Improving the direction and energy estimation of low-energy events in ANTARES with ML

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ANTARES in a nutshell

First large undersea neutrino telescope [1]:

- 12 vertical lines forming a 3D array of photo-sensors
- 25 floors per line
- 3 Optical Modules (OMs) per floor

It detects Cherenkov light induced by secondary particles from neutrino interactions

Problems

- Azimuth angle reconstruction is missing with classical approaches (BBfit) for low-energy single-line (SL) events [2].
- Other interesting parameters, such as energy, are not reconstructed for these events.
- The low-energy range is interesting for dark matter searches and other studies.

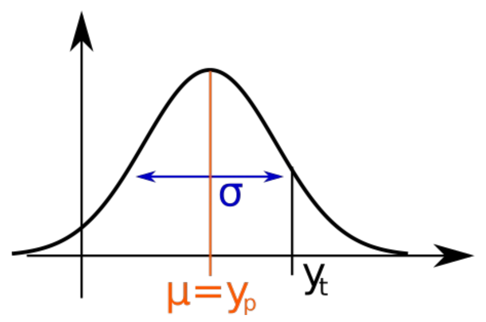
Solution

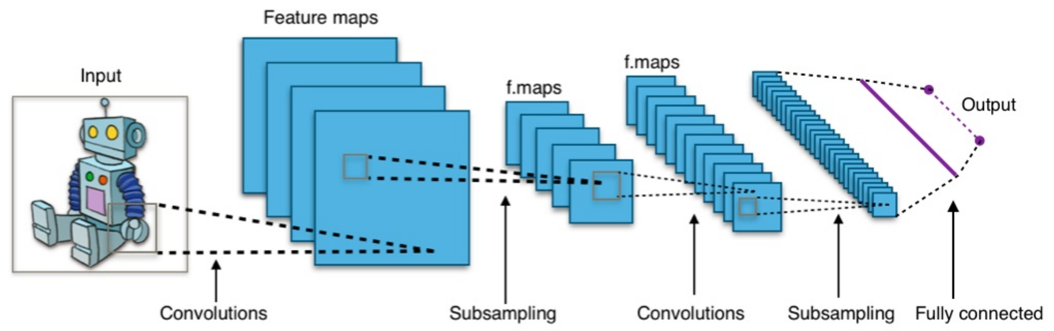
We present a method based on ML aimed to improve the SL event reconstruction, mainly focused on track events: (anti)muon-neutrino interactions.

- Direction angles of the neutrino [3].
- Closest point of the track to the telescope (track events) or interaction vertex (shower events).
- Neutrino energy (shower events) or muon energy (track events).

Track parameters approach: Neural Networks

We combined Deep Convolutional Networks (DCNs) [4] with Mixture Density Networks (MDNs) [5].





- MDNs allow to predict not only the direction angles but also their uncertainty.
- DCNs extract the important features.

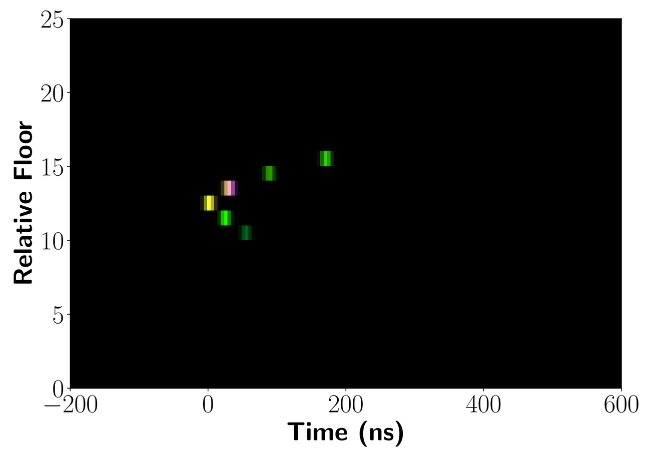
The network was trained with Monte Carlo simulations [6] of (anti)muon-neutrino interactions:

