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

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Aleksey Leonov, MIPT
Scientific supervisor: Oleg Kalashev, Doctor of Physical and Mathematical Sciences. INR RAS

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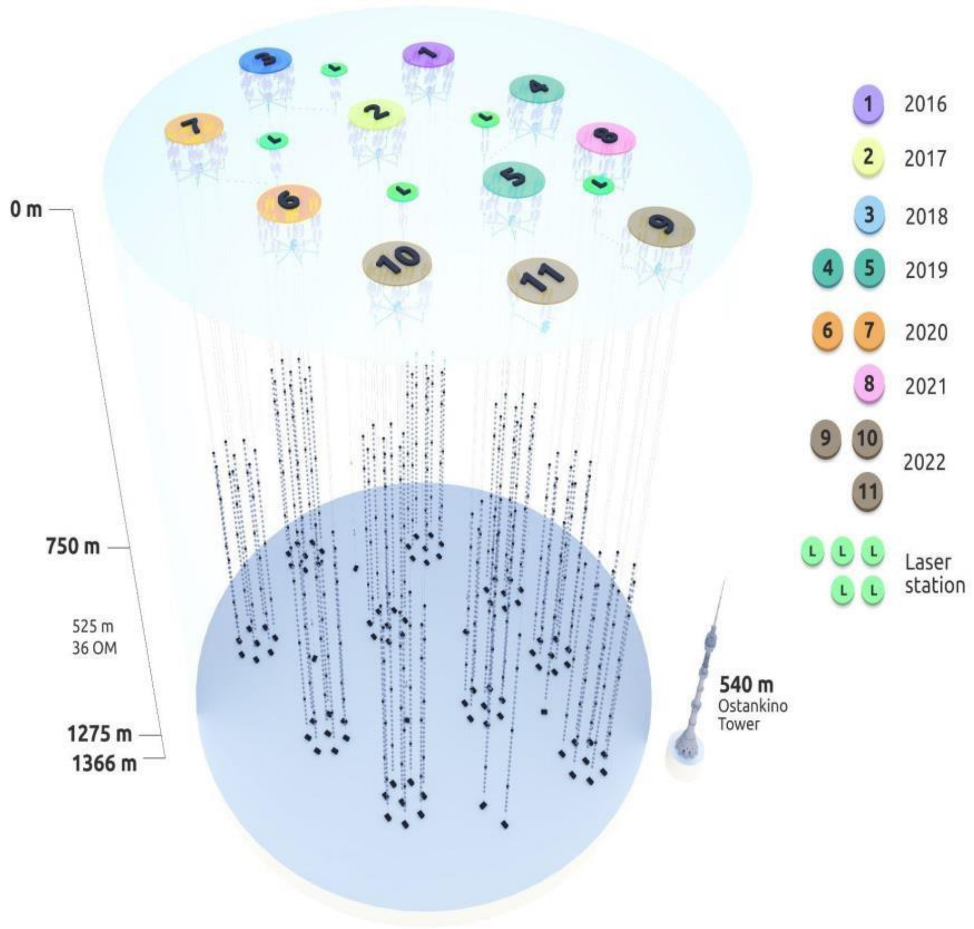
Baikal-GVD Experiment

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



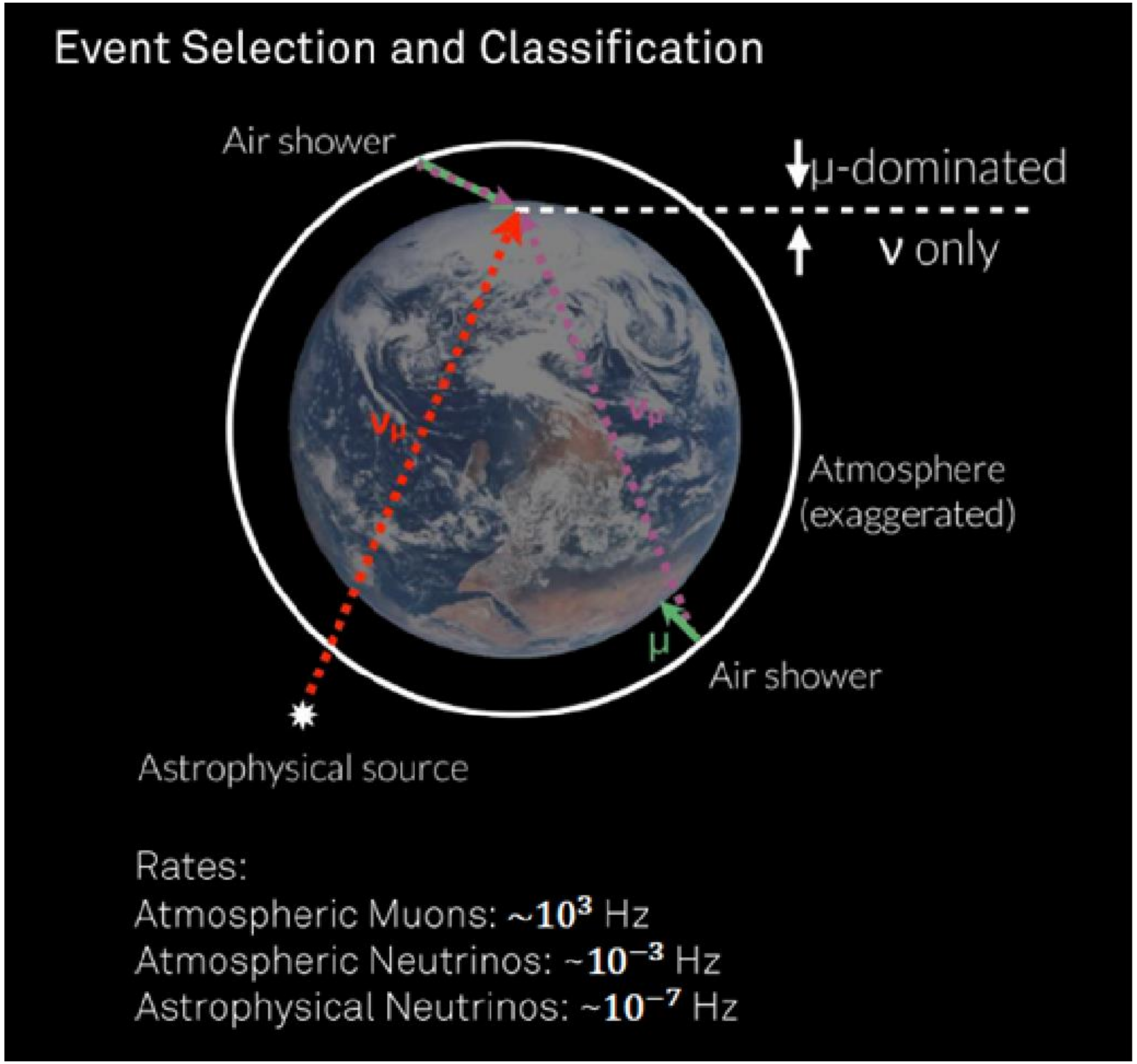
Status for 2021 [1]

[1] https://arxiv.org/abs/2109.14344

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

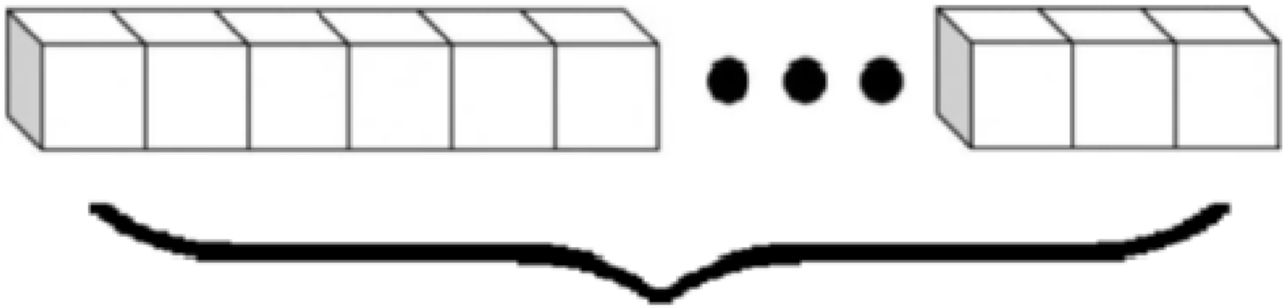
Monte Carlo simulation[2]

