Reconstruction of neutrino direction in the Baikal-GVD experiment by neural networks

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Baikal-GVD Experiment

Baikal-GVD - neutrino underwater telescope

-The telescope consists of 12 clusters (winter 2023)
-Cluster - 8 strings, in the form of a regular heptagon with a center
-Each string has 36 evenly spaced detectors


Status for 2021 [1]
Registered particles

1) Data - atmospheric muons (top) and neutrinos (bottom)

2) Goal - astrophysical neutrinos
Relevance

- Neutrinos are not deflected by a magnetic field and have a small interaction cross section.

- The angular distribution of atmospheric neutrinos is successfully modeled.

- Astrophysical neutrinos are an important source of information about high-energy astrophysical objects.

- Improving the angular resolution will make it possible to reduce the background of atmospheric events when studying astrophysical neutrinos.
Data

Monte Carlo simulation[2]

- ~1.6*10^6 events
- Single-cluster events (~90% of all events)
- String number > 1

Detector signal:
1) Charge
2) Response time
3-5) Coordinates

- Signals are ordered by time and cleared of noise

\[
\text{input} = \{x, y, z, t, Q\}
\]

\[N = 32\]

Reconstruction

Direction => 3-dimensional polar vector
Direction => polar/azimuth angles

\[ \vec{R} = (\cos \phi \sin \theta, \sin \phi \sin \theta, \cos \theta) \]

Angle distributions

Polar Angle distribution

Azimut Angle distribution

Neutrino  Muons
Models

- Convolutional neural network (CNN) based on the ResNet network [3]

- Graph neural network (GNN), based on EdgeCNN[4]

- Network performance is assessed using median angular resolutions

CNN architecture

Standard reconstruction[4]

Reconstructed Angles

Scatter plot for azimuth angle

Scatter plot for polar angle
Angular resolutions

CNN/GNN
• At small polar angles, the direction is restored more accurately
• The poorer recovery of the azimuthal angle can be explained by the specific structure of the clusters.
• The GCN and CNN model show similar performance, which outperforms the standard algorithm.
Conclusions

- In this problem, deep learning algorithms are applicable and comparable in metrics to standard reconstruction.

- Neural networks perform better in the region of small polar angles

Further development:

- Optimizing the architectures of the models

- Use neural networks to predict confidence in prediction

- Transformers
THANK YOU FOR YOUR ATTENTION!
Applications
CNN, Residual connection

\[ \mathcal{F}(x) + x \]

Input \quad Kernel \quad Output
Graph Convolution Layer
Distribution by the number of triggered detectors

Activated OM amount distribution

OM amount
Neutrino classification

[Diagram showing the classification of neutrinos based on energy. The diagram includes labels for different energy ranges such as TeV, PeV, EeV, and categories like Cosmological ν, Solar ν, Supernova burst (1987A), Reactor anti-ν, Background from old supernovae, Terrestrial anti-ν, Atmospheric ν, and v from AGN. The diagram also indicates the Baikal-GVD energy range.]
Interaction of neutrinos with matter
• Large arrays of PMTs in water or ice
• Cherenkov light detected by PMTs
• “Tracks”: $\nu_\mu$ CC
• “Cascades”: $\nu_e$ & $\nu_\tau$ CC + NC
• Direction reconstructed from hit positions and times
• Energy reconstructed from hit charges
Standard Reconstruction

Our Reconstruction
Technical data

Monte Carlo:
Interaction of neutrinos with nuclei: CTEQ4M (neutrinos with energies 10 GeV - 100 TeV)
Arrival of muons: CORSIKA 5.7 program on the QGSJET hadronic impact model
Propagation of muons to Baikal: MUM v1.3u
Cosmic rays: KASCADE based model (240 GeV – 20 PeV)
Time error 5 ns; 30% on charge
Muons: Angular resolutions

Azimuth resolutions

Polar resolutions

Direction resolutions
Muons: metrics

<table>
<thead>
<tr>
<th></th>
<th>1D Net</th>
<th>Standart Reconstruction</th>
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<tbody>
<tr>
<td><strong>Metrics</strong></td>
<td><strong>Azimut Angle</strong></td>
<td><strong>Polar Angle</strong></td>
</tr>
<tr>
<td>50% Resolution</td>
<td>5.34°</td>
<td>1.9°</td>
</tr>
<tr>
<td>68% Resolution</td>
<td>8.26°</td>
<td>3.09°</td>
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