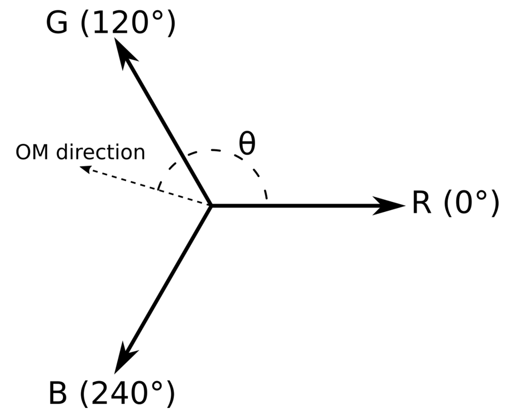
- Training set (60%)
- Validation set (20%), to avoid over-fitting through Early Stopping
- Test set (20%), to evaluate the generality of the results

Input (25,161,3)	Convolution 2D + ReLU Filters 16, Kernel 2x10	Max Pooling 2D Kernel 2x2	Convolution 2D + ReLU Filters 32, Kernel 2x10	Max Pooling 2D Kernel 2x2
Flatten + DropOut (0.2)	Max Pooling 2D Kernel 2x2	Convolution 2D + ReLU Filters 128, Kernel 2x10	Max Pooling 2D Kernel 2x2	Convolution 2D + ReLU Filters 64, Kernel 2x10
Dense + ReLU + Batch Normalization. Size 128	Dense + ReLU + Batch Normalization. Size 128	Dense + ReLU + Batch Normalization. Size 32	Dense + ReLU + Batch Normalization. Size 32	(Scaled) tanh: μ output ELU+1: σ output

From data to images

Two-dimensional images are created (floor x time) using the hit information. Images are then centered based on the reference hit.

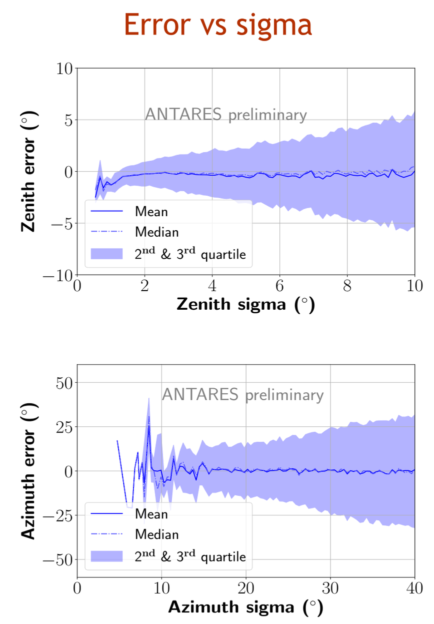




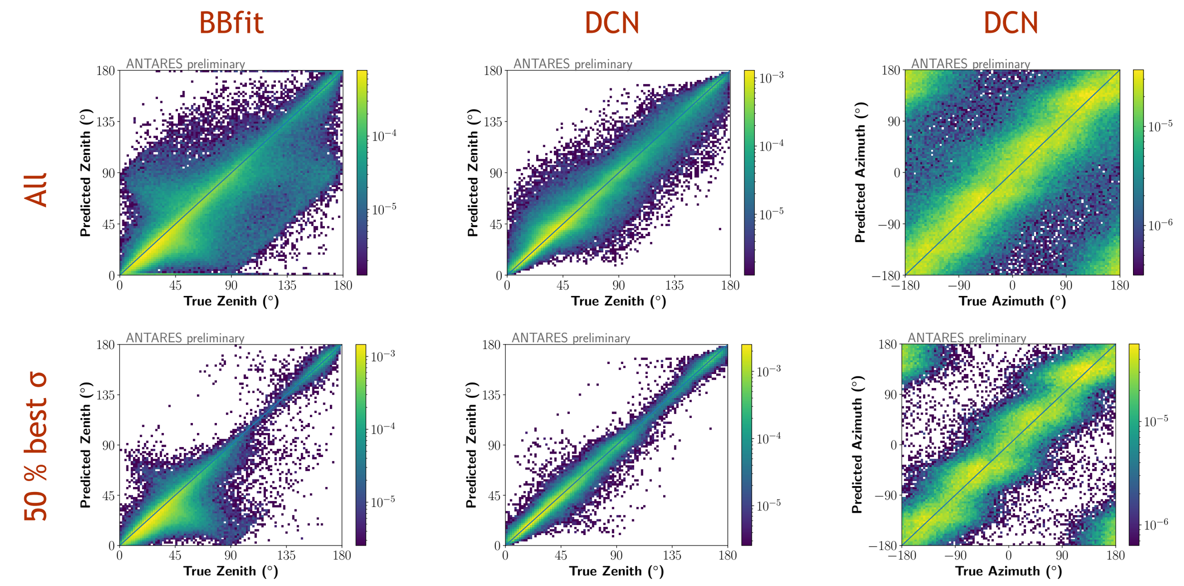
The RGB colors of the pixels are obtained by weighting the angle of the OM with the voltage amplitude of the hit.