- ~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

$$input = \{x, y, z, t, Q\}$$



$$N = 32$$

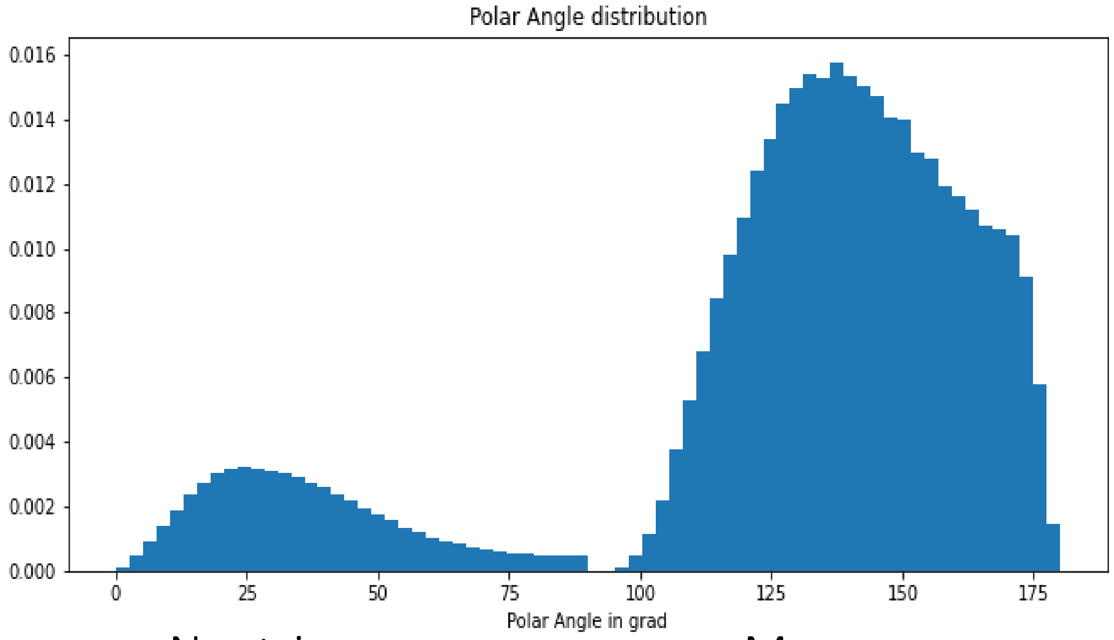
[2] arxiv.org/abs/2106.06288

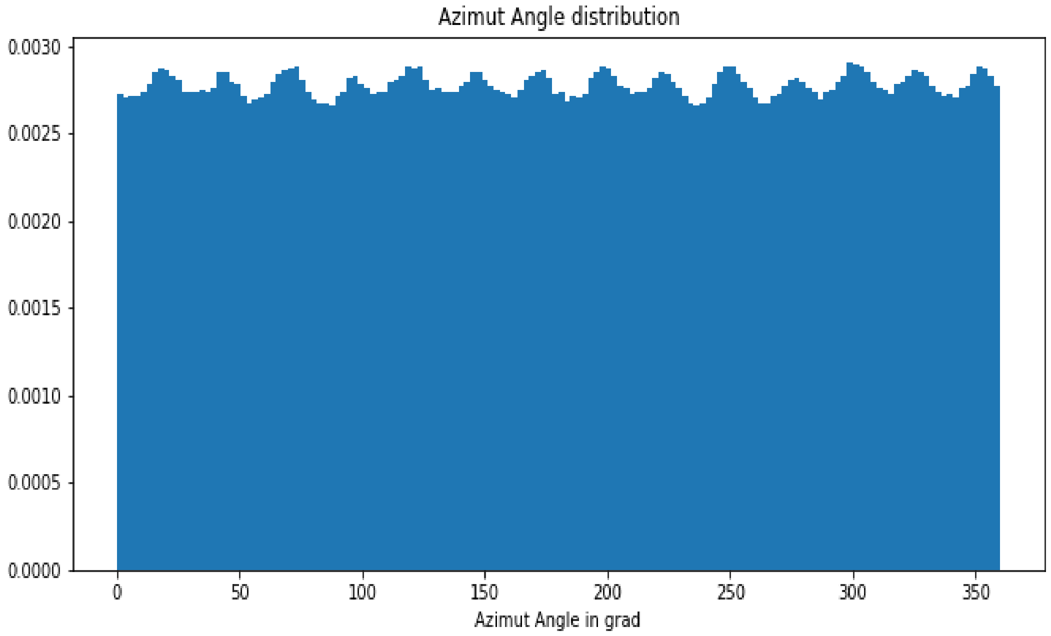
Reconstruction

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

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

Angle distributions

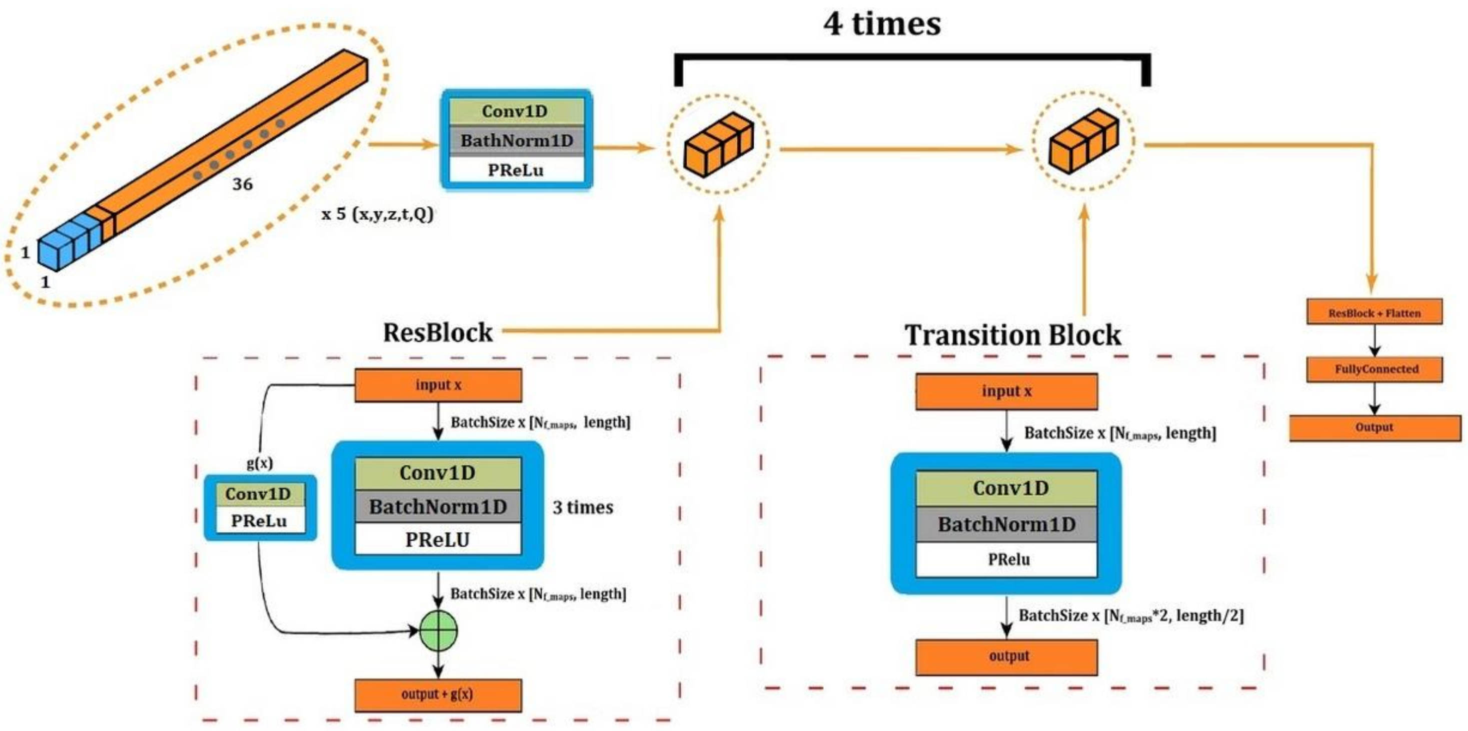




