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# AIDAinnova

Advancement and Innovation for Detectors at Accelerators

Horizon 2020 Research Infrastructures project AIDAINNOVA

## MILESTONE REPORT

# NEW PFA PROTOTYPES

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**Abstract:**

We report on the work to develop the Pandora toolkit software containing Particle Flow Algorithms (PFAs) for reconstructing particles for three next-generation detector themes, namely the emerging technology of dual-readout calorimeters, improving hadronic jets for the future linear collider and using new 3D-readout liquid argon detectors in neutrino experiments.

For more information on AIDAinnova, its partners and contributors please see http://aidainnova.web.cern.ch/

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## Delivery Slip

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## Executive summary

The AIDAinnova project is extending Pandora, the standard software toolkit for particle-flow reconstruction, to include cutting-edge ideas for the emerging detector technology of dual-readout calorimeters. Work is also ongoing to incorporate into Pandora the APRIL algorithm for particle reconstruction of hadronic jets for a future linear collider. For the DUNE Near Detector (ND), there is a new 3D pixel technology which uses timing information to measure particle drifts more accurately, and the plan is to extend the Pandora neutrino reconstruction algorithms, which are currently working for MicroBooNE, to take full advantage of this. The DUNE ND will experience around 50 neutrino interactions per second owing to its closeness to the neutrino production beam, and analysing such complex images is currently beyond state-of-the-art, and so AIDAinnova is developing so-called slicing algorithms to pick out and reconstruct the individual neutrino interactions.

# 1. INTRODUCTION

Particle flow algorithms (PFAs) are state-of-the-art reconstruction methods for high-energy physics calorimeters and neutrino detectors. These are available from the Pandora software toolkit [1], which is a general PFA framework that implements a multi-algorithm, step-by-step approach for reconstructing particle interactions, in which more sophisticated algorithms are deployed as the event picture develops. Pandora is being successfully used to identify neutrino interactions for MicroBooNE based at Fermilab [2] and has also been used to study detector designs for the International Linear Collider (ILC). The aim of this task is to develop reconstruction algorithms for the Pandora toolkit for three next-generation detector themes, namely the emerging technology of dual-readout calorimeters, improving the reconstruction of hadronic jets for the future linear collider, and using new 3D-readout technology for liquid argon (LAr) detectors in neutrino experiments. This report describes the progress made so far.

# 2. DUAL-READOUT CALORIMETERS

Dual-readout calorimeters can improve the energy resolution of hadronic particle showers by measuring separately their electromagnetic and hadronic components using scintillating and Cherenkov fibres. This new technology is being pursued for future circular and linear colliders and is one of the main components of the IDEA concept (Innovative Detector for future Electron-positron Accelerators) [3]. A full Geant4 simulation [4] of the IDEA design has been achieved within the Key4hep framework, incorporating both the tracking drift chamber and the dual-readout calorimeter. The simulated energy deposits in the calorimeter fibres include digitisation of the photon signals using a silicon photomultiplier model. Figure 1 shows the conceptual design and prototype fibre layout.

