Event reconstruction and tau neutrino appearance using CNNs for KM3NeT / ORCA

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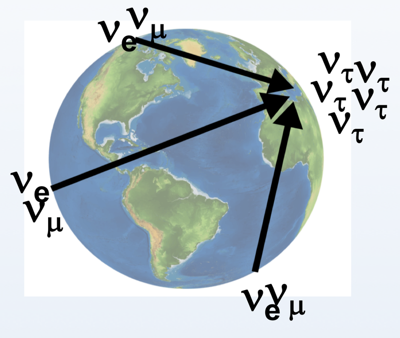
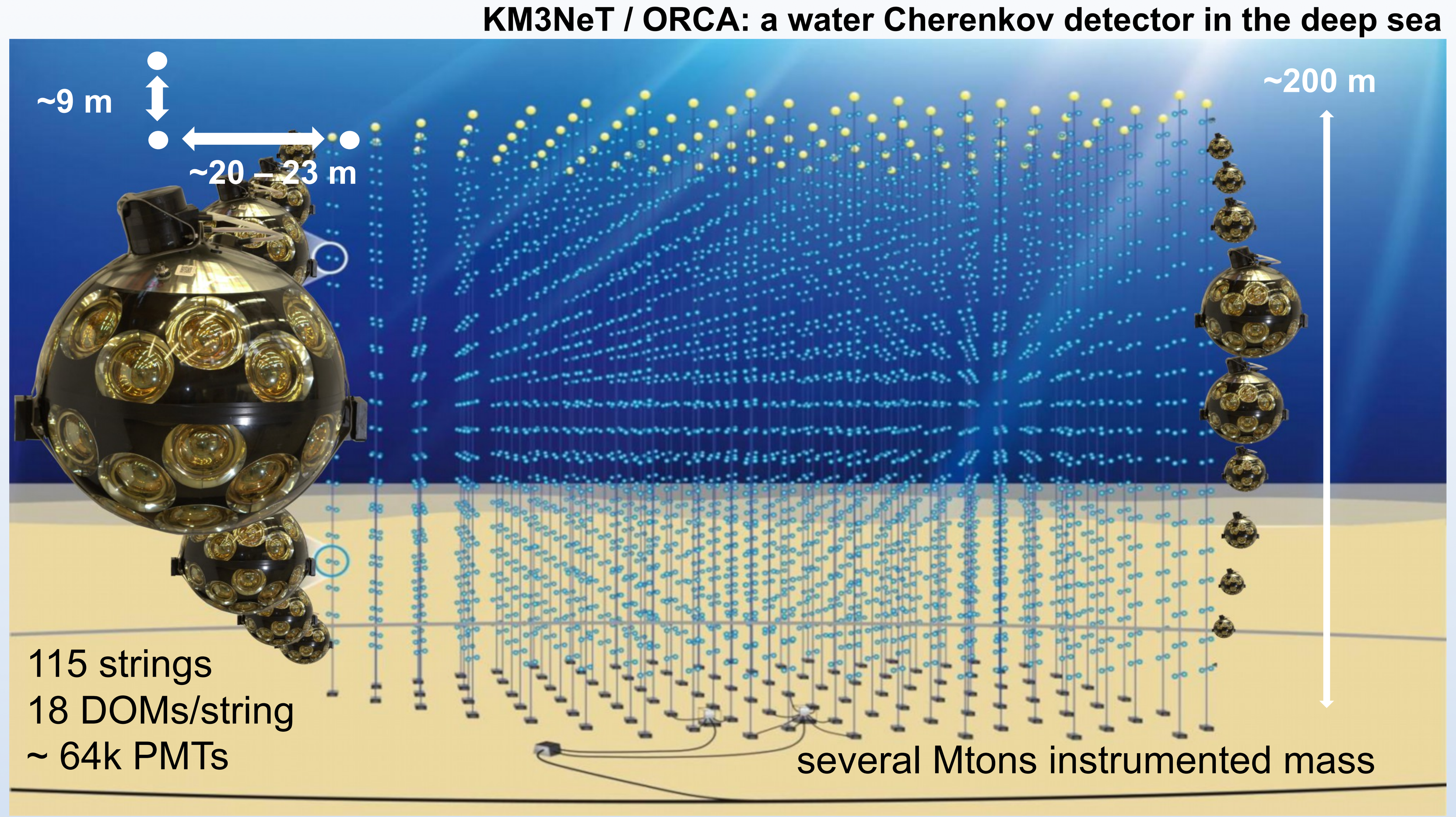