Neutrino Muons

Models

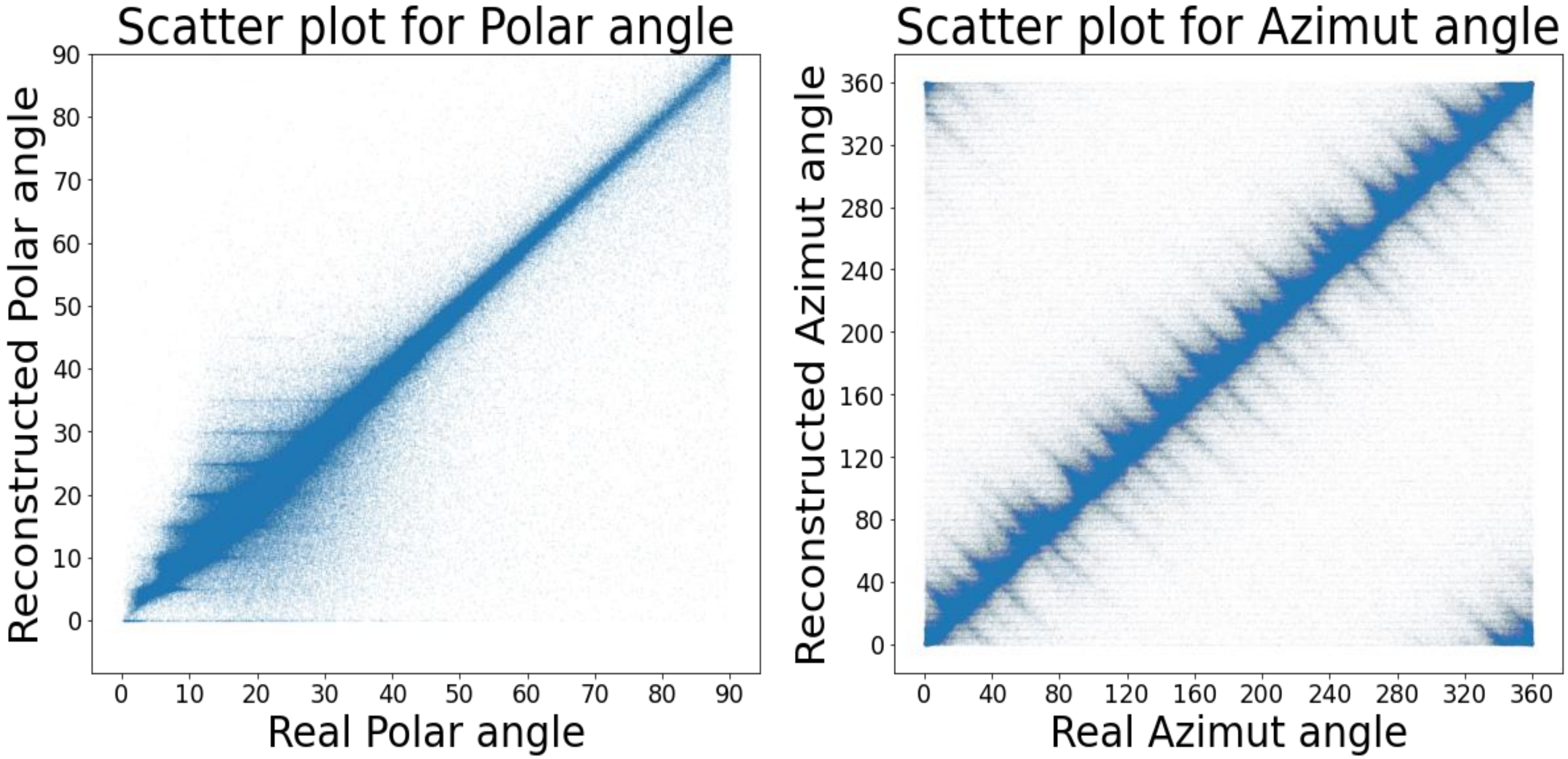
- Convolutional neural network (CNN) based on the ResNet network [3]
- Graph neural network (GNN), based on EdgeCNN[4]
- Network performance is assessed using median angular resolutions



CNN architecture

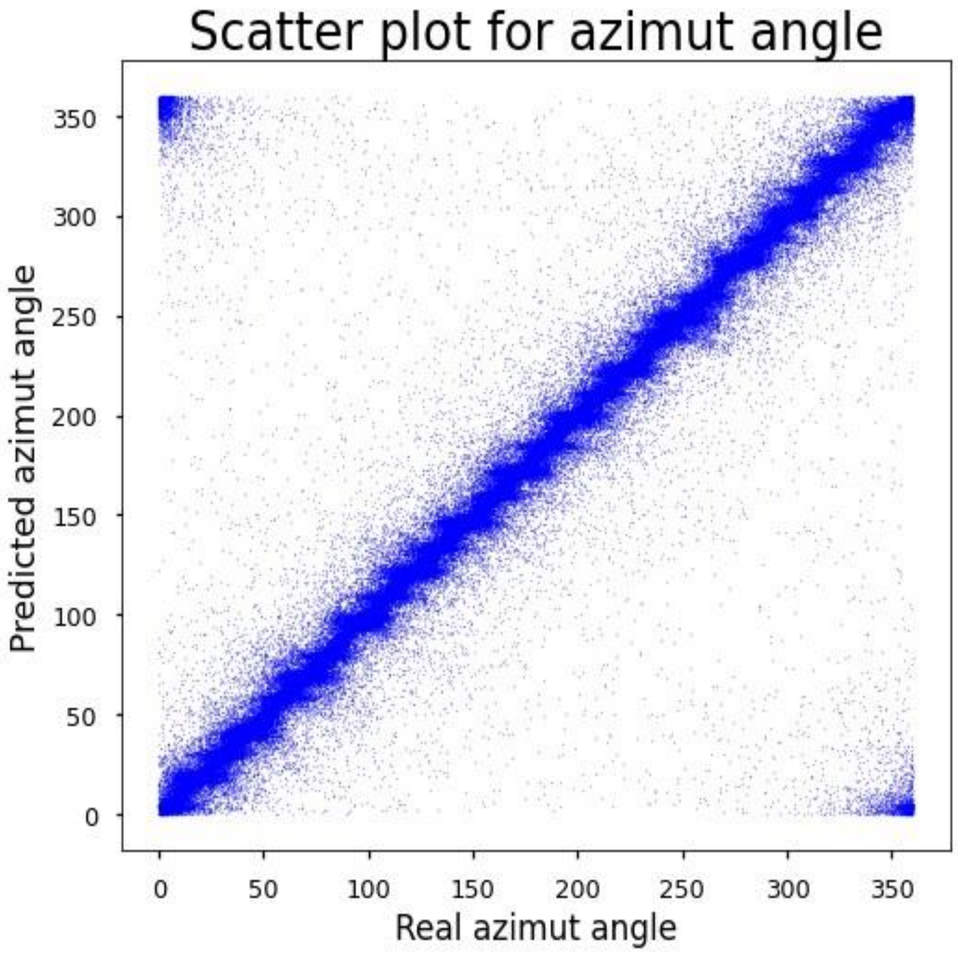
[3] arxiv.org/abs/1512.03385
[4] arxiv.org/abs/1801.07829