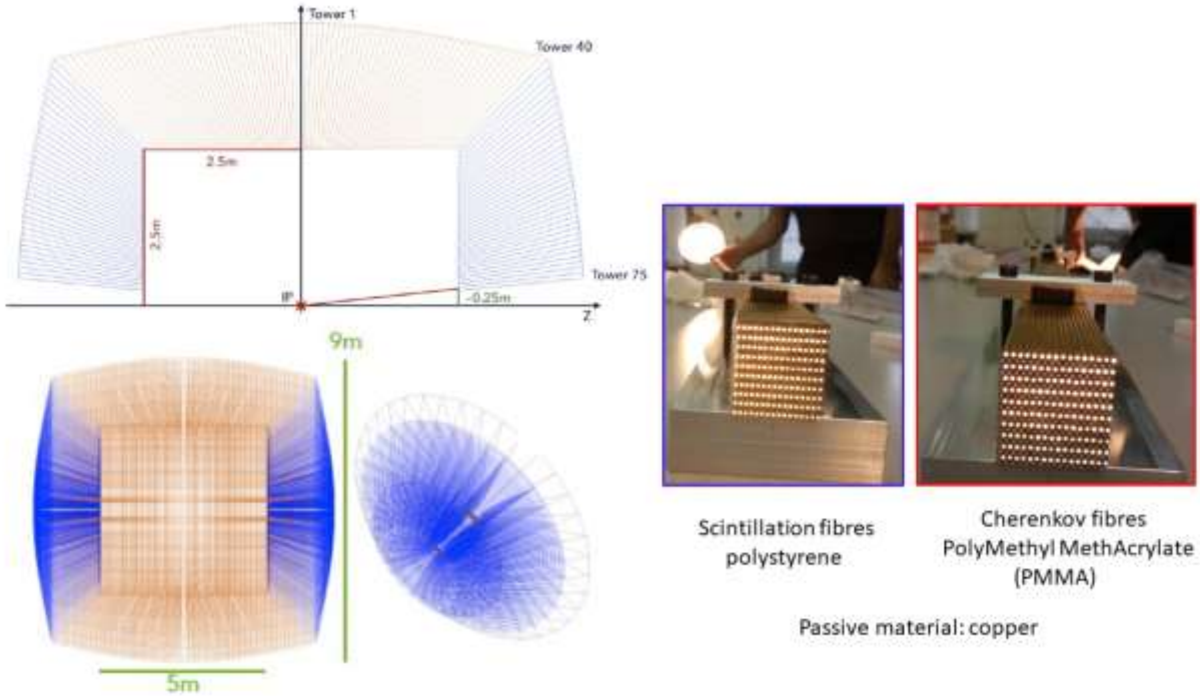


*Fig. 1 Conceptual design, simulation model and prototype fibre layout of the dual-readout calorimeter.*

The IDEA simulation is being used to generate event samples for developing and testing dual-readout calorimeter reconstruction software inside Pandora and Key4hep. Figure 2 shows some example multiplicity (number) and fractional energy distributions of 5 GeV pions passing through the fibres. As part of the effort to completely reconstruct jets, work is underway to select a suitable clustering algorithm based on neural network training done for Pandora neutrino reconstruction, and machine learning methods are being applied for particle identification using the TensorFlow and PyTorch toolkits, as illustrated in Fig. 3.