KM3NeT / ORCA: a water Cherenkov detector in the deep sea



Letter of Intent for KM3NeT 2.0, J.Phys. G43 (2016) no.8, 084001

Summary

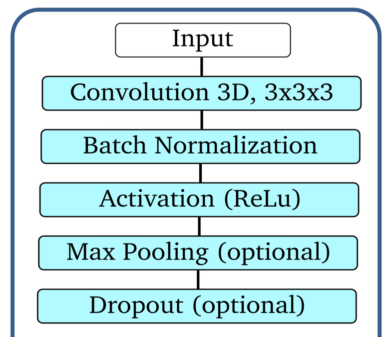
Simulated sets of KM3NeT data, on the level of individual recorded photosensor signals above a set threshold, are binned in space and time, and then used as inputs for different Convolutional Neural Networks (CNNs). A complete data classification and regression chain using these CNNs is provided, cf. arXiv:2004.08254. The classification tasks consist of the rejection of background events, induced by atmospheric muons and random noise, and the separation of track-like and shower-like event topologies induced by different neutrino flavours and interaction modes. The regression CNN allows for the reconstruction of the neutrino interaction position, the neutrino energy and direction, and of their corresponding uncertainties. This analysis chain reaches a competitive and partly superior performance with respect to classical approaches pursued in KM3NeT. Gains in sensitivity of 10% and more can be reached compared to classical approaches in event reconstruction and classification. The CNN-based reconstruction results are then used to calculate the sensitivity of KM3NeT/ORCA to deviations from the standard-model expectations for the purely oscillation-induced flux of tau neutrinos from the atmosphere.

KM3NeT is a distributed neutrino research infrastructure in the abyss of the Mediterranean Sea. One part of KM3NeT is the ORCA (Oscillation Research with Cosmics in the Abyss) detector. It is under construction and has been optimised to study the properties of neutrinos with GeV energies. Neutrinos are detected through the Cherenkov radiation induced by secondary particles generated in neutrino interactions in the water. To this end, several megatons of seawater will be instrumented with a 3D array of 2070 glass spheres (DOMs), each housing 31 3'' PMTs.

Image generation and CNN training

KM3NeT software for CNN training: OrcaNet [1], based on TensorFlow [2] and Keras [3].

- Recorded PMT signals above a set threshold, hits, are binned:
  - → Full dimension in space X, Y, and Z; at most one DOM per pixel
  - → Stacking channel:
    - in time T with respect to the mean time of triggered hits.
    - in PMT number P for position information within the DOMs.
  - → Input dimensions X Y Z x (T+P): 11 x 13 x 18 x (100+31) or 11 x 13 x 18 x (60 +31)

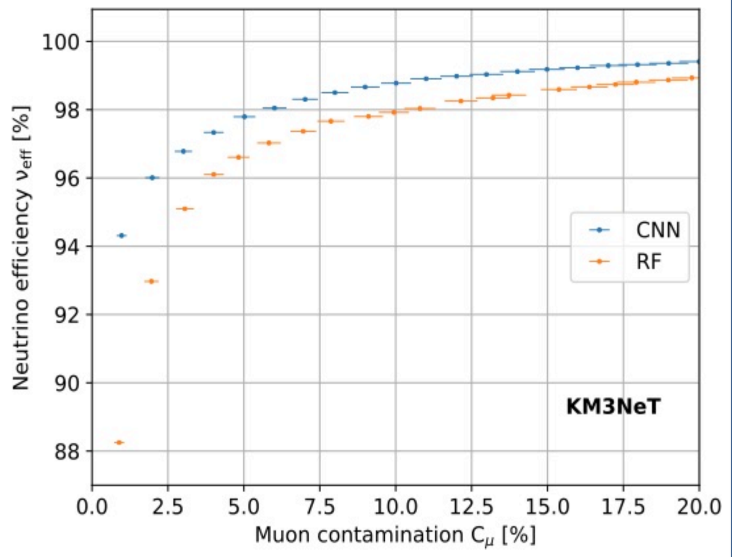


Scheme of a convolutional block

- CNNs defined as sequences of 3D convolutional blocks.
- Output neuron(s) connected through a small fully-connected network to serialized last convolutional layer.
- Outputs:
  1. classification: 'softmax' classifier with 2 output neurons to derive categorical output
  2. regression: 7 output neurons with linear activations to regress continuous variables (vertex x, y, z; direction x, y, z; E) with mean absolute error loss.
- Training takes 1 – 2 weeks on Nvidia Tesla V100 GPU with CUDA 10

