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First Look at Particle Flow in a LAr Calorimeter Using Pandora in the Key4hep Framework

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Future detector studies rely on advanced software tools for performance estimation and design optimization. Particle flow reconstruction is a key ingredient in optimal jet energy resolutions. While Pandora stands out as a well-established algorithm for particle flow analysis, its application has primarily been confined to high-granularity CALICE calorimeters. This limitation prompted exploration into its compatibility with other detector types. Key4hep, a turnkey solution for experiment lifecycles, offers a flexible framework that allows different experiments to benefit from its synergies. Leveraging Key4hep, PandoraPFA was successfully adapted to study particle flow in a Liquid-Argon calorimeter for the first time. This presentation examines the integration of Pandora PFA into the Key4hep framework and its application in a LAr calorimeter. Furthermore, it assesses Pandora PFA's ability to distinguish between particle showers and discusses its implications on the jet energy resolution.

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1. Pandora Particle Flow Algorithm and Key4hep

The Key4hep is a common turnkey software for future colliders [1]. It is built to share components to reduce maintenance and development costs and allow everyone to benefit from its improvements. Key4hep has a complete data processing framework that ranges from generation, simulation, and reconstruction to data analysis. In Key4hep, tools are developed natively or ported from other frameworks with the goal of making generic tools that can address the needs of all the experiments. One such tool is the Pandora particle flow algorithm (PandoraPFA). The particle flow reconstruction method is considered one of the most effective solutions for optimal jet energy resolutions at future Higgs factory experiments.

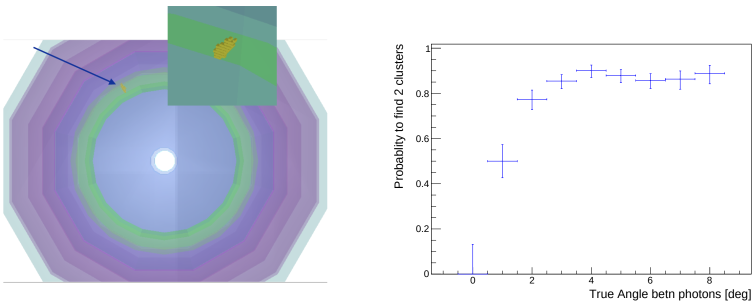
2. Using `Layered Calorimeter data` and `Material Manager`

Over the past two decades, PandoraPFA has been optimized for high-granularity sandwich Calorimeters (HG-SiW) developed by CALICE at linear colliders [2]. Recent efforts have focused on adapting PandoraPFA for various detector models, including its integration into the Key4hep framework and testing on a Noble Liquid Argon (LAr) ECAL — a geometry fundamentally different from HG-SiW Calorimeters [3]. PandoraPFA determines particle shower depth using material properties like radiation and interaction lengths, retrieved via the `DD4hep Layered Calorimeter Data` class. Unlike the HG-SiW detector, the LAr detector consists of steel/Pb absorbers and readouts immersed in liquid Argon, inclined at an angle of 50° relative to the radius [3]. Consequently, in a given cell of a LAr detector, the number of absorbers and readouts may vary from those in other cells. Furthermore, the probability of a particle encountering an absorber or a readout first can differ in each cell. These complexities make the determination of material properties for the LAr calorimeter more challenging compared to the high-granularity sandwich calorimeter. To address this, another `DD4hep` class `MaterialManager` is employed. `MaterialManager` retrieves all materials within a specified detector dimension, averages them, and estimates key properties such as radiation length and interaction length of the composite material. This approach allows for dynamic, model-independent determination of material properties [4].

3. Can Pandora PFOs be observed at a LAr Calorimeter ?

To enable PandoraPFA to extract material properties from the LAr detector, helper functions were configured, and a study was conducted to test its ability to reconstruct particle flow objects. In this initial test, 500 photon events at 10 GeV were simulated using a particle gun passing through the LAr ECAL. As Pandora relies on both `CaloHits` and tracking data for particle flow reconstruction [5], a full detector simulation was required. Due to the incomplete simulation software for the ALLEGRO detector, an alternative CLD geometry was used, substituting the LAr ECAL for the HG ECal. The results, shown in Figure 1, confirm that photon particle flow objects (PFOs) can be successfully reconstructed in the LAr ECAL.

Efficient photon cluster separation is critical for optimizing the energy reconstruction of the PFOs. As shown in Figure 1b, a separation probability above 80% is achieved only when photons are spaced by more than 2 degrees. This process depends on the LAr calorimeter's Molière radius (4



(a) **(b)**

Figure 1: (a) The event display for CLD-LAr with a photon reconstructed (yellow) in LAr (in green). A close-up version of the left event display is attached. (b) The probability of correctly separating two-photon clusters based on their true angular distance.

cm) and cell size (~2 cm), which result in lower granularity compared to HG-SiW calorimeters. The larger Molière radius in Liquid Argon, determined by its radiation length, spreads particle showers more broadly, requiring photon clusters to be separated by 5–6 cm for independent reconstruction. Current efforts focus on calibrating Pandora for the LAr calorimeter and refining these methods to improve reconstruction accuracy and performance.

4. Conclusion

This study demonstrated the successful integration of PandoraPFA into the Key4hep framework, specifically testing it on the LAr ECal. With the use of class `Material Manager` it was established that details of material properties can be provided to PandoraPFA irrespective of the geometry of the given detector making it a generic tool. However, the low-energy tail in the reconstructed energy distributions indicates the need for further calibration of Pandora's photon correction factors for the LAr detector. Efforts are ongoing to enhance accuracy and address these biases.

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