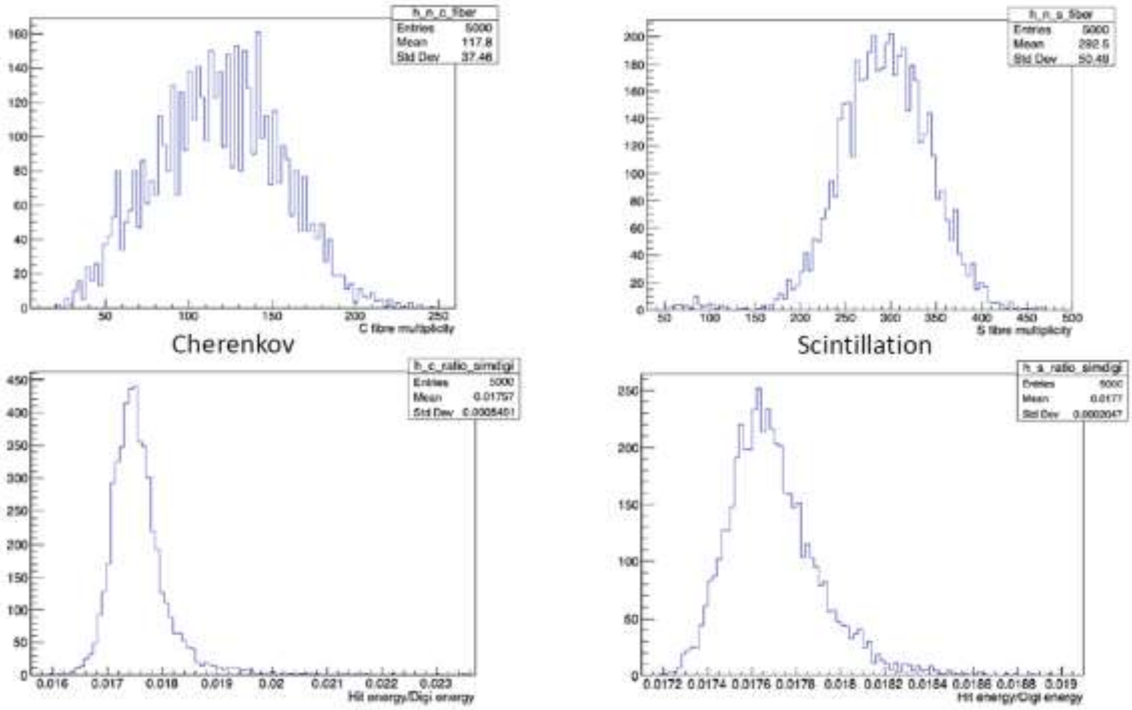


*Fig. 2 Number of energy deposits (top) and fractional energies (bottom) detected by the Cherenkov (left) and scintillation (right) fibres for a simulated sample of 5 GeV pions.*

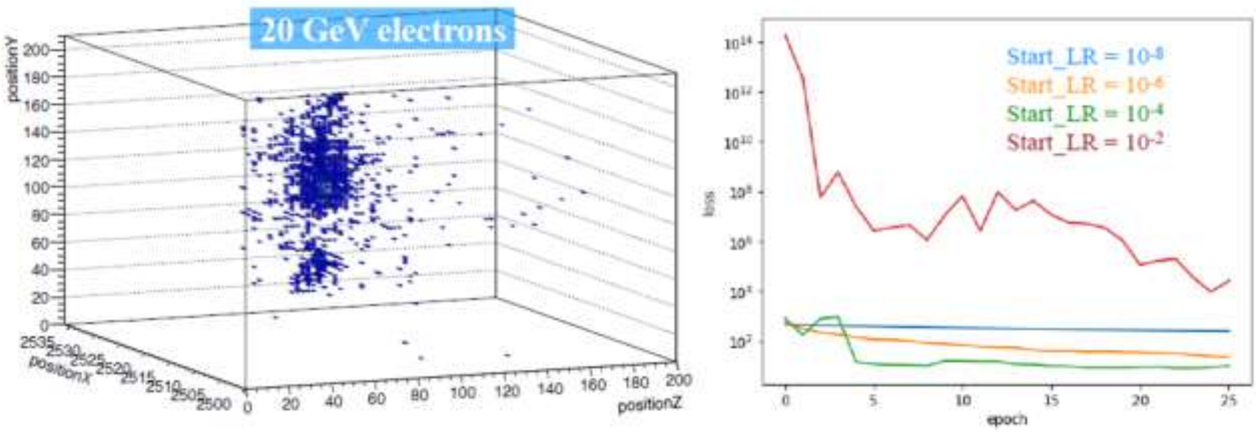


*Fig. 3 Simulated dual-readout energy deposits for 20 GeV electrons and the TensorFlow machine learning loss functions for different starting learning rates for the reconstruction.*

The dual-readout calorimeter is designed to have excellent lateral (transverse) granularity. However, it is not able to directly measure the radial or longitudinal profile of the energy deposits. This limitation could be overcome by including timing information from the fibre signals. Preliminary studies are showing that this approach has great promise, which could eventually realise the full potential of the detector performing as a particle flow calorimeter, as illustrated in Fig. 4.