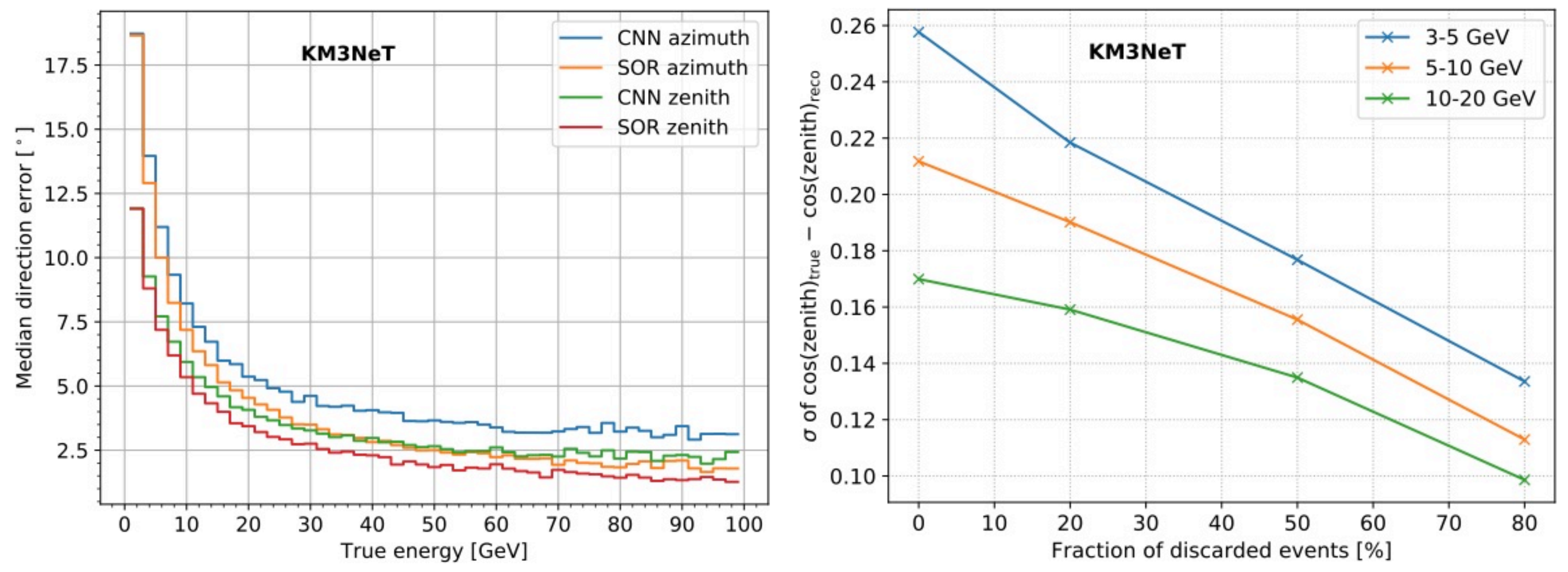
Classification: Background suppression

Recorded event data is dominated by atmospheric muons (several tens of Hz trigger rate) from cosmic-ray air-showers reaching the detector from above and pure-noise events due to ^{40}K decays and biological background light. An efficient selection of neutrino events (mHz rate) is necessary for physics analyses.



Fraction of atmospheric neutrinos having passed classical analysis pre-selection that survive the anti-muon cut vs. the contamination (fraction of atmospheric muons) in the final sample for the CNN and Random Forest (RF) anti-muon classifier.

Regression: Direction reconstruction and uncertainty estimate



Left: *Median absolute error of the zenith and azimuth angle reconstruction for the CNN event regressor and the KM3NeT shower reconstruction algorithm SOR versus true MC energy for ν_e^{CC} events.*

Right: *Standard deviation of the cos(zenith) residual distribution for all triggered ν_e^{CC} events vs. the fraction of discarded events after a cut on the CNN uncertainty estimate for different energy ranges.*