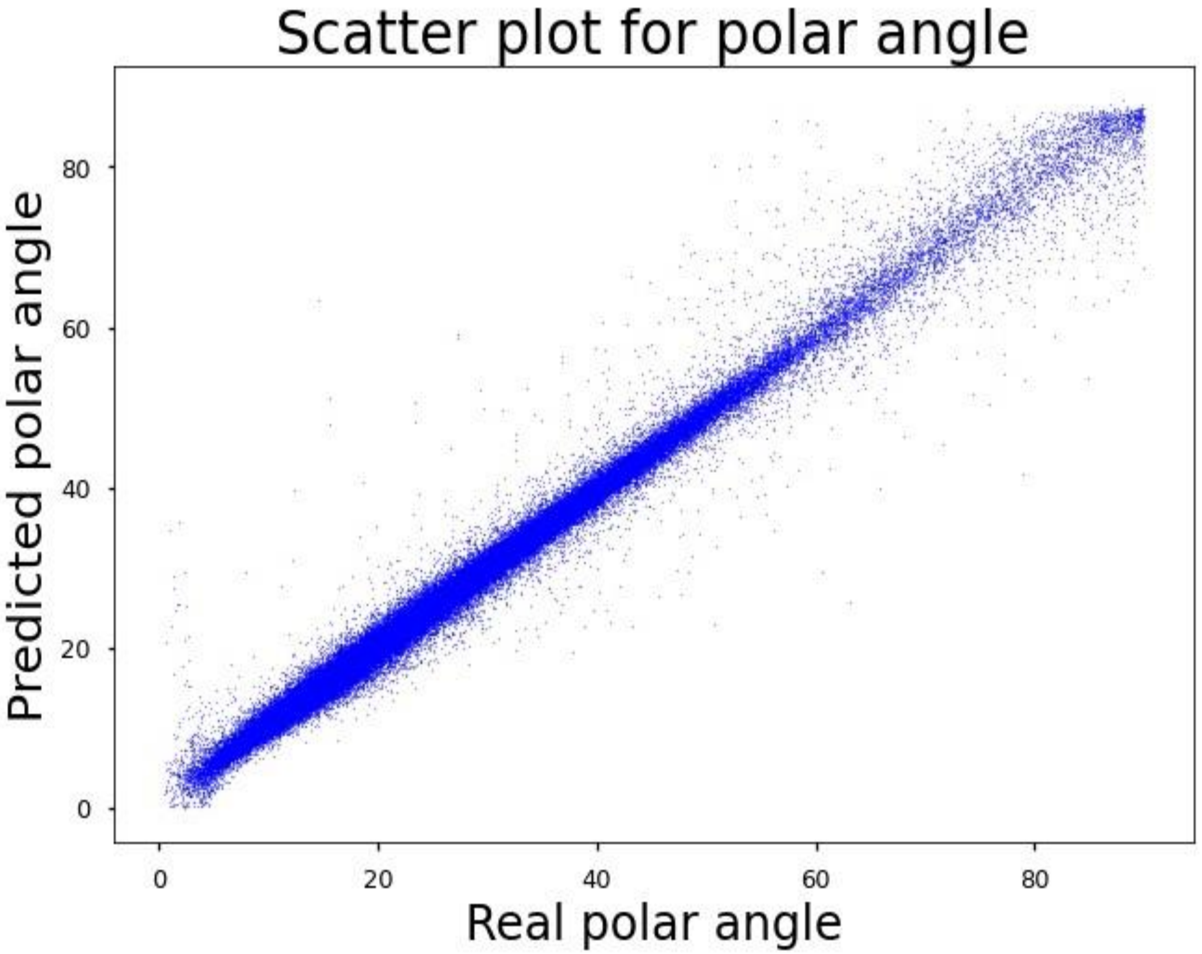
Standard reconstruction[4]



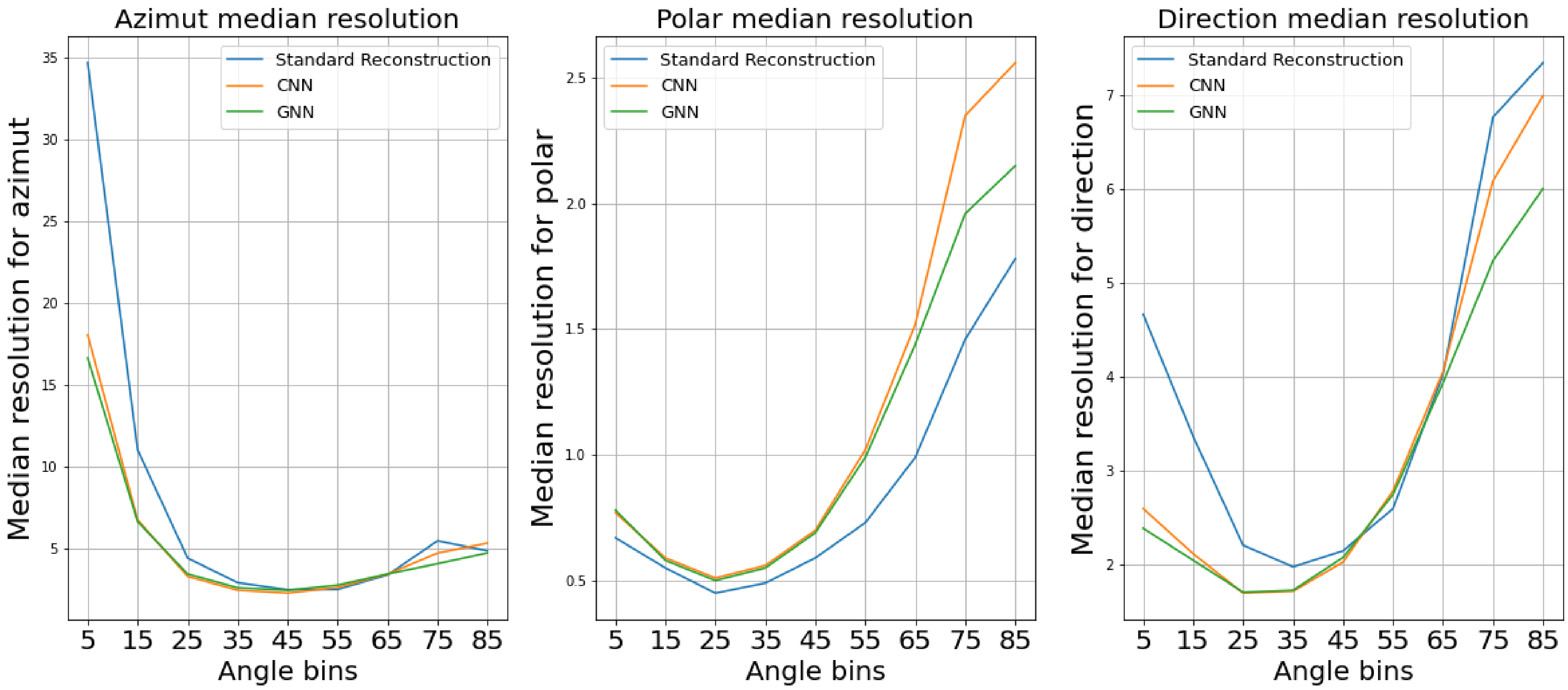
[4] arxiv.org/abs/2108.11217

Reconstructed Angles





Angular resolutions CNN/GNN



Models Metrics

Median Resolution	Azimuth Angle	Polar Angle	Direction
Standard Reconstruction	5.44°	0.52°	2.64°
GCN	3.90°	0.58°	1.93°
CNN	3.82°	0.59°	1.95°

- 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

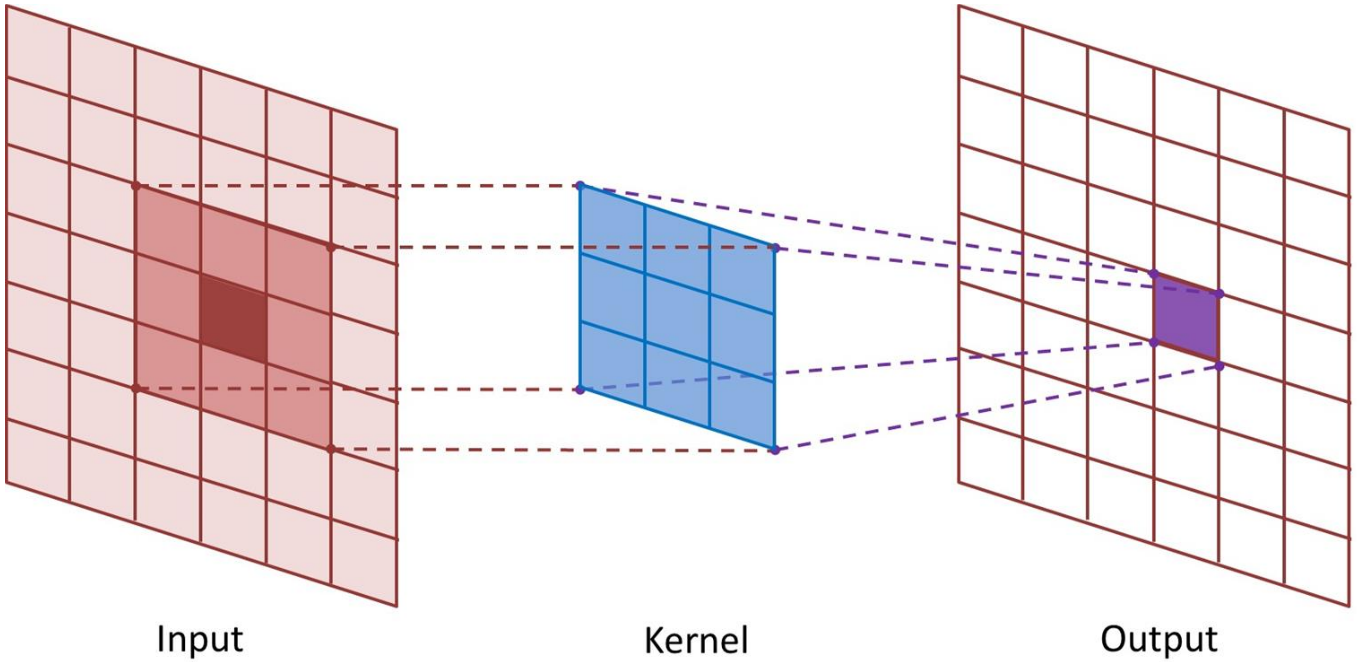
- Use neural networks to predict confidence in prediction

