Enhancing Events in Neutrino Telescopes Through Deep Learning-Driven Super-Resolution

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1. Introduction

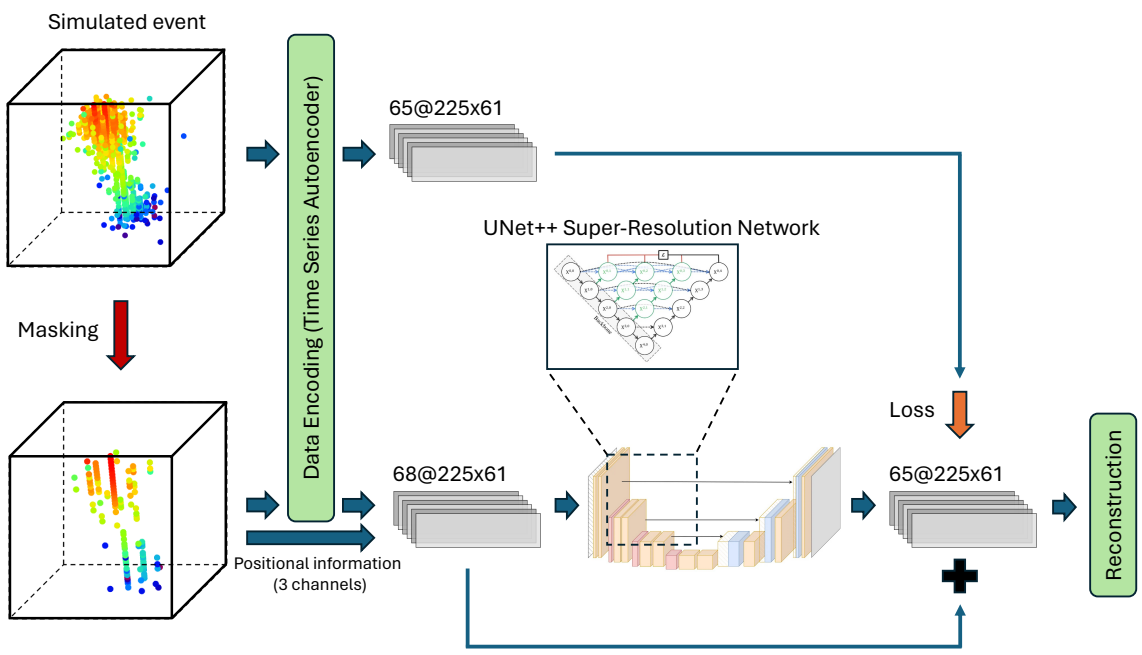

Fig. 1: Pipeline of the super-resolution framework. The OM timing information is encoded into a 64-parameter latent vector. Inputs to the UNet++ [1] contains 68 features: 64 (timing info) + 1 (number of hits) + 3 (3D position).

- Neutrino telescopes are **sparsely instrumented** volumes (string spacing ~100m)
- Prone to losing information between strings and optical modules (OMs)
- We propose a novel technique to partially recover that information, by training a neural network to **perform super-resolution** on existing events
- Data enhancement will be beneficial for most **reconstruction algorithms**

