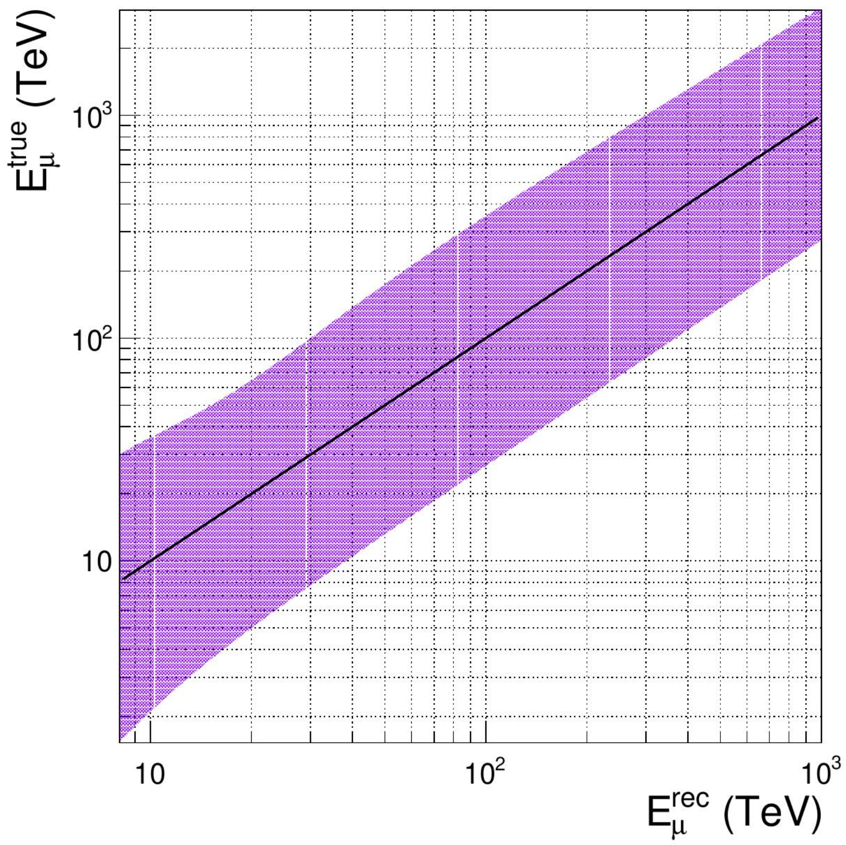
detector sensitivity to the track

path length

sum charge deposition

Factor 3 - 3.5 energy resolution in 8 TeV - 1 PeV range

multi-cluster reconstruction



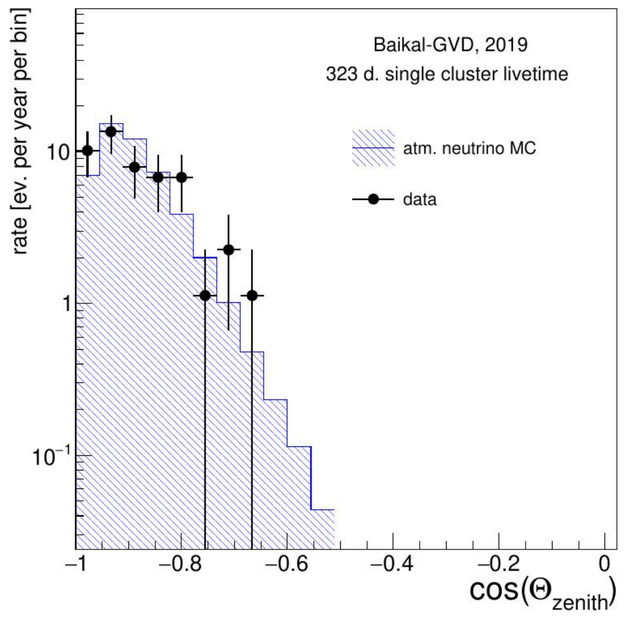
First muon neutrino candidate sample

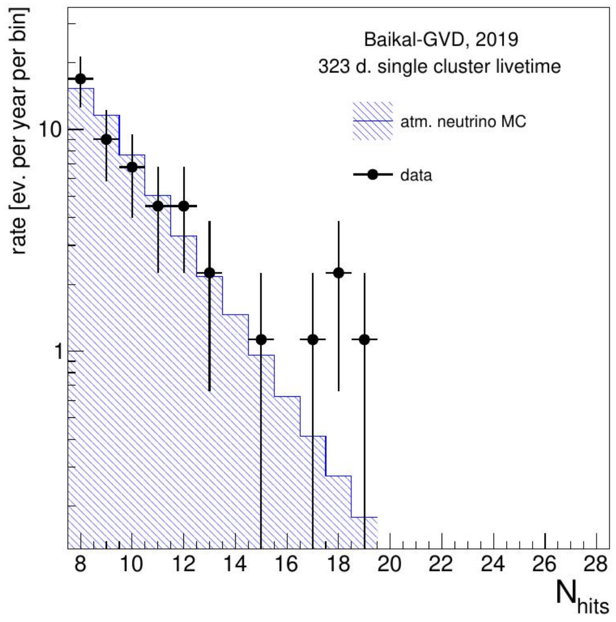
First set of muon neutrino candidates based on data from April-June 2019

- Cut-based analysis optimized for low-energy (atmospheric) neutrino, **<E$_\nu$> ~ 500 GeV**
- Runs from April 1st until June 30th (low-noise period): total single cluster exposition: 323 days

MC expected: 43.6