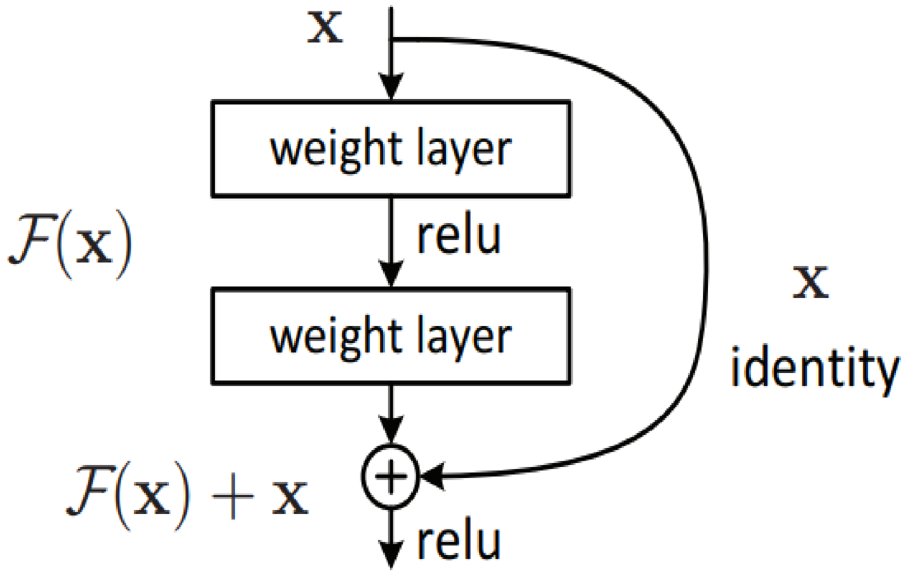
- Transformers

THANK YOU FOR YOUR ATTENTION!

