SMALL THINKS BIG: A JOURNEY WITH TRANSFORMERS

GENERALIZATION IN KM3NeT/ORCA FOR NEUTRINO EVENT RECONSTRUCTION

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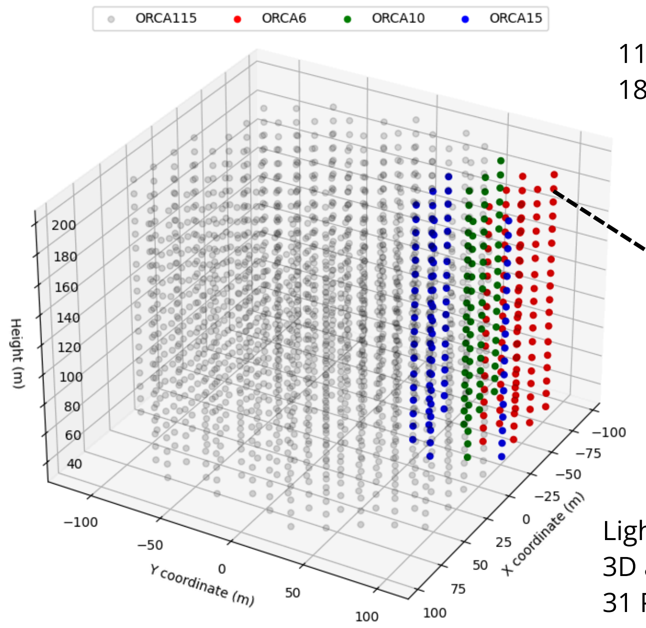
BUILDING KM3NeT/ORCA TELESCOPE

KM3NeT/ORCA is an **evolving detector**! We collect, process and analyze data while we build it. Transformers [1] as LLMs, help us **build neutrino physics language** in KM3NeT [2].



115 vertical detection units (DU)
18 digital optical modules (DOM) per DU

Light collection from **Cherenkov radiation**
3D arrays of 3" PMTs
31 PMTs per DOM

Finetuning training samples: 100k track (ν_μ^{CC}) and 100k shower (ν_e^{CC}) events.

PHYSICS GOALS OF KM3NeT

Deep-sea **neutrino telescopes** in the Mediterranean sea

- KM3NeT/ARCA: identify high-energy neutrino sources in the Universe.
- KM3NeT/ORCA: determine the mass hierarchy of neutrinos.

Optimized for 1 TeV - 10 PeV and 1-100 GeV energies, respectively.

Neutrino event reconstruction with transformers
Event topology, energy and direction, interaction vertex

WHY TRANSFORMERS?

Easily **scalable**.
Information is **retained** between detectors.
No specific fine-tuning of neighboring algorithms of GNNs.

From big to small...

- Train on simulations for the full KM3NeT/ORCA telescope [3, 4].
- Fine-tune on smaller telescopes: ORCA115 → ORCA6, ORCA10, etc.

...and vice versa

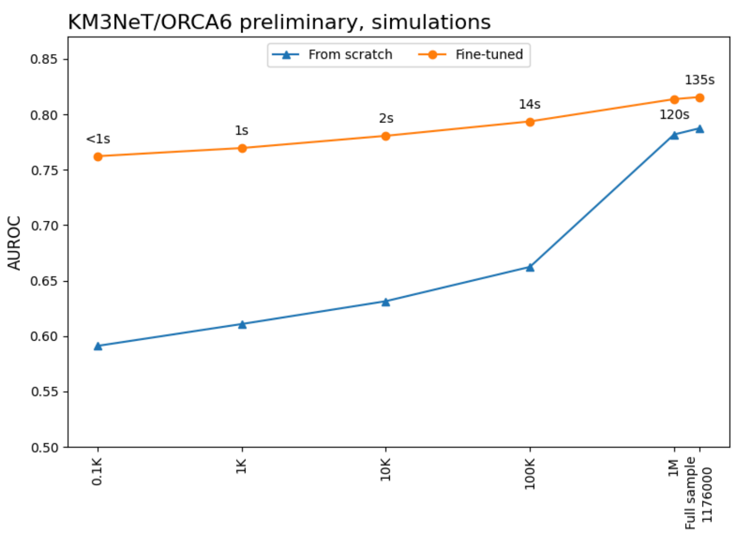
- **Fine-tune** on larger detectors: ORCA6 → ORCA10 → ORCA15 → ...

