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# Development of High-Granularity Dual-Readout Calorimetry with psec Timing

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**Abstract.** Dual-readout and particle flow algorithm (PFA) are technologies proposed for precise jet energy measurement in future colliders. While PFA requires highly granular calorimeters, dual-readout has mainly been used with fiber-based calorimeters that do not have highly segmented capabilities. It is still non-trivial to combine these two technologies in one calorimeter system because of the use of fibers in most of the dual-readout calorimeters, which is not compatible with the high granularity requirement of PFA technologies. The aim of this study is to develop a novel calorimetry that combines dual-readout and PFA by adopting a highly segmented tile-based configuration. This paper compares the improvement of energy resolution using dual-readout approach across several configurations of highly granular hadron calorimeters through simulation. Results indicate that setups with fine sampling and close placement of scintillators and Cherenkov detectors improve dual-readout performance.

## 1 Introduction

In future collider experiments, precise jet energy measurement will play an important role to maximize the scientific capabilities of the experiments. To achieve precision jet measurement, sophisticated calorimeter technologies are needed. In this context, dual-readout [1] and particle flow algorithm (PFA) [2] are the efforts aiming at achieving high-energy-resolution measurements.

Dual-readout is an advanced technology that improves the energy resolution of hadronic showers, which produce both electromagnetic (EM) and non-EM showers in the hadron calorimeter. The conversion efficiency from deposited energy to signals differs between the two types of showers, and the fraction of these showers varies from event to event, which causes energy resolution to deteriorate. Dual-readout technique, which measures these showers with two types of detectors, scintillators and Cherenkov detectors, can determine this fluctuation for each event. This energy resolution, thus, can be improved by a correction of the event-by-event basis.

PFA can improve energy-momentum measurement of individual particles with the most suitable sub-detector: charged particles are measured using the tracker, while neutral particles are measured using the calorimeter. To perform PFA effectively, it is essential to accurately identify and track particles generated within the detector. This requires highly granular calorimeters, which enhance particle identification and tracking by allowing for precise clustering of showers.

The goal of this study is to establish a new calorimetry method that combines dual-readout and PFA for high precision energy-momentum measurements in future collider experiments. Ongoing efforts focus on developing highly granular scintillators [3] and Cherenkov detectors [4] for the hadron calorimeter, and evaluating the performance of the hadron calorimeter designs though simulation.

In addition to the high granularity, the Cherenkov detector under development aims at psec timing resolution, which is generally faster compared to scintillators. This excellent timing information improves the ability of PFA. Amplifying the signals with a resistive plate chamber maximizes the benefit of prompt generation of Cherenkov photons, aiming at the achievement of this high level timing resolution.

This paper focuses on performance evaluation of the highly granular dual-readout hadron calorimeters through simulation. While dual-readout has primarily been studied using fiber-based hadron calorimeters [1], its application to highly granular tile-based calorimeters has not been extensively investigated. To address this gap, this simulation study started to identify the conditions necessary for enhancing dual-readout performance in a highly granular environment.

In this paper, Section 2 describes the methodologies of simulation and reconstruction. Section 3 presents the re-

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sults and discussions of the simulations. Finally, Section 4 summarizes the findings.

## 2 Method of simulation and reconstruction

### 2.1 Simulation setup

The study employed a hadron calorimeter beam test simulation framework. DD4hep [5], along with its interface to Geant4, was utilized to describe the geometry, materials, and to perform the simulation.

We prepared several tile-based detector setups for this study, such as the Analogue Hadron Calorimeter (AHCAL) of the CALICE collaboration [6], which is a candidate for future linear collider detectors.

One layer of one setup is shown in Figure 1, consisting of highly granular segmented tiles. The total number of layers is 60, with a combined thickness equivalent to approximately eight times the nuclear interaction length.

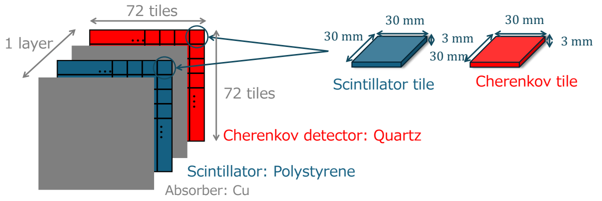


Figure 1: One layer structure of one hadron calorimeter setup. The gray layers represent the absorbers, which are made of Copper, and each is 10.5 mm thick. The blue and red layers represent the polystyrene scintillation layer and the quartz Cherenkov layer respectively. They are composed of $30 \times 30$ mm$^2$ and 3 mm-thick tiles, and each has 72 rows and columns.

The details of all six setups, which primarily vary in material's thickness and layer structure, are shown in Figure 2. To ensure a fair comparison of energy resolution improvement, the total volume of each material was kept constant across all setups, as maintaining the consistent sampling fraction. The two main variables were the sampling fineness and the closeness of the scintillators and the Cherenkov detectors in one layer. For clarity, the setups with fine sampling will be referred to as "fine sampling" setups, while those with the closely placed two detectors will be called "S & C in pairs" setups. S represents a scintillator and C represents a Cherenkov detector. The motivation for investigating these variations stems from previous results with fiber-based calorimeters [1], which inherently featured fine sampling and S & C in pairs, and whose dual-readout energy resolutions were actually improved.