- atm. neutrino :43.6
- atm. muon: 0

Observed: 44





Excellent agreement of MC expectation and data

Neutrino selection is restricted to low energies and θ_{zenith} > 120°

Analysis is published in: Eur. Phys. J. C 81, 1025 (2021)

Single-cluster muon flux

Improved analysis with more sensitive reconstruction algorithms

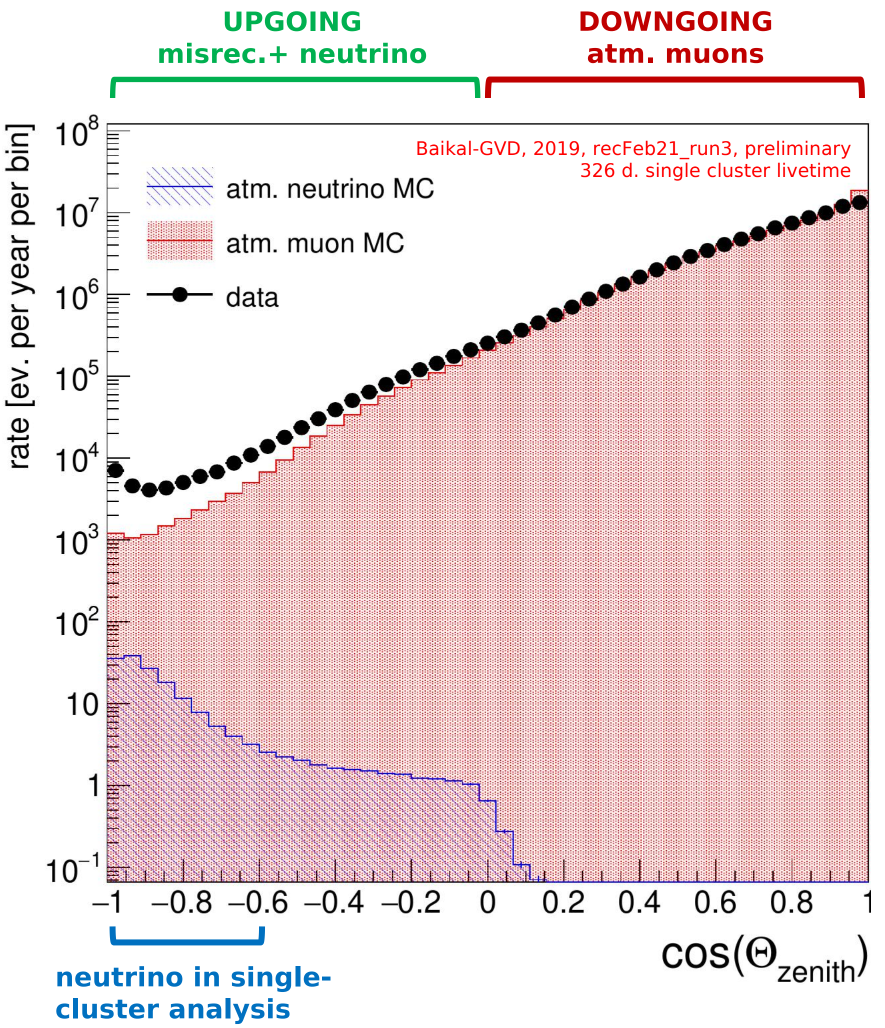
Reconstructed muon rate (8 hits at 2 strings): ~ 3 Hz
- Excellent data-MC agreement in downgoind region
- Some disagreement in upgoing region

Neutrino signal region
- Upgoing and nearly-horizontal muons
- In single-cluster analysis: $\theta_{zenith} > 120°$