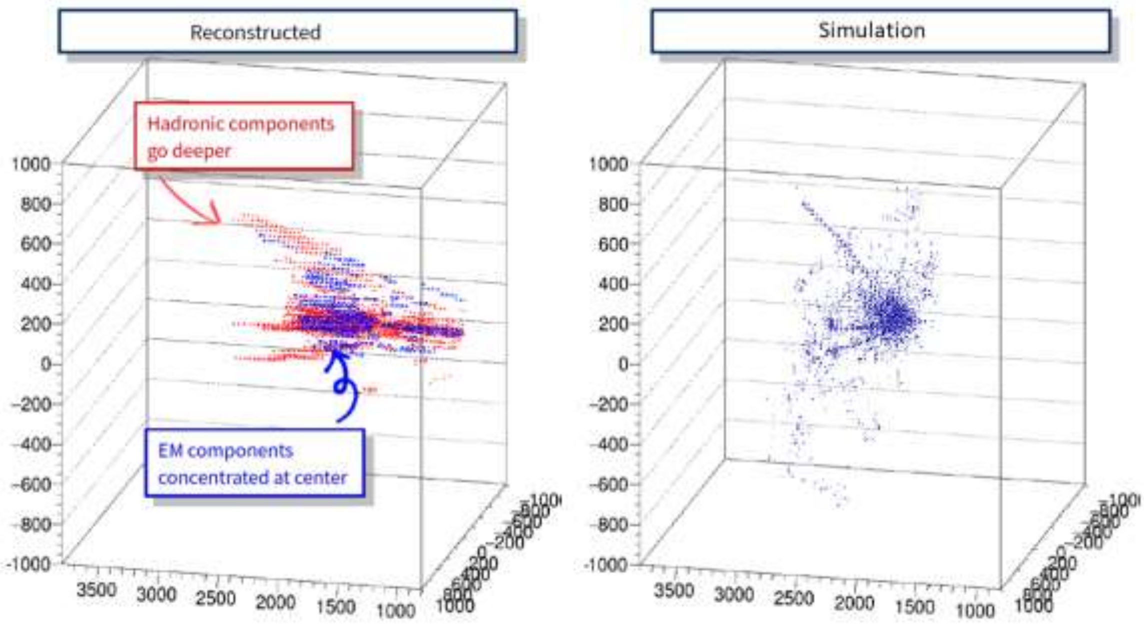


*Fig. 4 Example simulated (right) and reconstructed (left) shower profile for a 20 GeV charged pion when combining the dual-readout lateral granularity with the longitudinal timing information.*

# 3. APRIL FOR HADRONIC JETS

This section summarises the progress towards PFAs for the International Large Detector (ILD) options using silicon-tungsten electromagnetic (SiW-ECAL) and semi-digital hadronic calorimeters (SDHCAL). APRIL, the algorithm for particle reconstruction (of hadronic jets) for the future ILC, is being implemented for the Pandora framework and is based on the ARBOR concept [5], which is an algorithm for clustering energy deposits inside a calorimeter shower assuming a tree-like topology.

Development work is ongoing for AMSTER, an algorithm using a minimum spanning tree for energy reconstruction, which will be used to perform cluster-splitting for APRIL. It uses the Boost Graph library and initial tests have been performed using a standalone Geant4 SDHCAL prototype simulation. Figure 5 shows an example AMSTER reconstruction of an event containing one 30 GeV charged pion with a 10 GeV neutral kaon simulated inside the prototype SDHCAL volume. Most of the energy deposits are correctly assigned to the corresponding particles, apart from those that are around the outer edge of the charged pion shower. Improvements to the reconstruction could be made by including timing information, which would give the capability to perform 4D calorimetry (3D positions with time), and a study has begun to investigate this possibility.

To progress further on the integration with the ILC and Pandora software frameworks, a range of particle simulation samples have been generated with the ILC DIRAC grid. Energy calibration studies have also been done by finding suitable photon and neutral hadron energy ranges for accurate dijet calibration and comparing hit counts with energy sums for optimising the SiW-ECAL energy resolution.