Results

DCN outperforms classical reconstruction methods for the direction angles (θ,φ).

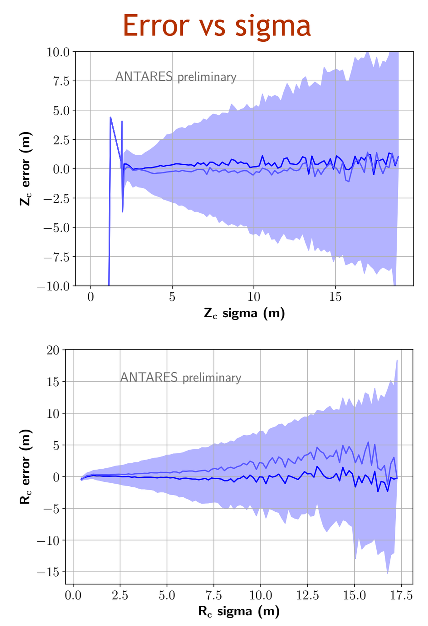


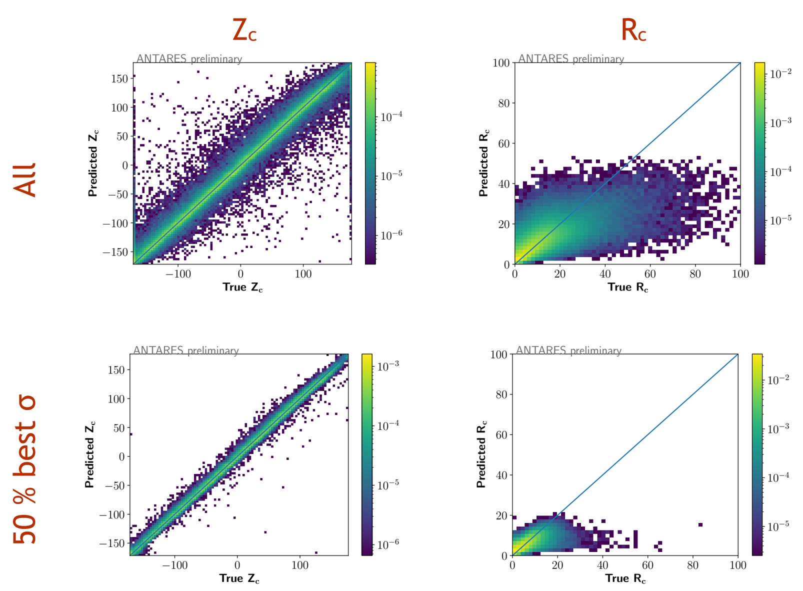
Absolute error	BBfit		DCN		DCN (50% lowest σ)	
	Mean	Median	Mean	Median	Mean	Median
Zenith	15.5º	8.5º	7.4º	4.4º	3.7º	2.5º
Azimuth	-	-	41.4º	31.5º	29.3º	23.6º
Total	-	-	28.1º	22.4º	18.3º	13.2º



Moreover, our uncertainty parameter behaves as expected for a standard deviation value.