Misreconstructed atmospheric muon background exceeds signal by the factor 10^2 - 10^4

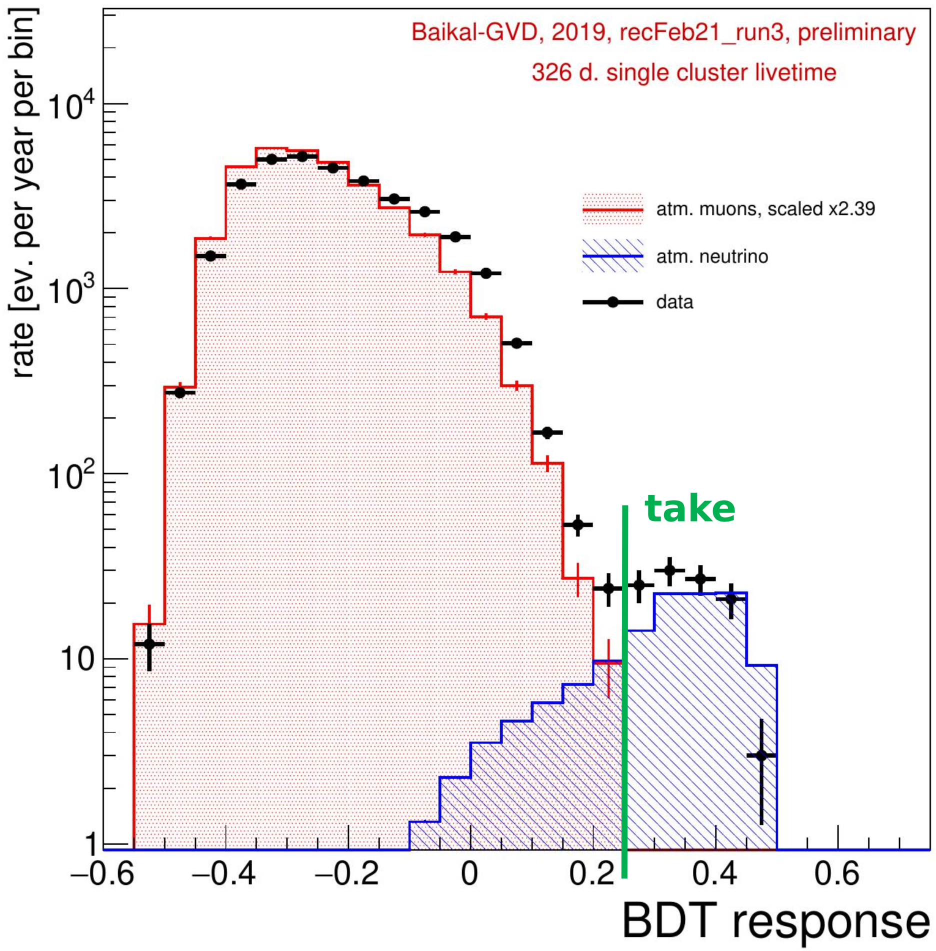
Atm. muon MC: **CORSIKA 5.7 + MUM v1.3u**
Atm. neutrino MC: **Bartol flux + CTEQ4M + MUM v1.3u**

Muon events before quality cuts:



Neutrino selection

Upgoing events: $\theta_{zenith} > 120°$



Data-MC disagreement for upgoing region is compensated by single normalisation factor 2.39

Misreconstructed background is suppressed with the boosted decision tree (BDT) event classifier

Low-energy BDT classifier based on 15 input variables

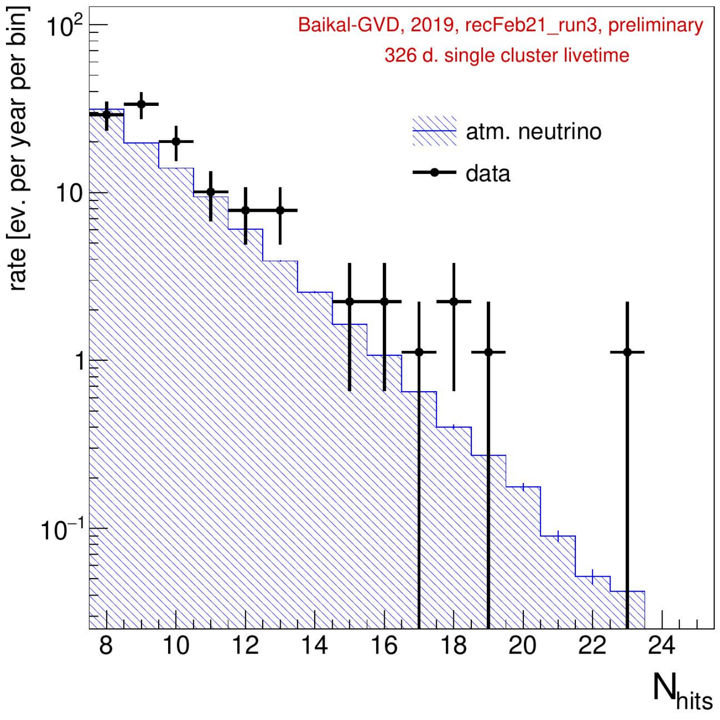
- Signal/background samples: atmospheric neutrino/muons reconstructed $\theta_{zenith} > 120°$
- Cut BDT > 0.25: fully suppressed background, 70% signal efficiency

