nuT: Neutrino Reconstruction with Transformers

Transfer Learning Across KM3NeT/ORCA Telescopes for Neutrino Oscillations Physics

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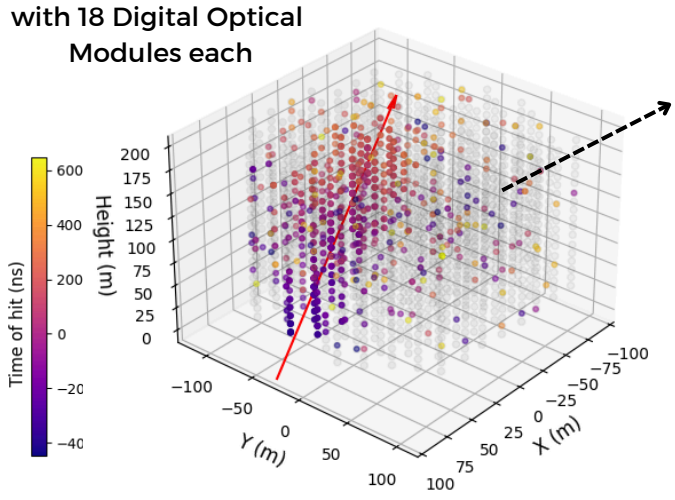
KM3NeT in search of neutrinos

Deep-sea neutrino telescopes in the Mediterranean sea [1]

- KM3NeT/ARCA: identify high-energy neutrino sources in the universe
- KM3NeT/ORCA: study of neutrino properties

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

KM3NeT/ORCA
115 vertical detection units with 18 Digital Optical Modules each

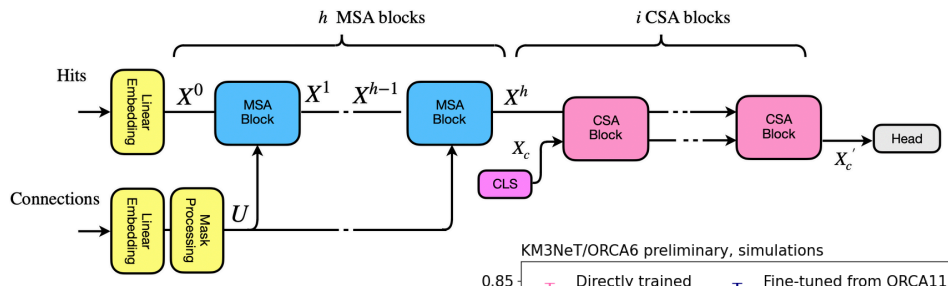


DIgital Optical Module
3D glass sphere
31 inches PMTs(x31)

*A **muon** from a neutrino interaction near the sea bottom travels through the telescope radiating Cherenkov photons collected by the **PMTs with high time and position resolution***

One Model, Many detectors

A transformer-based model [2] tailored for neutrino event reconstruction
Reconstructs from sparse light patterns detected in the telescope
Uses attention masks inspired by physics principles and detector geometry [3, 4]
Uses transfer learning to propagate information across detector configurations



Challenge:

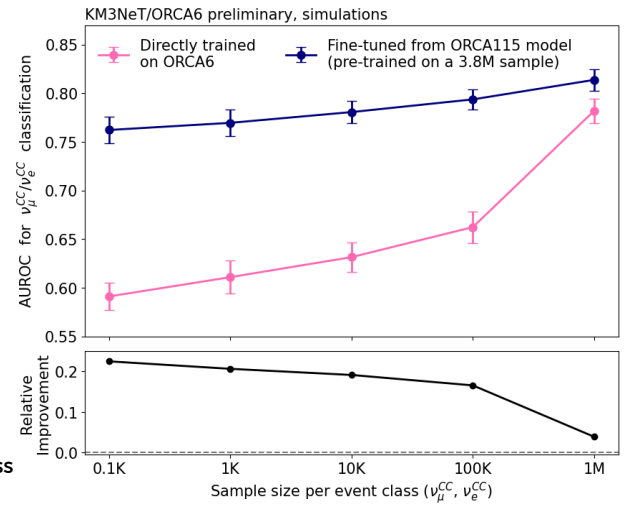
- KM3NeT/ORCA telecope grows!
- Tzraining for every detector response update is costly.