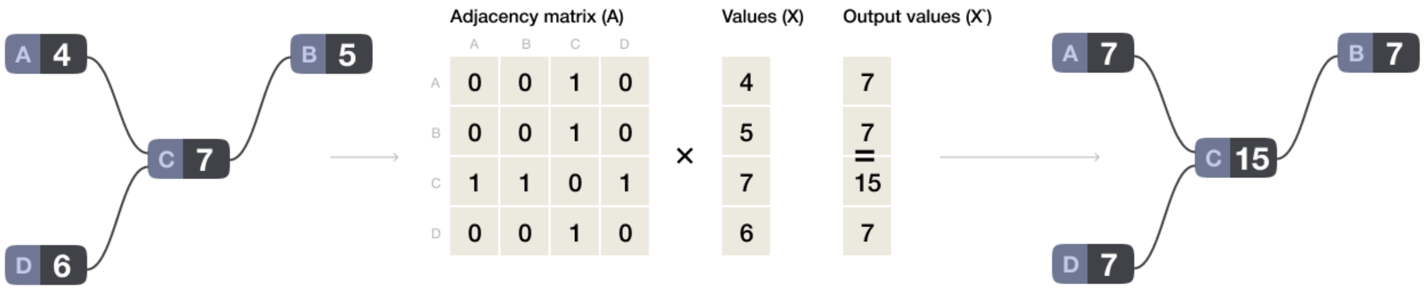
Applications

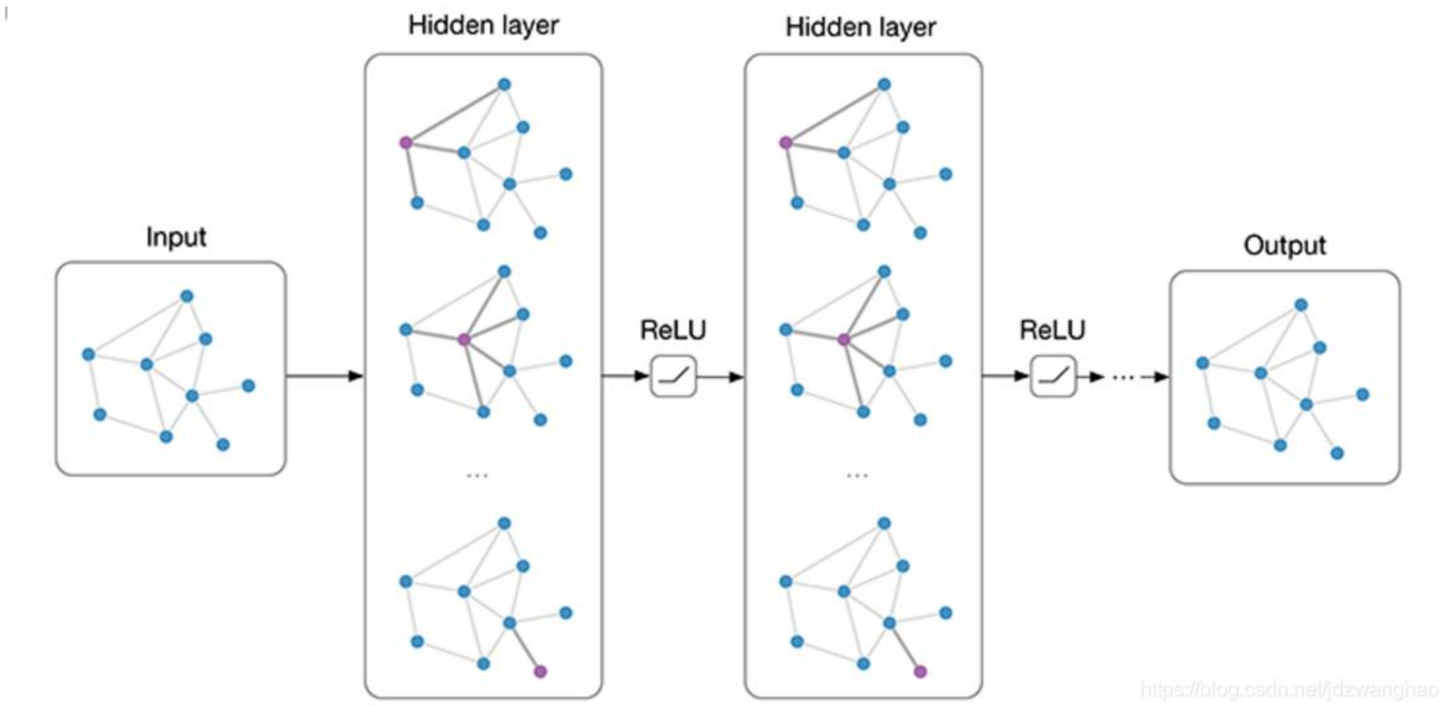
CNN,Residual connection



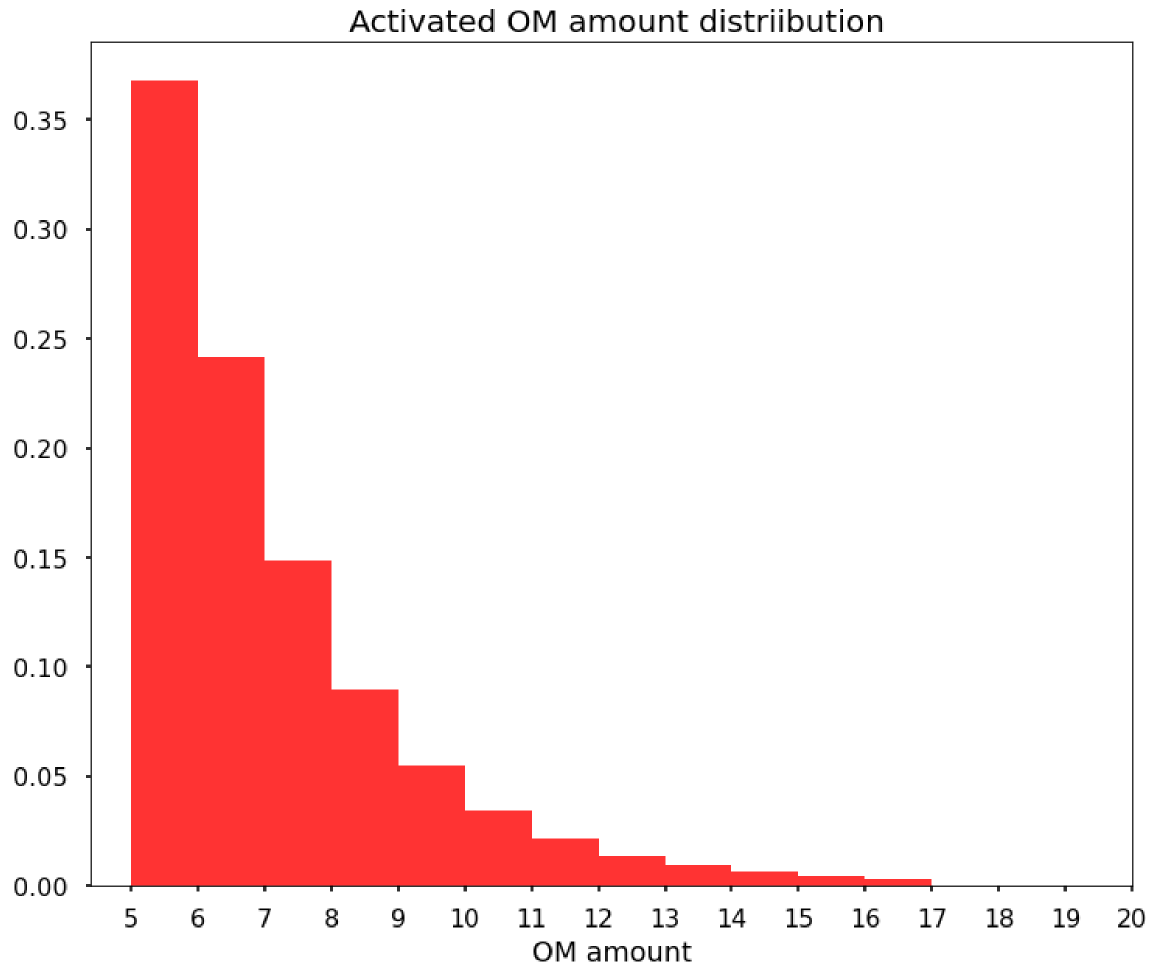


Graph Convolution Layer

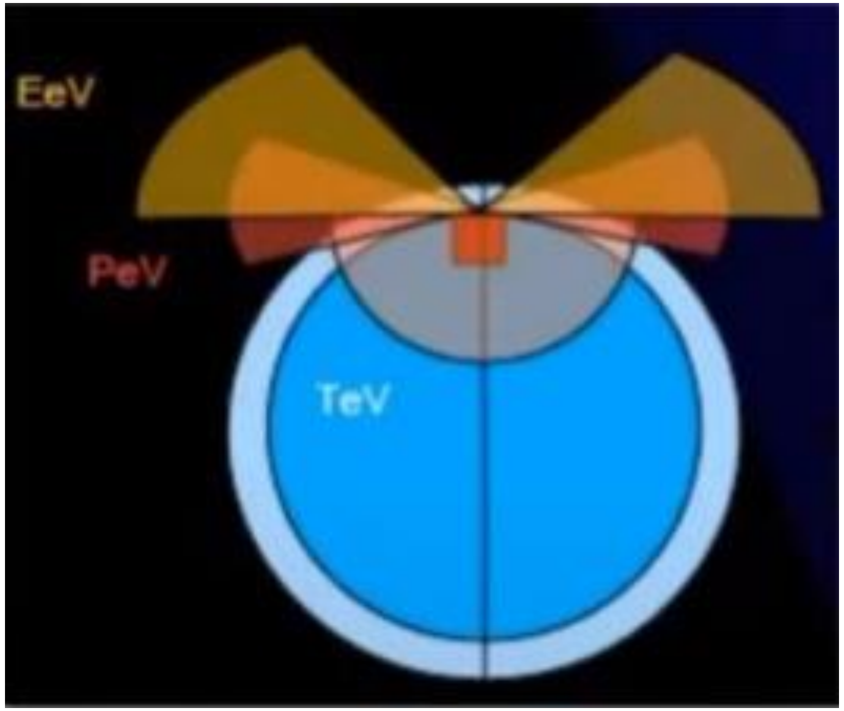


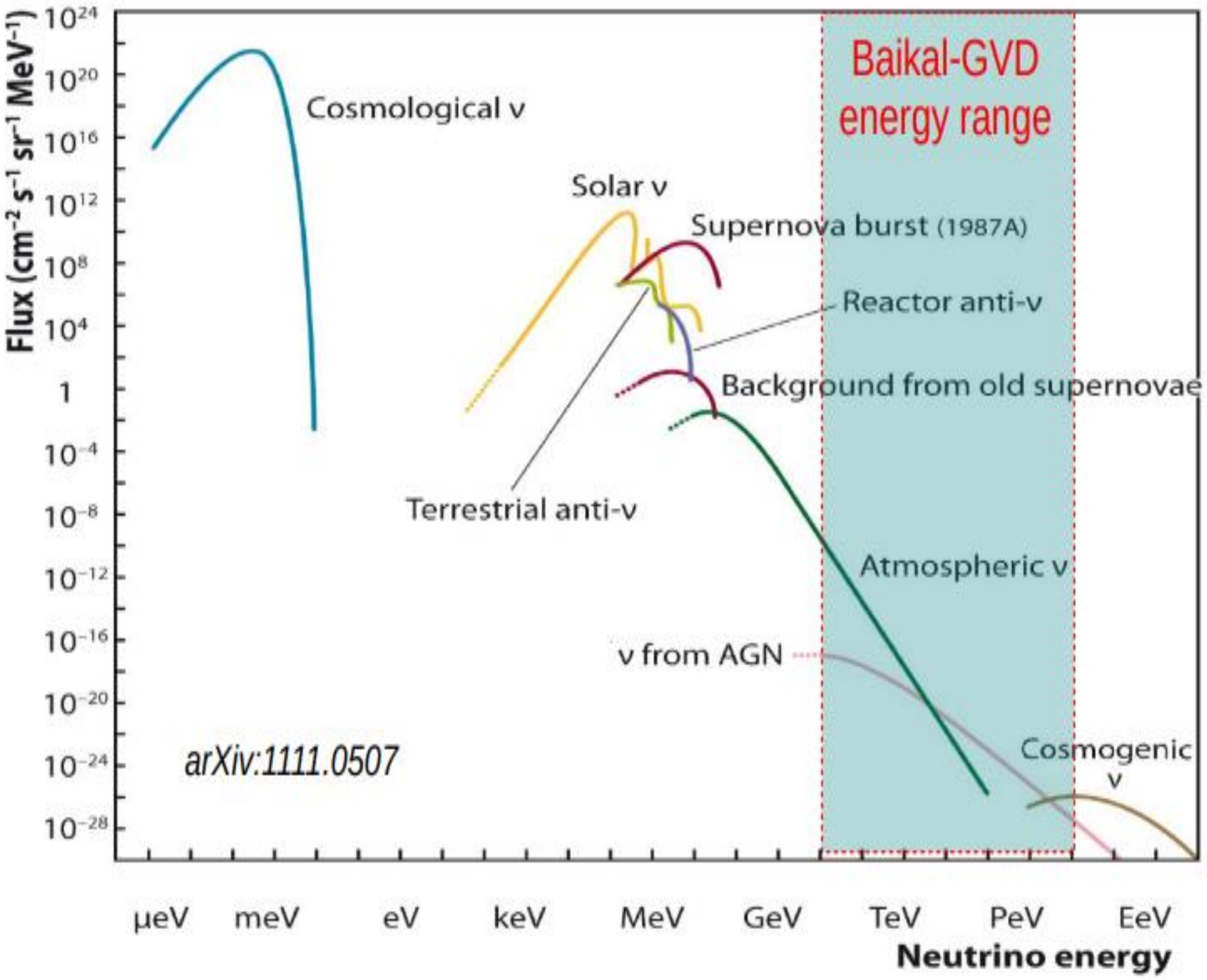


Distribution by the number of triggered detectors

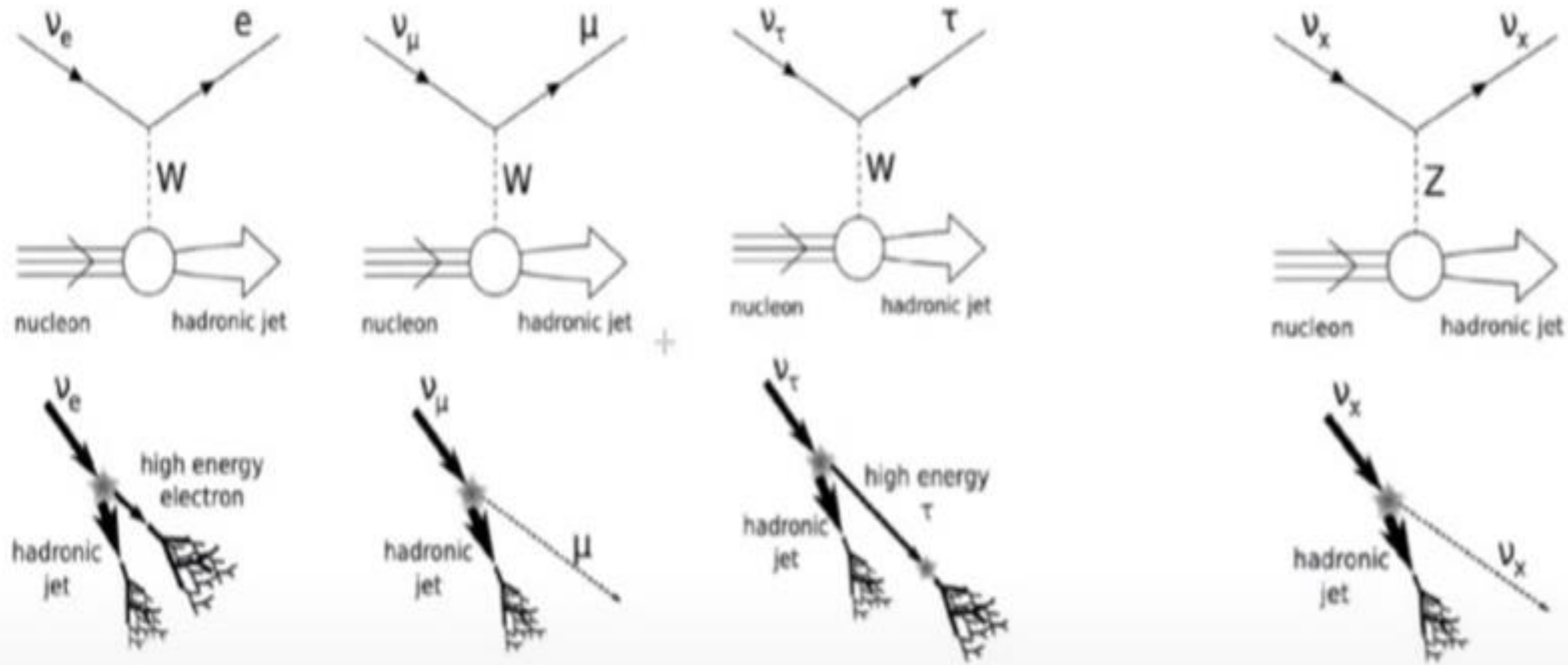


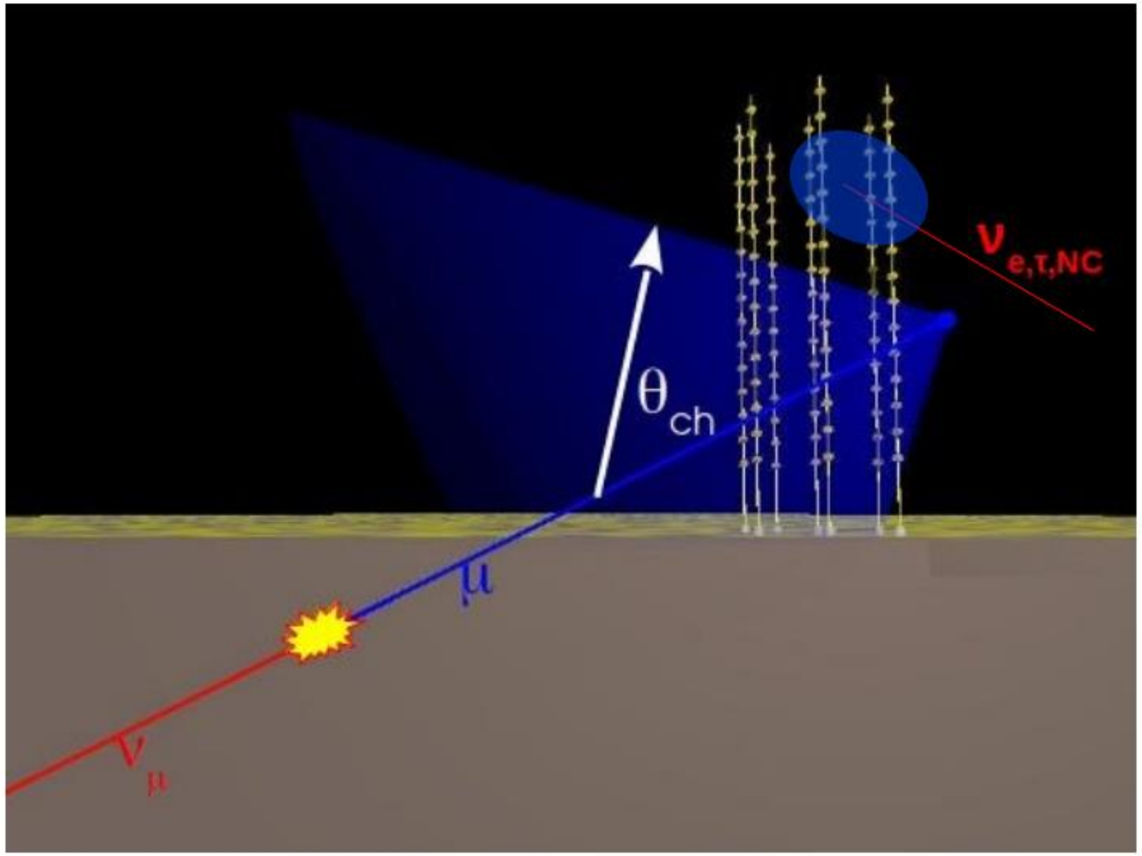
Neutrino classification





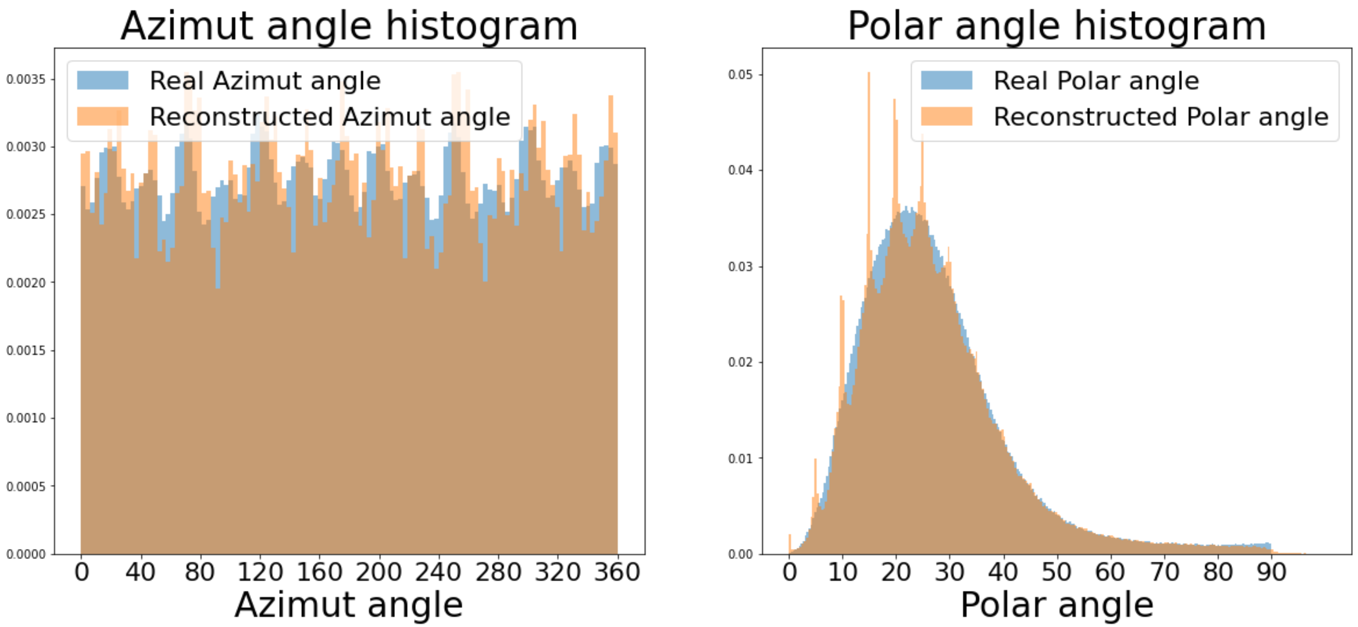