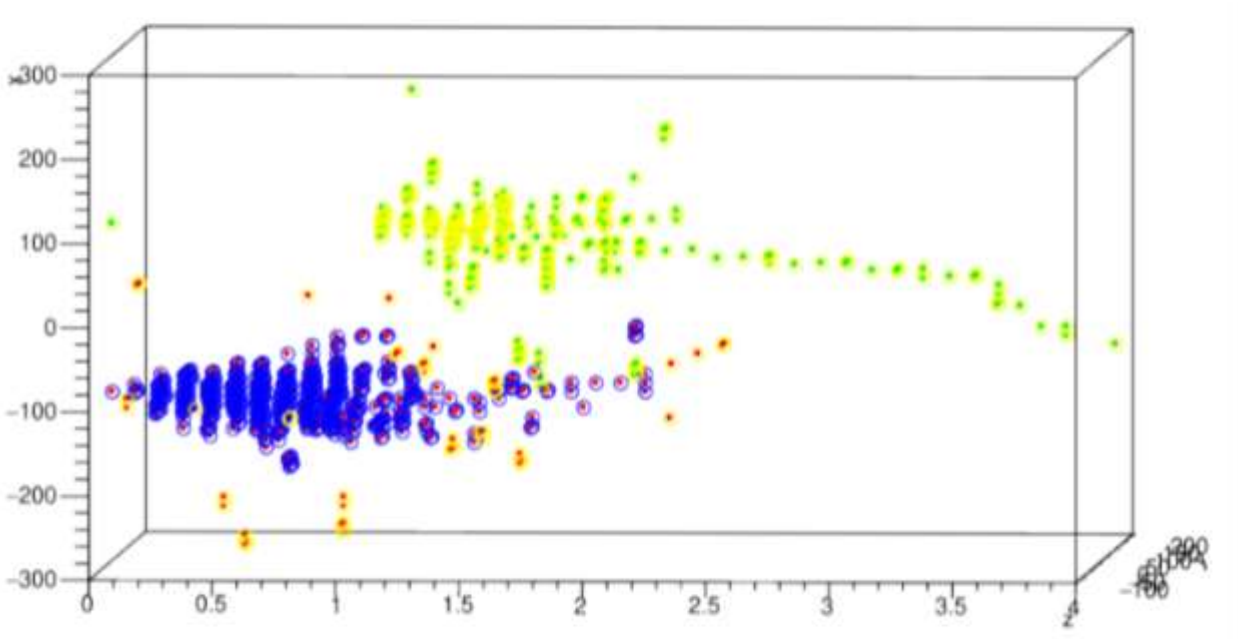

*Fig. 5 AMSTER reconstruction of a simulation of a 30 GeV charged pion (red simulated and blue reconstructed) with a 10 GeV neutral kaon (green simulated and yellow reconstructed) separated by 20 cm inside a prototype SDHCAL volume.*

Figure 6 shows the calibration curves relating the reconstructed to the simulated particle energy for single photons in the ECAL and neutral kaons in the SDHCAL, where the latter needs an extra correction scaling factor due to the particle incidence angle. Figure 7 shows the reconstructed energy of 20 GeV neutral kaons in both the endcap and barrel regions of the SDHCAL, where for the latter the mean energy value is reduced by around 10% due to the angle of incidence.

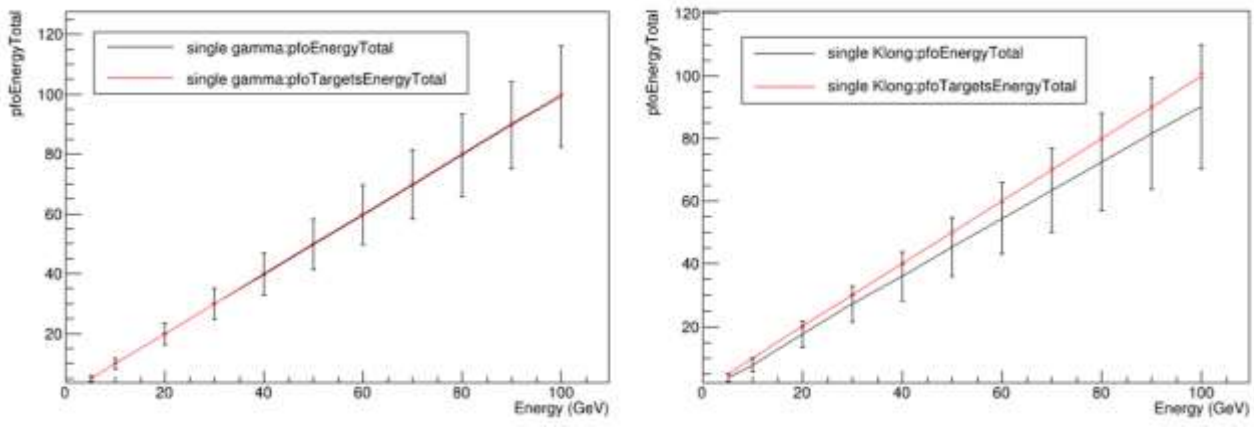


*Fig. 6 Reconstructed versus simulated particle energy for single photons in the ECAL and neutral kaons in the SDHCAL. The vertical error bars represent the width of the reconstructed cluster energy distributions.*