Reconstruction of the closest point of the track to the telescope (R_c, Z_c):

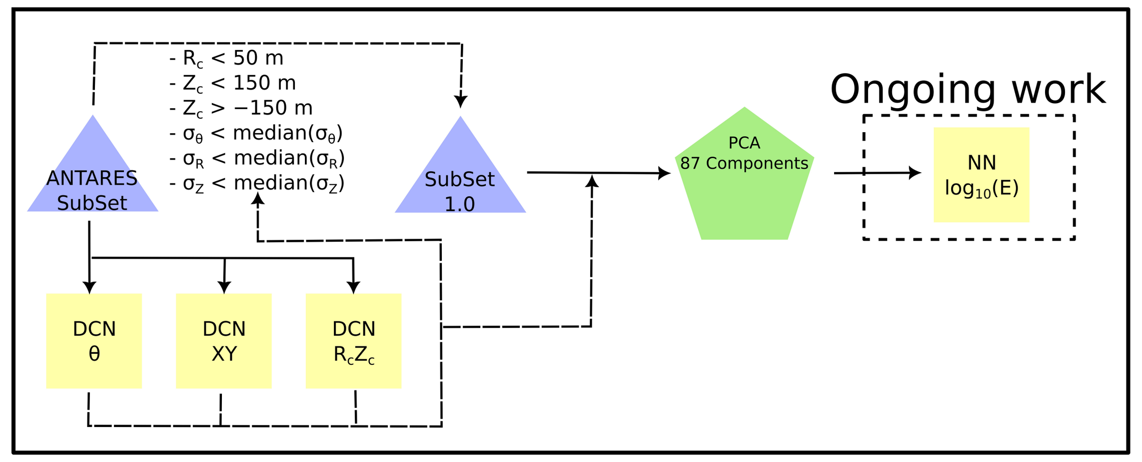




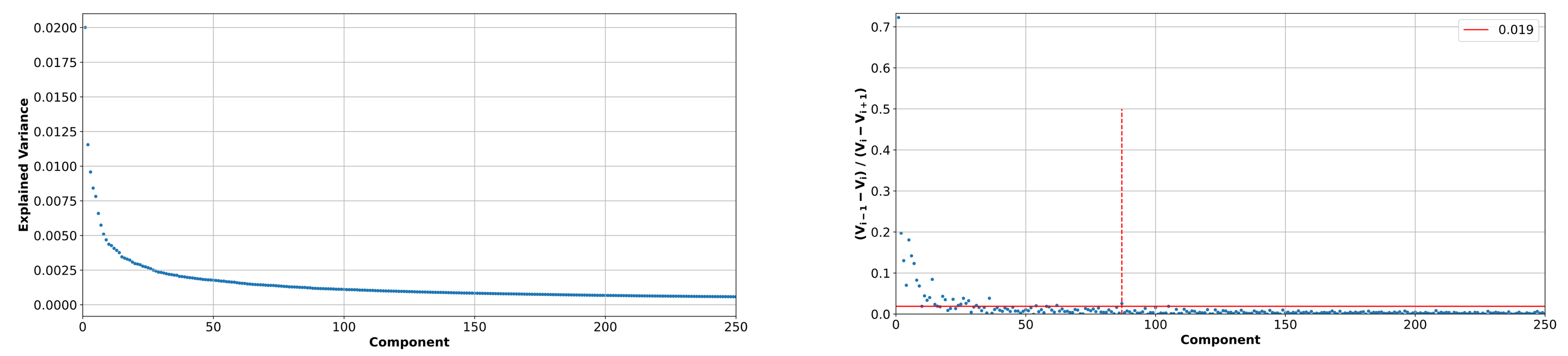
The results are good and will be used in the energy reconstruction.