2. Data Preparation

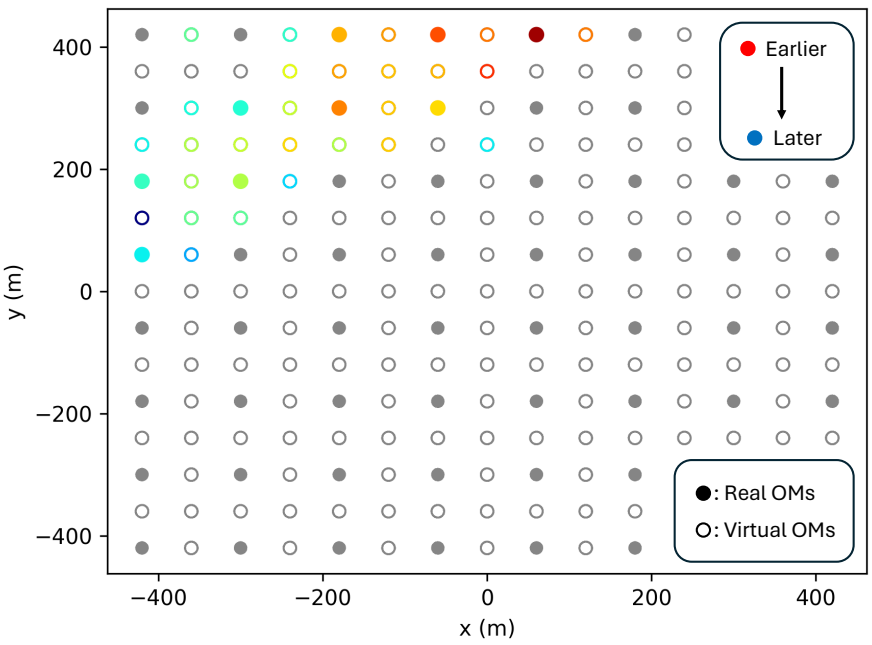

Fig. 2: Top-down view of a simulated track event, showing both real and virtual OM strings. Color indicates a hit and its timing.

- ν_μ track-like events are simulated in a custom orthogonal geometry (with dense, 60m string spacing) using Prometheus [2]
- **"Virtual" strings** are then chosen and masked out, so that string spacing in the input events are 120m
- The timing information on each OM is **encoded** through a pre-trained variational autoencoder (VAE), into a 64-parameter **latent space**
- VAE allows for operating in **compressed, uniformly sized** latent space

[1] Zhou, Zongwei *et al., UNet++: A Nested U-Net Architecture for Medical Image Segmentation* (2018), arXiv:1807.10165
[2] J. Lazar *et al.*, *Prometheus: An Open-Source Neutrino Telescope Simulation* (2023), arXiv:2304.14526
[3] F. J. Yu *et al.*, *Trigger-level Event Reconstruction for Neutrino Telescopes using Sparse Submanifold Convolutional Neural Networks* (2023), Phys. Rev. D **108**, 063017

3. Results

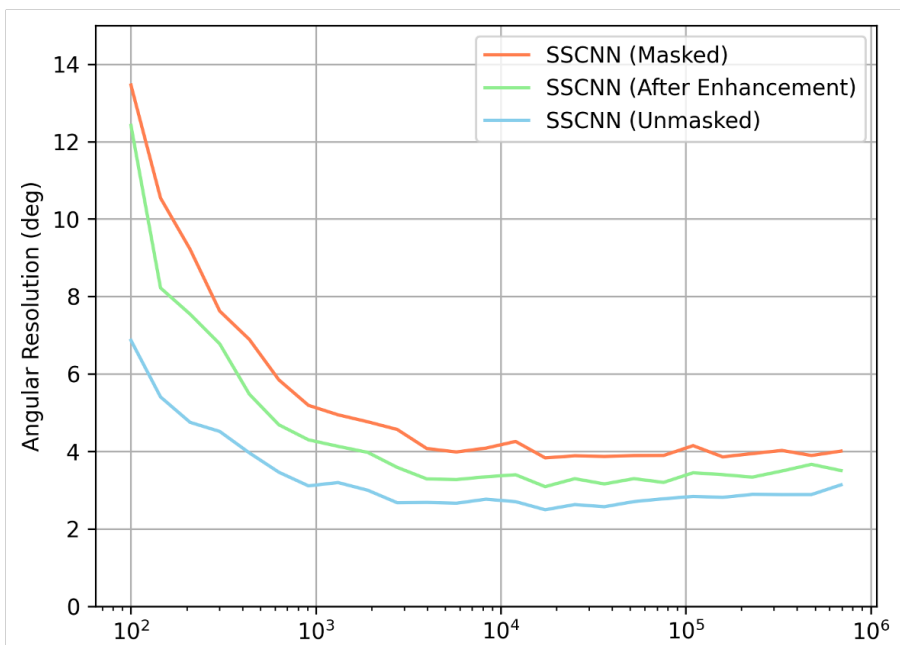

Fig. 3: Angular resolution as a function of the true neutrino energy.