Transfer Learning solution:

- ORCA115 pre-training: the largest configuration, but idealistic.
- ORCA6 fine-tuning: limited, but simulated from real data-taking.

Improvements:

- Faster convergence
- Better performance with limited data
- Generalization and robustness across detectors



Challenges of neutrino physics reconstruction in KM3NeT/ORCA

Reconstruct neutrinos from light

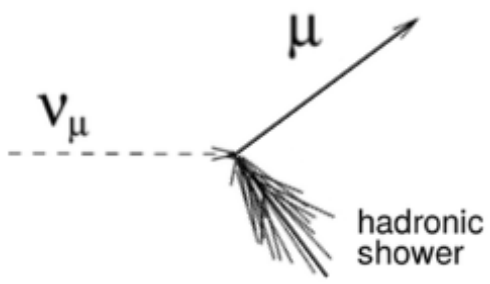
Maximum Likelihood Fit (MLF) algorithms:

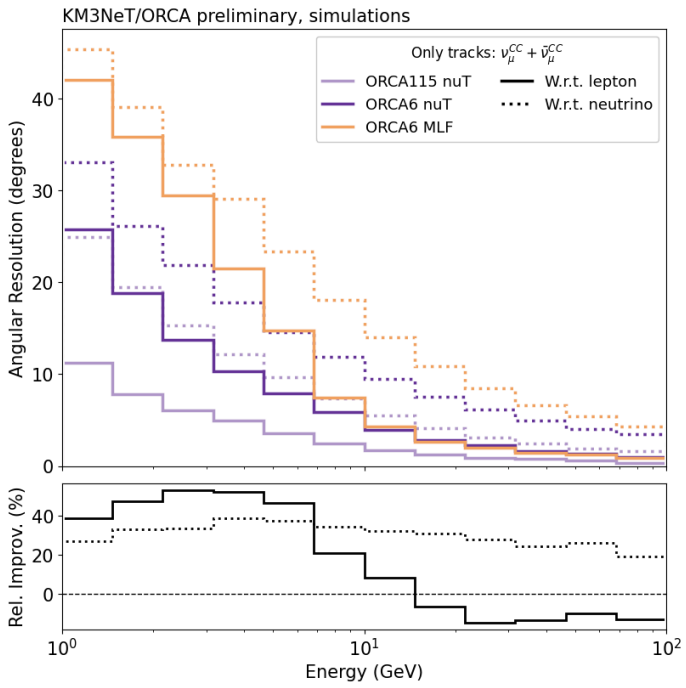
- Reconstruct under track or shower hypothesis
- Do not reconstruct the neutrino itself

nuT model beyond MLF:

- Directly reconstructs neutrinos from
- Simultaneously reconstruct all event types

Altough not compared here, an MLF algorithm simultaneously reconstructing the track and shower is in development [5]