We build a model that learns as the detector grows!

TRANSFORMERS ARE HUNGRY FOR DATA!

The run-by-run approach simulates MC runs based on the data runs to reduce discrepancies. Nevertheless, there is not always enough data to train large models from scratch.

Small detectors require large amounts of data to describe the neutrino topology:
track-like or shower-like



Evolution of the AUROC (Area Under the ROC curve) value for track/shower classification as function of the training data size in KM3NeT/ORCA6.

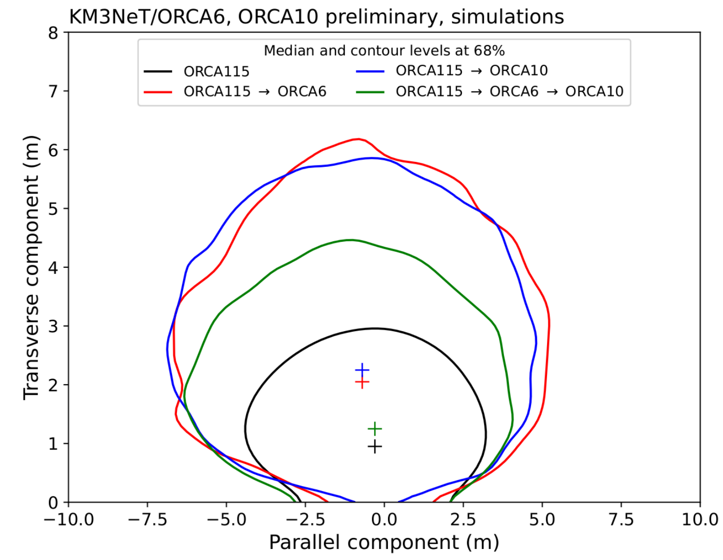
Fine-tuning yields remarkable results with very limited data **(above 15% improvement).**

Models trained from scratch **never beat** the fine-tuned ones.

Computing resources and time are efficiently handled by leveraging pre-trained models and optimizing data usage.

WHY GETTING BIGGER?

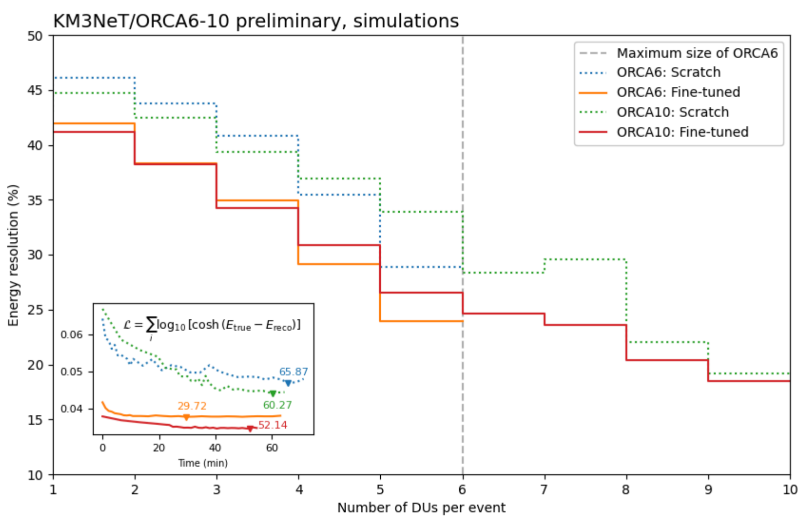
Even though our current detector has very promising results [5], a better event containment will be a major improvement, **it needs to grow!**
Meanwhile, we use our **knowledge from the full telescope...**



Interaction vertex reconstruction at KM3NeT/ORCA6, KM3NeT/ORCA10 and KM3NeT/ORCA115 projected over the neutrino direction for 1-100 GeV atmospheric neutrinos.