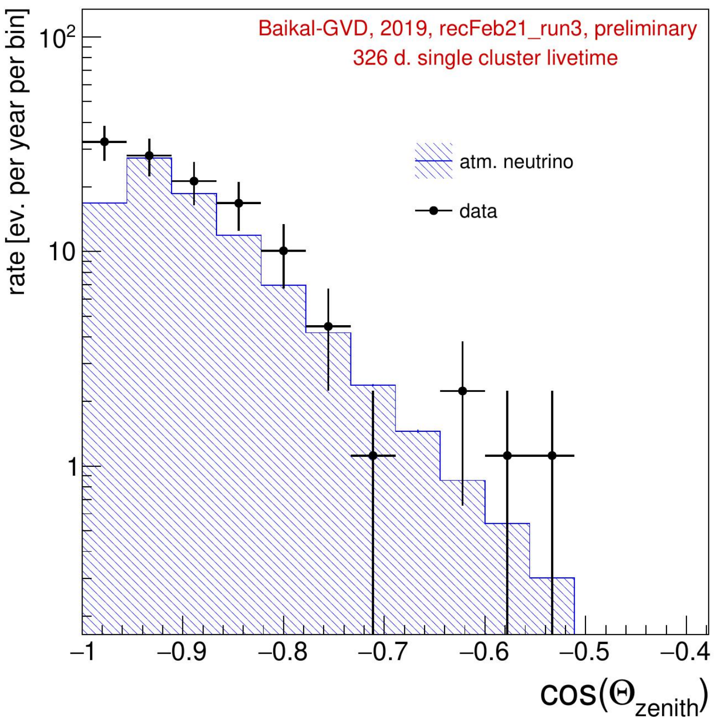
Extended neutrino candidate sample

Analysis was applied to 326 days single-cluster livetime in April-June 2019

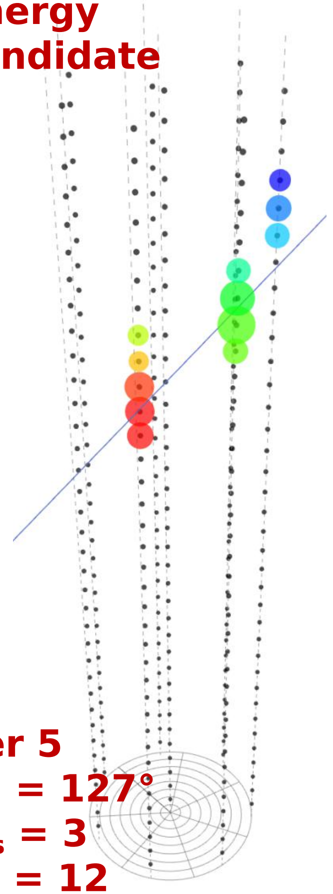
- 106 neutrino candidates were selected
- 81.2 are expected from atm. neutrino MC
- ~30% disagreement in neutrino yield ⇒ up to 30% sample contamination with background muons, analysis will be improved