This study simulated single $\pi^-$ events with energies of 30, 40, 50, 60, 100, and 150 GeV, which were shot perpendicularly into the center of the detectors.

### 2.2 Signal digitization

The scintillation signals were read out using SiPMs, with the assumption that a minimum ionizing particle produces 10 photoelectrons per 3 mm-thick scintillator tile in the SiPM.

The Cherenkov signals were digitized based on the equation governing the number of generated Cherenkov photons $N$:

$$\frac{d^2N}{dx d\lambda} = \frac{2\pi Z^2 \alpha}{\lambda^2}\left(1 - \frac{1}{n^2(\lambda)}\right), \tag{1}$$

where $x$ is the path length of charged relativistic particles, $\lambda$ is the wavelength of Cherenkov photons, $Z$ is the charge of the particle, and $\alpha$ is the fine structure constant. $n(\lambda)$ is the refractive index of the quartz, based on the data from the NIFS-V quartz, made by NIKON [7]. The Cherenkov photons were transmitted according to the internal transmittance data [7], with all other factors of light collection efficiency assumed to be unity. The photons, after passing through the quartz, were converted into photoelectrons with a 10 % quantum efficiency by the typical transmission-mode CsI photocathode, made by Hamamatsu [8] The detected Cherenkov photons were simulated by integrating Equation (1) along the total path length and the wavelength range. Here, the minimum of the integration range over the wavelength was set to 150 nm, based on the lower transmittance limit of the quartz [7], and the maximum was set to 200 nm, which corresponds to the upper sensitive limit on the CsI photocathode [8].

### 2.3 Energy reconstruction by dual-readout

In dual-readout analysis [1], a reconstructed scintillation energy ($S$) and a reconstructed Cherenkov energy ($C$), calibrated with electrons, behave as

$$S = E\left[f_{\mathrm{em}} + (1 - f_{\mathrm{em}})(h/e)_S\right], \tag{2}$$

$$C = E\left[f_{\mathrm{em}} + (1 - f_{\mathrm{em}})(h/e)_C\right], \tag{3}$$

where $E$ is the energy of incoming particles. The fraction of the EM energy relative to the total energy of the incident particles, $f_{\mathrm{em}}$, fluctuates event-by-event. The ratios of the response to the non-EM components compared to the response to the EM components in hadron showers for scintillators and Cherenkov detectors, $(h/e)_S$ and $(h/e)_C$ respectively ($(h/e)_S \neq (h/e)_C$), do not depend on energy and particle types.

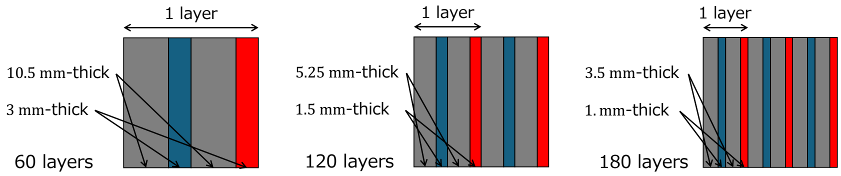
While in conventional hadron calorimters, energy resolution is degraded due to the $f_{\mathrm{em}}$ fluctuation corresponding to the use of only Equation (2), in dual-readout calorimeters this issue is mitigated by solving Equations (2) and (3):

$$E = \frac{S - \chi C}{1 - \chi}, \tag{4}$$

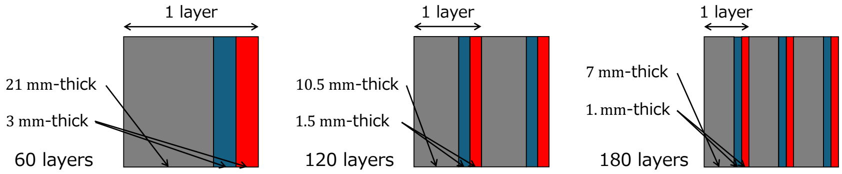
where

$$\chi = \frac{1 - (h/e)_S}{1 - (h/e)_C}, \tag{5}$$

which is also independent with energy and particle types. The energy $E$ in Equation (4) will be referred to as $E_{\mathrm{DR}}$ hereafter. The parameter $\chi$ was estimated for each setup by solving Equation (4) for $\chi$ using the known energies of the incoming particles.