... as we learn the real detector configurations.

STEP BY STEP: ENHANCING PERFORMANCE WITHIN DETECTOR CONSTRAINTS



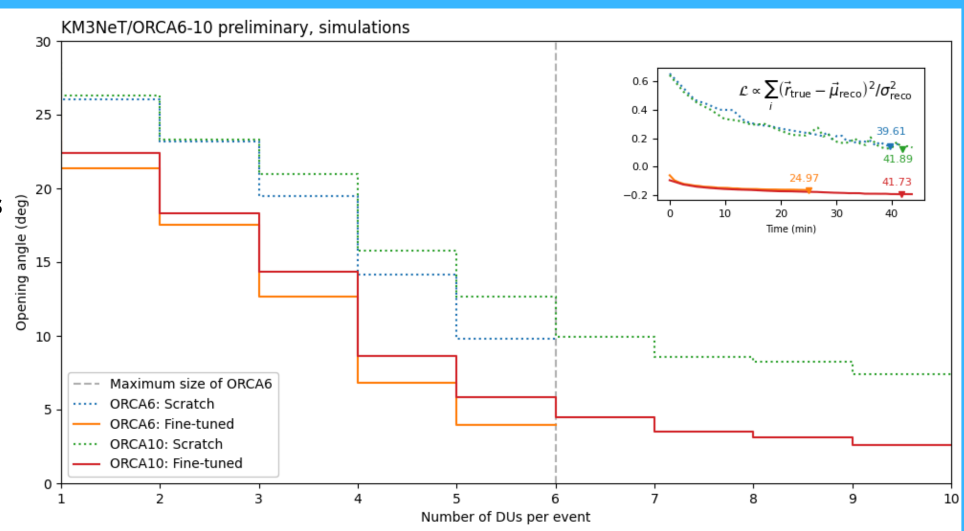
Energy resolution at KM3NeT/ORCA6 and KM3NeT/ORCA10 as a function of the number of active DUs per event for 1-100 GeV atmospheric neutrinos.

Fine-tuned models retain information from the **missing detector lines.**

Energy resolution is better in **less training time.**

Direction reconstruction improved significantly.

Loss curves reveal fine-tuning's **performance boost.**



Opening angle resolution at KM3NeT/ORCA6 and KM3NeT/ORCA10 as a function of the number of active DUs per event for 1-100 GeV atmospheric neutrinos.

THE ROAD AHEAD

From simulations to data: ensure consistency and accuracy when transitioning to real detector data.
Robustness: validate model reliability across different conditions and detectors.
Benchmarking: Compare standard and GNN-based reconstructions.
Understanding limitations: identify constraints in the model and physics.
Estimate improvements as the detector grows to optimize scalability.

REFERENCES

[1] A. Vaswani et al. Attention is all you need. NIPS (2017).
[2] KM3NeT Collaboration, Letter of intent for KM3NeT 2.0, J. Phys. G 43 (2016) 084001.
[3] J. Prado. A Comprehensive Insight into Machine Learning Techniques in KM3NeT (indico.phys.ethz.ch/event/113/contributions/843/)
[4] I. Mozun. Transformer models for neutrino event reconstruction with KM3NeT/ORCA115 (indico.phys.ethz.ch/event/113/contributions/831/)
[5] V. Carretero. Measurement of neutrino oscillation parameters with the first six detection units of KM3NeT/ORCA (arxiv.org/abs/2408.07015)