- Sparse submanifold convolutional neural networks (SSCNN) [3] are used as a baseline reconstruction method for the study
- SSCNN angular reconstruction networks are trained three separate times on the **masked, unmasked, and super-resolution** network output events
- Reconstruction is **improved** by ~1.5° at low energies, and ~0.8° across the whole energy range, compared to masked input events

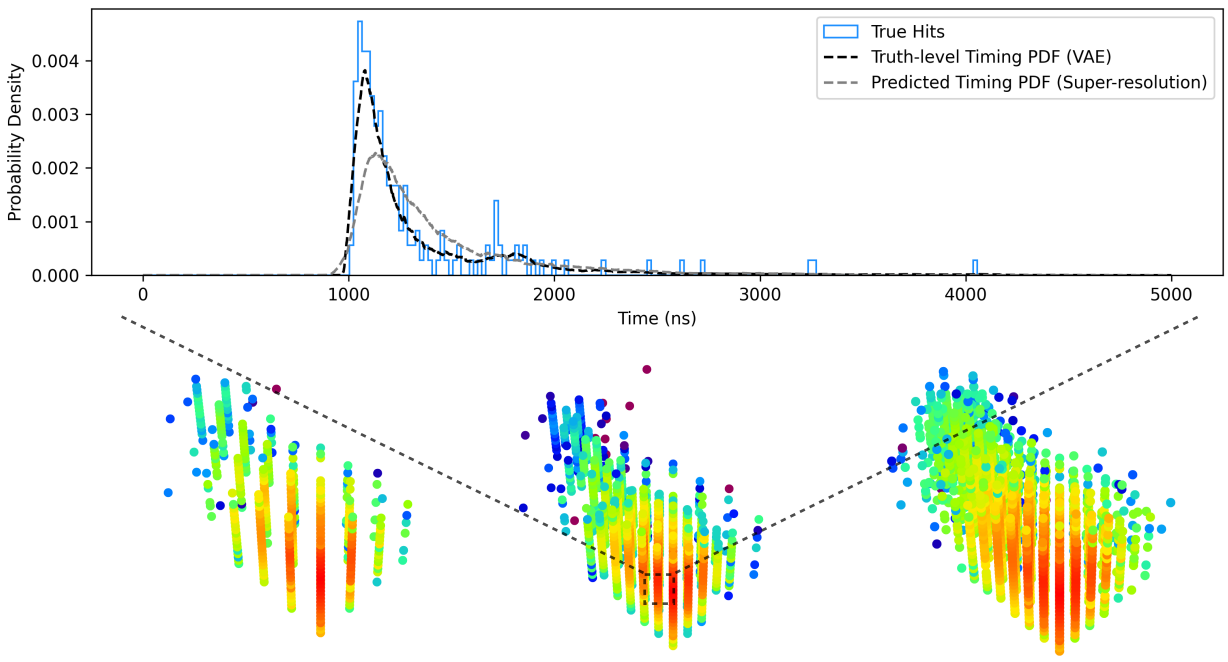

Fig. 4: Masked, after enhancement, and unmasked (from left to right) event displays. The top plot shows timing PDF results from the super-resolution network and the pre-trained VAE on a particular OM.

- We can **produce super-resolved events** and visualize them, by **sampling** from the super-resolution network predicted timing PDF
- While the network can produce reasonable results near OMs with many hits, it tends to struggle in producing OMs with few hits
- We also showcase the ability of the VAE to **accurately encode** and **reconstruct** finely-binned timing distributions

Summary

- Developed a deep learning-based super-resolution network to recover inter-string information in neutrino telescope events
- Implemented a novel way to represent OM-level timing information, through the use of a VAE
- Applying super-resolution to track-like events results in noticeable improvement in angular reconstruction performance, particularly in the low-energy regime