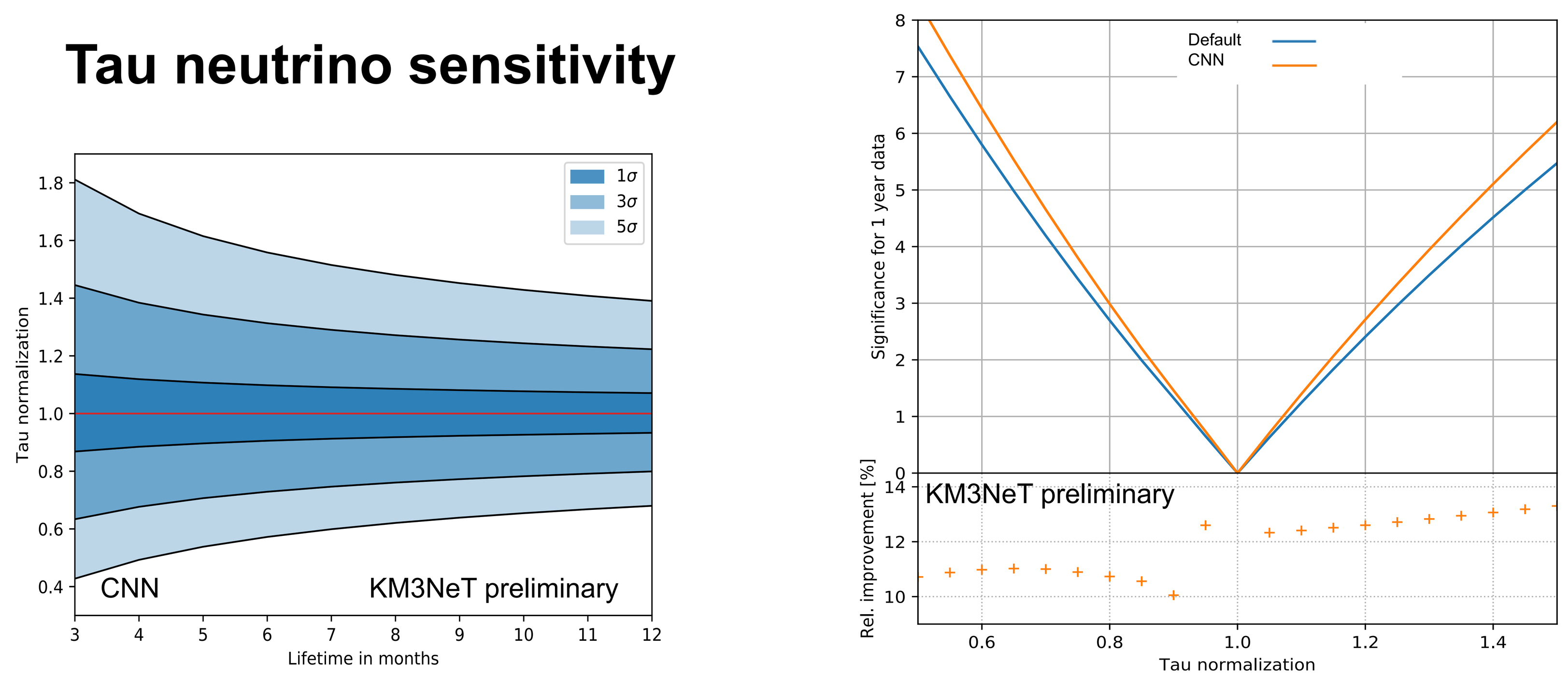
Uncertainty estimate: obtain estimates for uncertainties on reconstructed variables y_{reco}

- additional neuron per reconstructed regression variable yields the estimated uncertainty $\sigma_{\rm reco}$. Loss function used:

$$L = \frac{1}{n}\sum_{i=1}^{n}\left(\sigma_{\rm reco} - |y_{\rm true} - y_{\rm reco}|\right)^2$$

- with this the network learns to estimate the average absolute residual $\sigma_{\rm reco} \approx \langle y_{\rm abs} \rangle$.