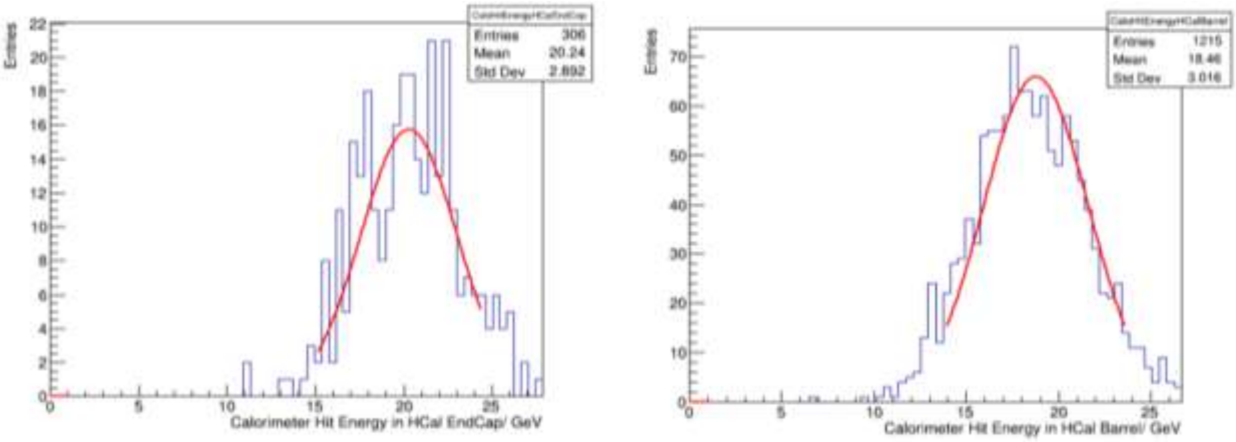


*Fig. 7 Reconstructed energies of 20 GeV neutral kaons in the endcap (left) and barrel (right) regions of the SDHCAL.*

## 4. DUNE NEAR DETECTOR

The Pandora neutrino reconstruction work is aiming to optimise the performance of the Near Detector (ND) of the Deep Underground Neutrino Experiment (DUNE) based at Fermilab [6]. The role of the ND is to characterise the initial state of the neutrino beam for comparisons with observations at the Far Detector (located in South Dakota) to extract neutrino oscillation parameters. The core component of the ND will be an ArgonCube design [7] that will contain a seven-by-five array of 1m x 1m x 3m LAr modules, each instrumented with two time-projection chambers (TPCs) which use pixels to readout the ionisation charge and scintillating light deposits from the interacting particles. Information from the TPCs allows us to create 3D neutrino interaction images by combining the 2D projection views of the particle trajectories along with the drift (time) coordinate.