Factor ~2 improvement in sensitivity wrt. the previous analysis



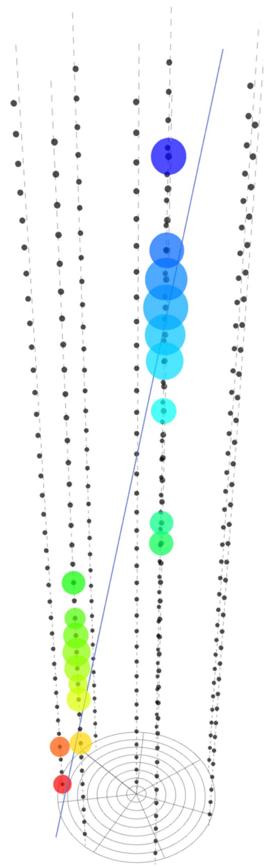


the highest energy candidate

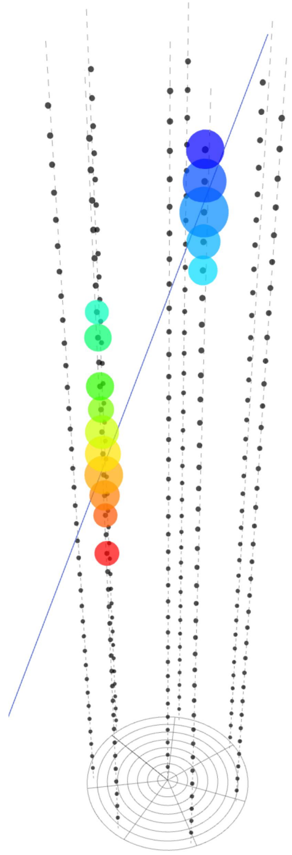


cluster 5
θ_{zenith} = 127°
$N_{strings}$ = 3
N_{hits} = 12
E_{rec} = 28 TeV
68.2% CI:
$5.16 < E_{\mu} < 85.13$ (TeV)

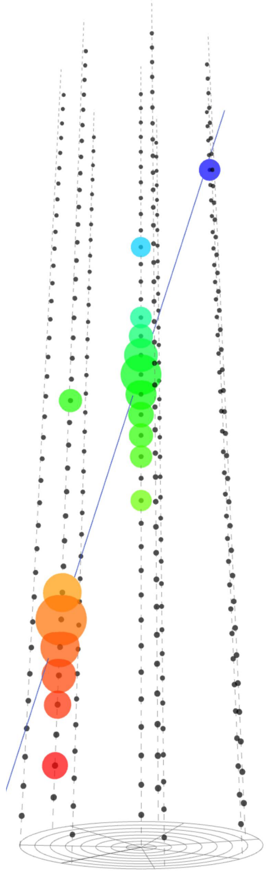
Muon neutrino candidates



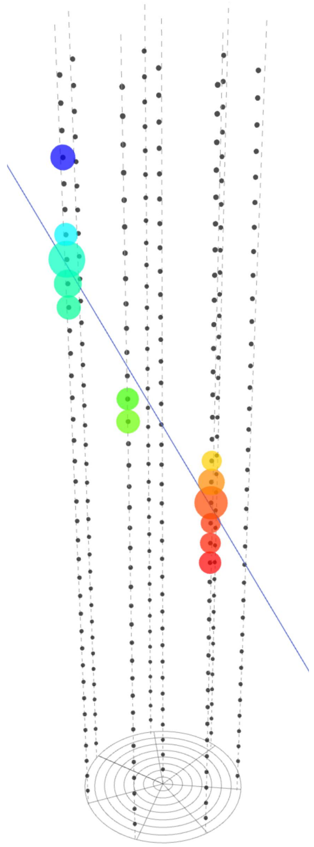
cluster 3, run 122
evt. 1549343
θ_{zenith} = 169.78°
$N_{strings}$ = 3
N_{hits} = 19



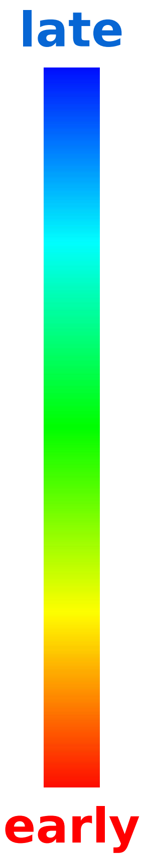
cluster 1, run 157
evt. 1414137
θ_{zenith} = 161.78°
$N_{strings}$ = 2
N_{hits} = 15



cluster 4, run 99
evt. 438088
θ_{zenith} = 162.22°
$N_{strings}$ = 3
N_{hits} = 18



cluster 5, run 162
evt. 1939721
θ_{zenith} = 148.07°
$N_{strings}$ = 3
N_{hits} = 13



Conclusions

Baikal-GVD detector includes 10 full-scale clusters

A number of muon reconstruction techniques have been adopted

Angular presicion better than 0.5° is attained for sufficiently long muon tracks

Reconstructed atmospheric muon bundle flux is in good agreement with MC predictions

Reconstructed low-energy muon neutrino candidate yield is in excellent agreement with atmospheric neutrino MC prediction

Work on high-energy muon track analysis is ongoing, stay tuned!