Tau neutrino sensitivity

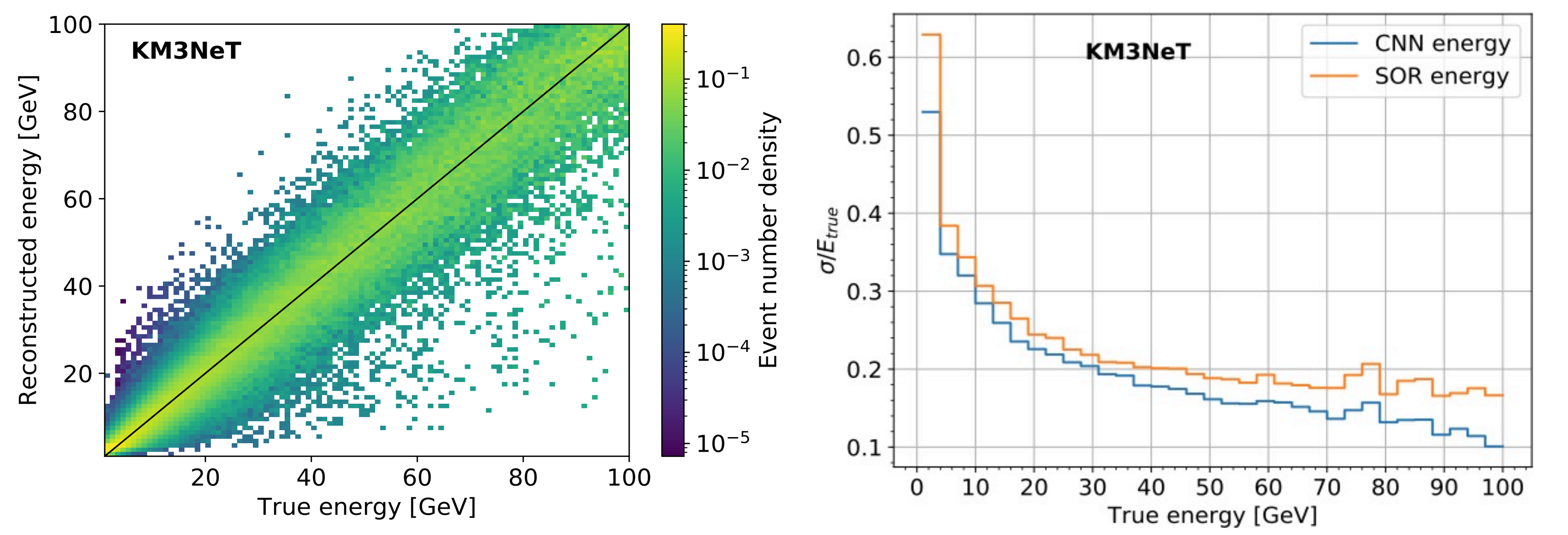


Non-appearance (=0) exclusion at 5σ level possible within a few months of operation with full ORCA detector. Fit results robust against θ_{23} and assumed mass ordering:

→ first physics results during construction phase

Power to constrain deviations from the expected tau neutrino normalisation (CC+NC) for 1 year of data taking with the full ORCA detector. Using the CNN event reconstruction chain improves the sensitivity by more than 10% with respect to other reconstruction methods pursued in KM3NeT.

Regression: Energy reconstruction

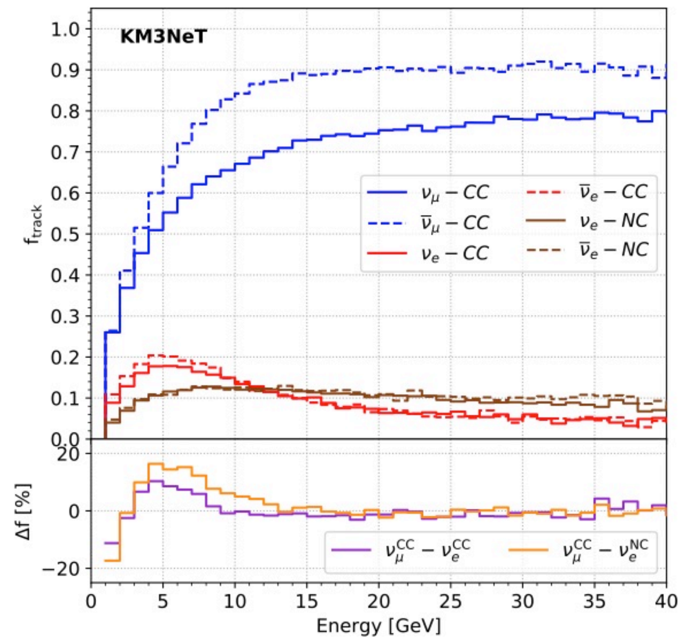


Reconstructed energy vs. true MC neutrino energy for ν_e^{CC}. The distribution is normalised to unity in each true energy bin.

Relative standard deviation on the reconstructed energy vs. true MC energy for ν_e^{CC}, performance of the CNN vs. KM3NeT shower reconstruction algorithm SOR.

Classification: Event topology

Neutrino interactions lead to different event topologies:
Track-like: ν_μ **charged-current** (CC) interactions create a final-state μ that travels ~4m/GeV leaving a long track-like light signature.
Shower-like: e with short radiation length (ν_e^{CC}), τ with short lifetime (ν_τ^{CC}) and neutral current (hadronic cascade only) events are localised around the interaction vertex.



Top: *Fraction of events classified as track (track score > 0.5) by the CNN as a function of neutrino energy.*
Bottom: *Relative improvement using the CNN compared to the RF classifier in terms of classification distance between ν_μ^{CC} and the respective shower-dominated electron neutrino channels.*

References: [1] http://github.com/KM3NeT/OrcaNet [2] http://www.tensorflow.org [3] http://keras.io

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