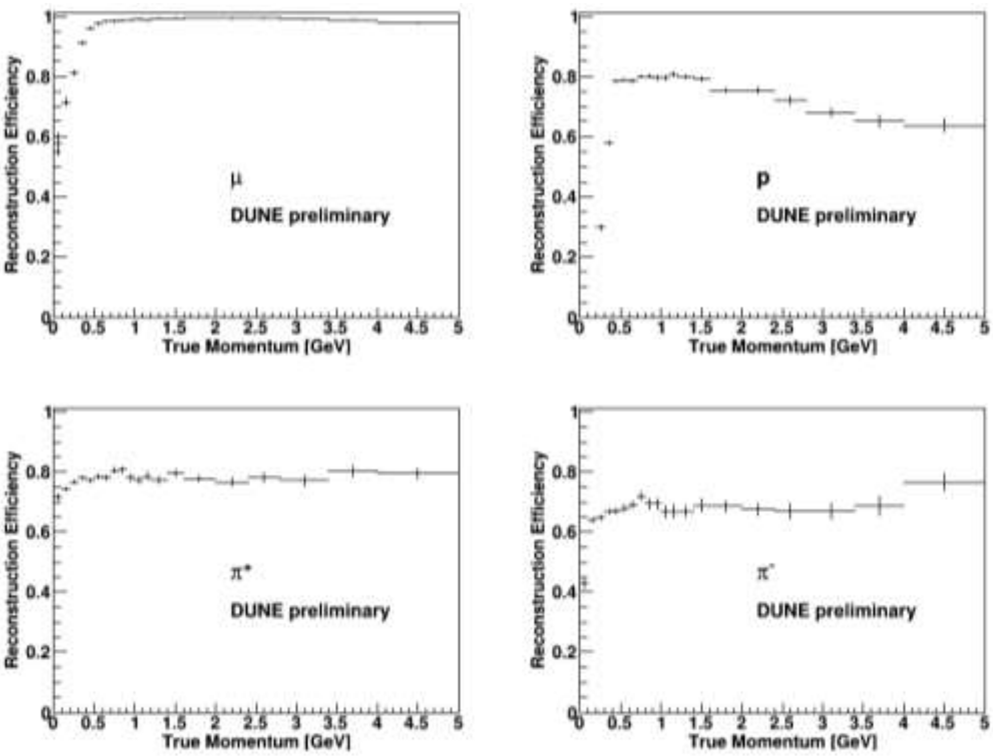


*Fig. 8 Particle reconstruction efficiency versus generated momentum for simulated muon-neutrino ArgonCube events.*

A preliminary study has been made to see if the algorithms currently being used for MicroBooNE could also be applied to the DUNE ND. Neutrino events (from GENIE [8]) and single particle tracks such as muons and electrons were generated and passed through a GEANT4 simulation of the ArgonCube detector, with energy deposits (hits) collected into 4 mm-sized voxels to mimic the detector response. For each event, three 2D views of the voxels are passed to the Pandora reconstruction algorithms, creating particle flow objects that are then compared to the generated information. Figure 8 shows the preliminary efficiency of reconstructing muons ($\mu$), protons (p) and charged pions ($\pi^{\pm}$) from a wide range of possible muon-neutrino interactions, typically containing one muon and proton along with potentially several charged (or neutral) pions, in the ArgonCube detector as a function of the generated momenta.

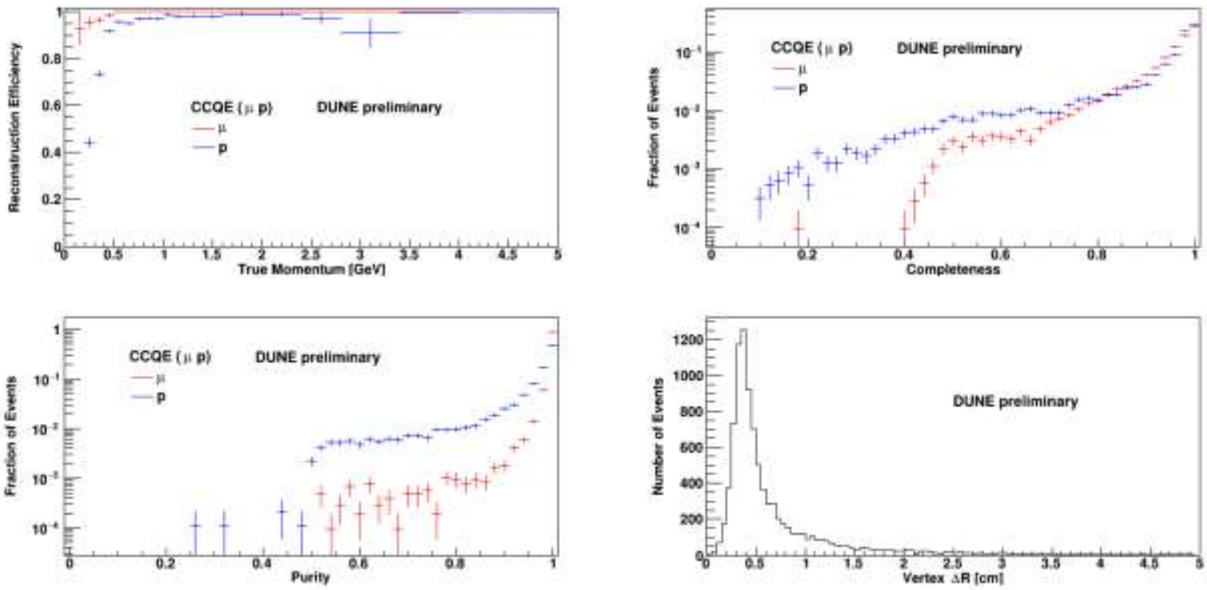


*Fig. 9 Reconstruction performance of charged-current quasi-elastic (CCQE) muon-neutrino ArgonCube events.*