Energy reconstruction approach (ongoing work)

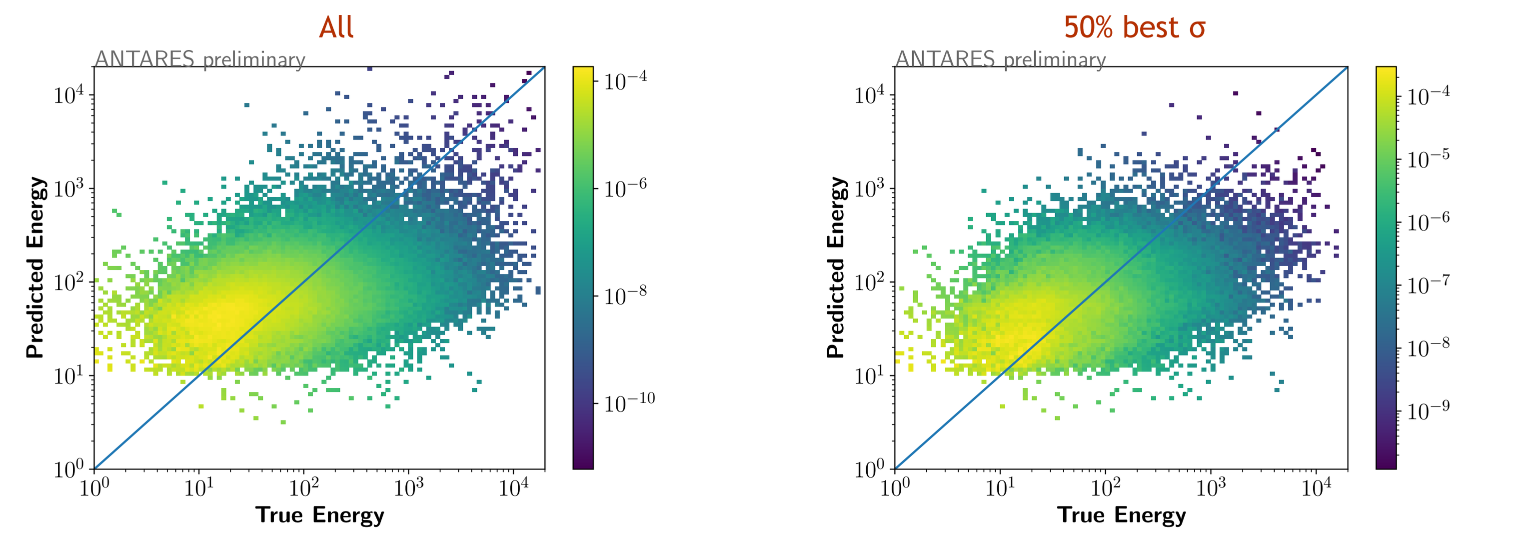
For the energy reconstruction, we take the layer activations of the previous networks and perform a Principal Componente Analysis (PCA). We also reduce the size of the DataSet by applying criteria based on the above reconstructions. This is done to try to keep events as close to the telescope as possible, since for these the energy reconstruction is more feasible.



The number of relevant components are chosen by the elbow rule and those are used to train a Feedforward NN that predicts the decimal logarithm of energy.



Preliminary results



Conclusion

- We clearly outperform classical direction reconstruction methods for single-line events.
- A prediction of the azimuth angle is made, which was previously missing.
- The reconstruction of the closest point of the track is in good agreement with the true values.
- A first estimation of the muon energy of track events is achieved with the combinaiton of two ML methods (PCA + NN) showing promising results.

References:

[1] ANTARES collaboration, Nucl. Instrum. Meth. A 656 (2011) 11 [arXiv:1104.1607]
[2] ANTARES collaboration, Astropart. Phys. 34 (2011) 652 [arXiv:1105.4116].
[3] J. García-Méndez et al, JINST 16 (2021) C09018.
[4] J. Gu et al., Pattern Recognition 77 (2018) 354.
[5] C.M. Bishop, Neural Computing Research Group NCRG/94/004, (1994).
[6] ANTARES collaboration, JCAP 01 (2021) 064 [arXiv:2010.06621].

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