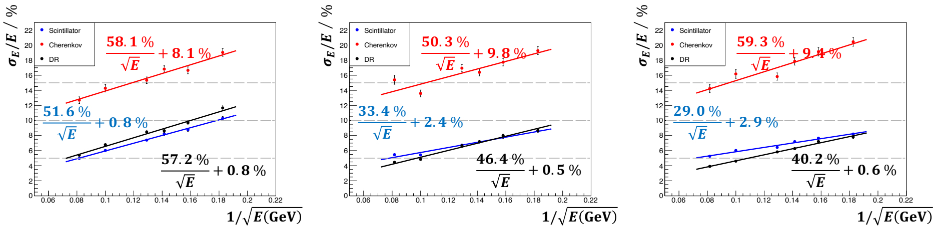


(a) Setup 1 (b) Setup 2 (c) Setup 3

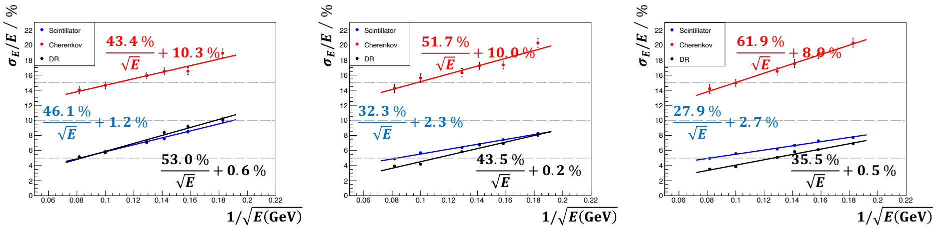


(d) Setup 4 (e) Setup 5 (f) Setup 6

Figure 2: Side view of the unit for the six hadron calorimeter configurations: the gray layers represent the absorbers, the blue and red layers represent the scintillation layers and the Cherenkov layers. (a) this setup is the same as the one in Figure 1. (b) and (c) feature finer sampling than (a), with each material's thickness reduced by a factor of 2 and 3, respectively, and the total number of layers increased by a factor of 2 and 3, respectively. (d), (e), and (f) are setups with adjacent scintillation and Cherenkov detectors in each layer, corresponding to (a), (b) and (c), respectively. All these units have same total thickness.



(a) Setup 1 (b) Setup 2 (c) Setup 3



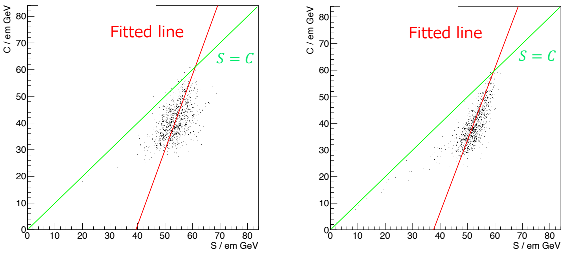
(d) Setup 4 (e) Setup 5 (f) Setup 6

Figure 3: Energy resolutions of the scintillation detectors, the Cherenkov detectors and the dual-readout for 30 – 150 GeV $\pi^-$: the blue line represents the resolution of the scintillation detector, the red line represents that of the Cherenkov detector, and the black line represents that of the dual-readout. The resolution values are indicated by the corresponding colors. The resolutions of (a) - (f) correspond to the setup 1 - 6 shown in Figure 2 respectively.

Figure 3 shows the energy resolutions of the scintillators and the Cherenkov detectors for each setup, as well as the dual-readout energy resolutions derived from Equation (4).

## 3 Comparison of energy resolution for different detector setups

The finer the sampling is, the better the performance of the dual-readout is. In Figure 3, as the sampling becomes finer from setup 1 to 3 and from 4 to 6, the stochastic term of the dual-readout resolution improves, and the energy range where the dual-readout is better than the scintillator becomes wider. For the fine sampling setups, increasing the number of measurement points to pick up shower development reduces fluctuations of the energy deposition measurement in the unit with same material thickness shown in Figure 2, thereby decreasing the spread from the red fitted line in the $(S, C)$ scatter plot, as shown in Figure 4, which represents the dual-reaout resolution.



(a) Setup 1 (b) Setup 6

Figure 4: $S$ - $C$ diagrams of 60 GeV $\pi^-$ events: the red line represents the linear fit of the scatter plot. The green line represents $S = C$.

The dual-readout resolutions are better in the S & C in pairs setups than in the non-pairs setups. Focused on the pairs setups, the stochastic term of the dual-readout resolution improves, and the energy range where the dual-readout is better than the scintillator becomes wider. For S & C in pairs setups, the absence of thick absorbers in each layer compared to the nuclear interaction length allows more homogeneously reading almost the same part of the showers by the scintillators and the Cherenkov detectors simultaneously. The performance improvement by dual-readout can be achieved through this homogeneous reading.

## 4 Summary

A novel calorimetry by combining dual-readout and PFA together with psec timing is being developed.

Simulation studies on the optimal design of a high-granularity tile-based dual-readout hadron calorimeter have been performed. We found that a finer sampling and a closer placement of the scintillators and Cherenkov detectors are crucial for better dual-readout performance.

Future simulation studies will focus on studying performance improvement when combining PFA and dual-readout with psec-timing in a full detector simulation on top of the optimal dual-readout configurations studied in this research, enhancing the overall performance of the jet measurement.

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