Interaction of neutrinos with matter



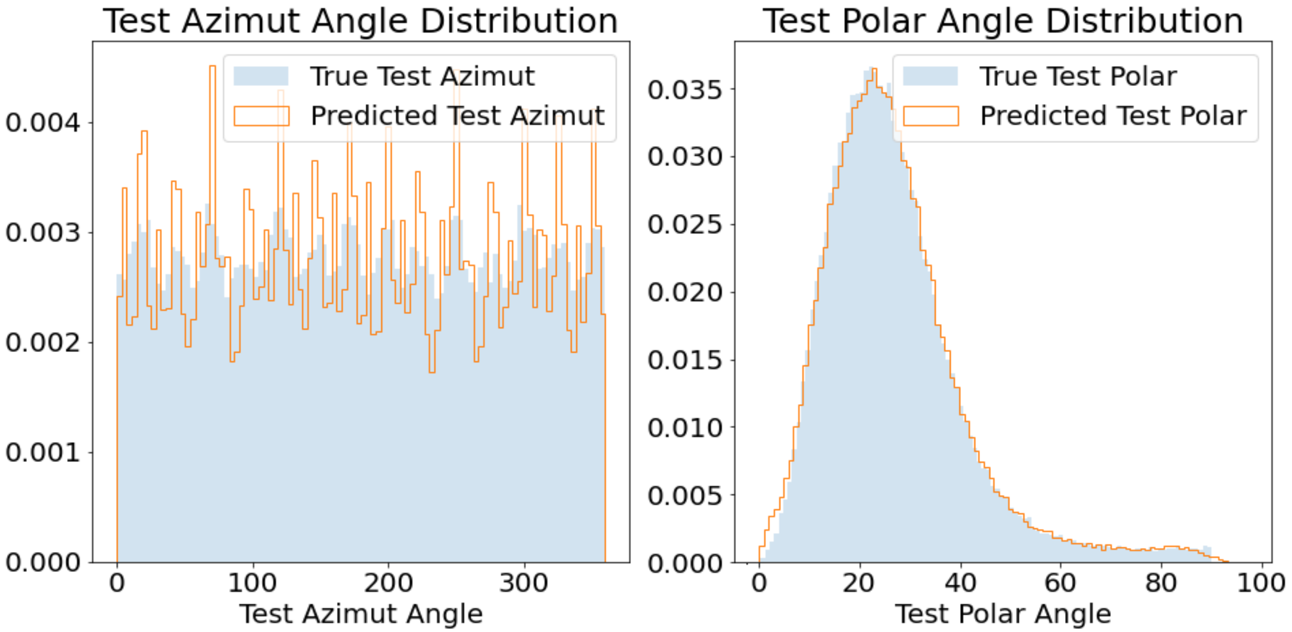


- Large arrays of PMTs in water or ice
- Cherenkov light detected by PMTs
- “Tracks”: ν_μ CC
- “Cascades”: ν_e & ν_τ CC + NC
- Direction reconstructed from hit positions and times
- Energy reconstructed from hit charges

Standard Reconstruction



Our Reconstruction



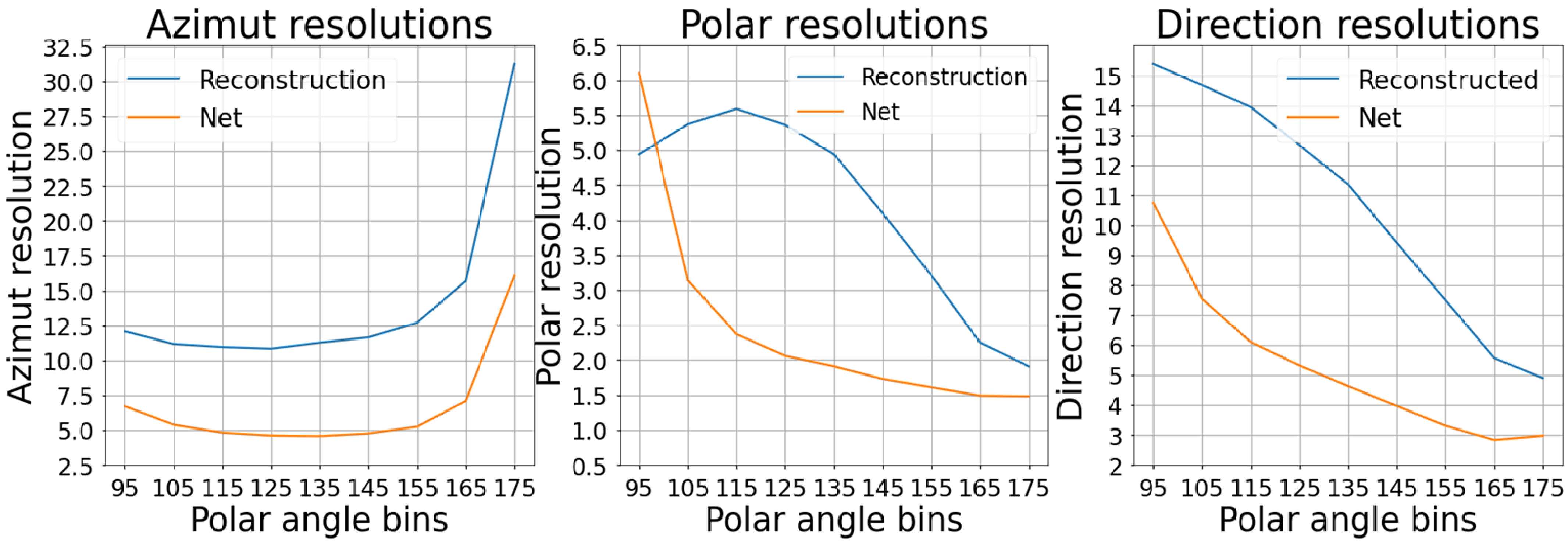
Technical data

$\lambda^{eff}_{scattering} \approx 480$м при 475 nm $\quad \lambda^{max}_{absorption} \approx 24$м

Tracking events: arrival angle accuracy≈ 0, 25^{o}
Cascade events: resolution≈ 2^{o}

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



Muons: metrics

1D Net			
Metrics	Azimut Angle	Polar Angle	Direction
50% Resolution	5.34°	1.9°	4.35°
68% Resolution	8.26°	3.09°	6.0°
Standart Reconstruction			
Metrics	Azimut Angle	Polar Angle	Direction
50% Resolution	12.51°	3.82°	9.11°
68% Resolution	20.73°	6.53°	13.68°