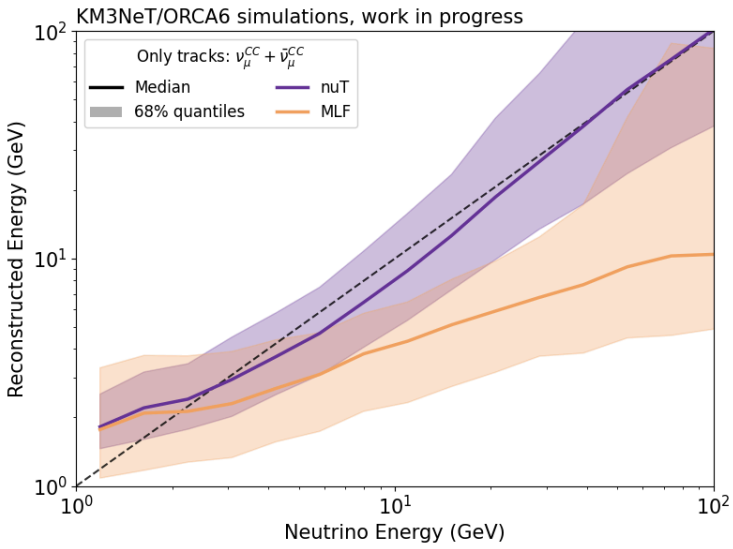


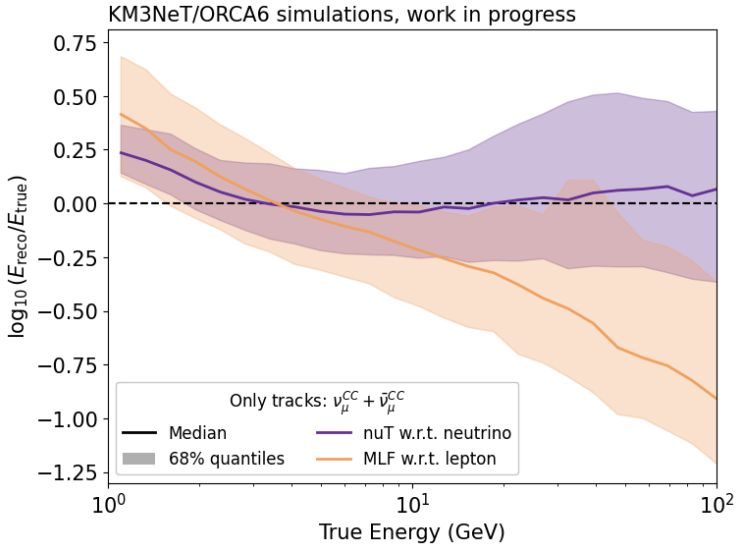
Training large models

KM3NeT generates realistic Monte Carlo samples based on actual data-taking runs, capturing the complexities of deep-sea conditions.
The efficiency of the nuT model and the use of data and computing resources are maximized by leveraging pre-trained models.

Scaling up with precision

KM3NeT/ORCA6, with already promising physics results [6], limits the reconstruction. Nevertheless, with increased detector and statistic, the understanding of neutrino physics improves.





Angular resolution

- **MLF:** <10˚ resolution above 10 GeV
- **nuT:**
  - +30% improvement below 10 GeV
  - Improved resolution w.r.t. neutrino

Energy reconstruction

- **MLF:** underestimation from missing hadronic component.
- **nuT:** accounts for both visible and non-visible energy.

Saturation effect caused by to limited detector size (6 DUs).

Further improvements

Shower events (ν_e^{CC}) reconstruction with nuT model

Angular resolution: relative improvement of 40% w.r.t. MLF (<10˚ above 10 GeV)
Energy reconstruction: better accuracy w.r.t. to tracks because of its containment

Background signal suppresion

Atmospheric muons: <1% reconstructed as upgoing (< 8% of contamination)
Optical background: effectively removed from quality cuts in reconstruction

References

[1] KM3NeT Collaboration, Letter of intent for KM3NeT 2.0, J. Phys. G 43 (2016) 084001.
[2] A. Vaswani et al. Attention is all you need. NIPS (2017).
[3] H. Bukhari, D. Chakraborty, P. Eller, T. Ito, M. V. Shugaev and R. Ørsøe, IceCube – Neutrinos in Deep Ice The Top 3 Solutions from the Public Kaggle Competition, (arxiv.org/abs/2310.15674, 2023).
[4] Huilin Qu, Congqiao Li and Sitian Qian. Particle Transformer for Jet Tagging, (arxiv.org/abs/2202.03772, 2023).
[5] B. O Fearraigh. Following the light - Novel event reconstruction techniques for neutrino oscillation analyses in KM3NeT/ORCA, (2024).
[6] V. Carretero. Measurement of neutrino oscillation parameters with the first six detection units of KM3NeT/ORCA (arxiv.org/abs/2408.07015, 2024)