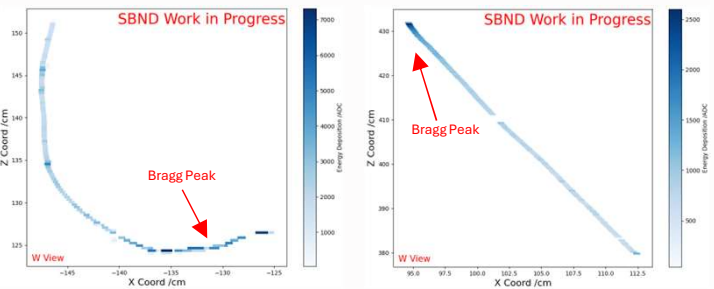


Abstract

The Pandora Event Reconstruction package [1] is an advanced program that aims to identify and reconstruct particle interactions within detectors. Over the course of my project, I evaluated the common failure cases for the reconstruction using simulated data from the SBND collaboration. From this, I elected to create a **proof-of-principle** for a directional analysis algorithm making use of energy deposition information for stopping cosmic-rays.

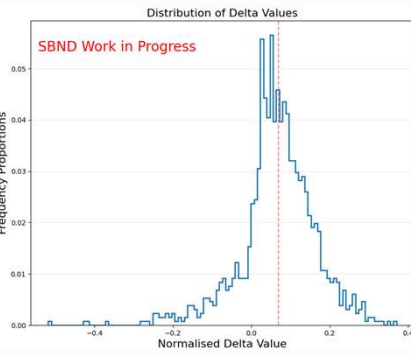
What is the SBND?

The Short Baseline Near Detector (SBND) is a Liquid Argon Time Projection Chamber (LArTPC) located at Fermilab, USA. It is the third of three detectors in the Short Baseline Neutrino (SBN) program and is exploring the low-energy limits of previous experiments, measuring neutrino cross-sections, and testing the existence of sterile neutrino oscillations. It is presently detecting **millions** of neutrino interactions in the **low GeV range** (a step-change from previous experiments).



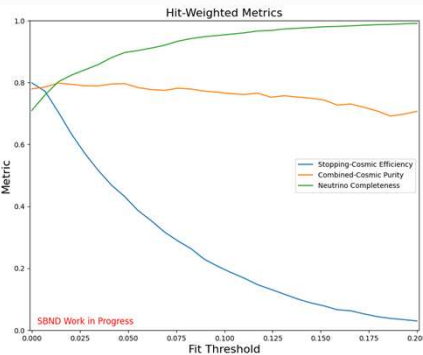
Example Event Displays

The above displays shows the ends of two true cosmic-rays that stop within the boundaries of the detector. When they halt, cosmic-rays leave a clear spike in their energy deposition spectra known as a **Bragg peak**. This information can therefore be used to determine the direction of travel of these cosmic-rays.



Results

The overall distribution of $\Delta\chi^2$ values shows a clear peak at ≈ 0.07 . This is expected behaviour as the forward-peak hypothesis is favoured given that almost all cosmic-rays enter through the top of the detector.



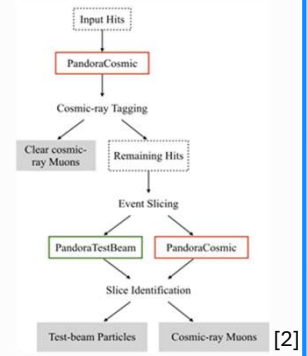
The hit-weighted metrics show, as expected, that a higher fit threshold lowers the algorithm's efficiency but also improves the impact to the neutrino hits. At a neutrino completeness of **98.5%**, **5.3%** of initially missed stopping-cosmics are correctly tagged.

The algorithm is not intended to be used without the inclusion of **additional topological information** however, this **proof-of-principle** shows that an energy deposition approach has the potential to allow potentially significant improvements in the **tagging efficiency** of stopping cosmic-rays.

- Stopping-Cosmic Efficiency:** Proportion of true stopping cosmic hits that are tagged as cosmics.
- Combined-Cosmic Purity:** Proportion of particle hits tagged as cosmics that are true cosmics.
- Neutrino Completeness:** Proportion of true neutrino interaction hits that are not tagged as cosmics. (All metrics are hit-weighted.)

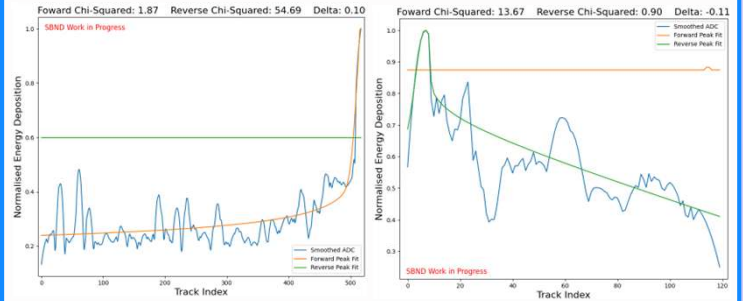
Cosmic-Ray Tagging in Pandora

Pandora breaks its reconstruction into distinct stages each implementing a distinct algorithm. Without any addition, **89.8±0.1%** of through-going cosmic-ray hits are correctly tagged. This drops to **55±1%** for stopping cosmic-rays (cosmics that stop within the detector). Stopping cosmics represent **8.7±0.4%** of all cosmics (by hit) showing a clear motivation for improvements in this area.



The Fitting Algorithm

The algorithm I created attempts to find a **Bragg peak** in the energy spectrum using a **weighted dual-fit** approach. The energy data is smoothed and normalised and then is twice fitted to a test peak model, once considering a forward-peak hypothesis and once considering a reverse-peak hypothesis. The fits are weighted to prioritise higher energy values and the χ^2 value is calculated for each fit. The difference between these values ($\Delta\chi^2$) determines the fitted direction. The algorithm checks that the absolute value of $\Delta\chi^2$ is above a specified **fit threshold** and that the best fit is of a good-quality before marking the direction as determined or ambiguous.



Conclusions & Further Work

As a **proof-of-principle**, this algorithm has shown that there are likely efficiency gains to be made in this area. I have consolidated my proposal and submitted it to the Pandora team to be taken forward.

Whilst a dual-fit algorithm was used for my proposal, exploring a machine-learning approach is worth consideration as it could allow for a more flexible and accurate tagging result. Additionally, my algorithm only considered the W-view. Moving the algorithm to 3D would almost certainly be worth the effort of implementation particularly in the case of evaluating particle containment.

It is also possible to expand this algorithm to decrease the loss of neutrino hits in the current clear-cosmic tagging stage of Pandora's reconstruction. In my evaluation, I found that, presently, Pandora misstags **1.5±0.6%** of neutrino hits. Whilst this is not fatal for the reconstruction, reducing this figure is still a priority and using directional analysis could help in this area.

I would like to thank my supervisors [Supervisor 1], [Supervisor 2], and [Supervisor 3] for their excellent support and guidance over the summer. They made my project possible.

References

- [1] R. Acciarri *et al.*, European Physical Journal C **78**, (2018).
- [2] DUNE Collaboration, Eur. Phys. J. C **83**, (2023).