Figure 9 shows the preliminary efficiency for finding the muons and protons that are simulated in charged-current quasi-elastic events, in which muon-neutrinos interact with argon nuclei in the detector to produce muons and protons (and no pions) via the process $\nu_{\mu} + n \rightarrow \mu + p$. Also shown are the completeness and purity metrics, which quantify how many generated hits (voxels) are found for the reconstructed muon and proton objects and how many are of the correct particle type, as well as the radial difference between the reconstructed and generated neutrino vertex 3D positions, which peaks at 4 mm due to the finite voxel width. Overall, the initial performance for the DUNE ND reconstruction shows that the pattern recognition is of a broadly similar quality to that documented for MicroBooNE [2], but that there are some specific differences that will need to be addressed, alongside an optimisation of algorithm parameters.

A key issue is that we expect a pile-up of around 50 neutrino interactions in the DUNE ND per second during normal operations, since the ND will be close to the neutrino production target facility. Work has begun to study how we can split up the particle interaction energy deposits into slices to reconstruct the individual neutrinos, where the aim is to associate one slice as one neutrino interaction. A slice here means a collection of hits that are grouped together based on pattern recognition criteria for reconstructing track and shower objects without first assuming any vertices. Once the hits have been organised into slices, algorithms are then used to find the neutrino interaction vertices which also refine the particle flow objects that have been previously reconstructed. Figure 10 shows an illustration of the 2D projection views of the reconstruction of simulated pile-up neutrino interactions, where each slice is represented by a different colour. Broadly speaking, the slicing technique looks promising, however much more work is needed to improve its performance, such as reducing the number of cases where particles from different neutrino interactions can appear in the same slice.

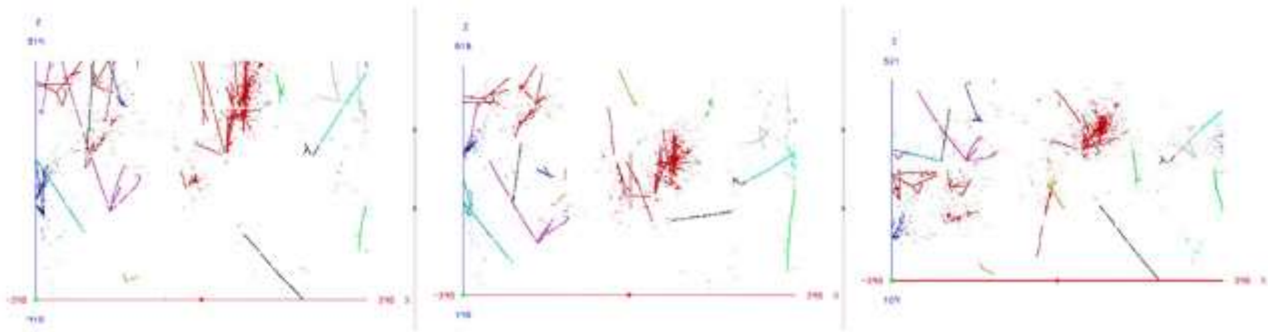

*Fig. 10 Two dimensional views of the sliced reconstruction of simulated multiple neutrino interactions.*

During 2023, DUNE will install and commission a prototype 2x2 array of LArTPCs at Fermilab's NuMI facility, and data from this will need to be reconstructed using software tools such as Pandora. Currently, a simulation challenge is underway to study the expected Pandora neutrino reconstruction performance for the 2x2 detector geometry, and work has also started to incorporate the coordinate and timing information from the 3D pixel readout technology to improve the reconstruction of multi-neutrino interaction events for the DUNE ND.

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# ANNEX: GLOSSARY

| Acronym | Definition |
|---|---|
| PFA | Particle Flow Algorithm |