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CALICE scintillator-based calorimeter prototypes: highlights of developments and beamtests

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Two CALICE high-granularity calorimetry prototypes based on the plastic scintillator option have been successfully developed to address system integration challenges and precision measurements of particle showers. The ScW-ECAL prototype features around 6,720 readout channels and 32 longitudinal layers of scintillator strips and copper-tungsten plates. The CEPC-AHCAL prototype has a total of 12,960 readout channels and 40 longitudinal layers with scintillator tiles and iron plates. Both prototypes are based on the silicon photomultiplier (SiPM) readout and have compact front-end electronics fully embedded in sensitive layers. Successful beam tests were performed at CERN PS and SPS beamlines during 2022-2023 with beam particles ranging from 1 to 350 GeV. This contribution on behalf of the CALICE collaboration and CEPC-calorimetry working group will present prototype developments, highlights of beam tests, and ongoing performance studies of particle showers.

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1. Introduction

The precision measurements of the Higgs boson and searches for physics beyond the Standard Model remain most critical questions in particle physics to be addressed in the coming decades. Several options have been proposed for future lepton collider experiments or Higgs factories, including the International Linear Collider (ILC), the Compact Linear Collider (CLIC), the Circular Electron Positron Collider (CEPC) and the Future Circular Collider (FCC) [1] [2]. The CEPC, as one of the earliest possible options, plans to cover the centre-of-mass energy in the range of 91-240 GeV and to be upgradable to 360 GeV for top quark studies [3] [4] [5]. The physics programs require the detector system to achieve an unprecedented jet energy resolution, where the calorimetry system plays a crucial role. Calorimetry based on the particle flow algorithms (PFA) [6] is a promising option to achieve the Boson Mass Resolution (BMR) within 4%.

PFA-oriented calorimetry requires fine transverse and longitudinal segmentations for an excellent separation capability of close-by particle showers and needs to be instrumented with millions of readout channels. Various technical options of PFA calorimetry have been explored within the CALICE collaboration over the past two decades [7] [8] [9] [10]. This contribution will mainly focus on the scintillator option for electromagnetic and hadronic calorimeters. Section 2 will briefly describe the calorimeter designs and prototype developments, followed by highlights of CERN beam test campaigns in Section 3 and ongoing studies on the validation of simulation and detector performance based on the test beam data in Section 4. Summary and prospects for future activities will be presented in Section 5.

2. Prototype developments

Two technological prototypes based on the plastic scintillator and the SiPM readout technology have been developed within the CALICE collaboration. The Scintillator-Tungsten electromagnetic calorimeter (ScW-ECAL) prototype with a total of 6,720 readout channels was developed during 2016-2021 (show in Fig. 1). It consists of 32 longitudinal layers with a transverse size of 22×22 cm^2 with a total depth of 23.7 X_0 (hereby X_0 denotes the radiation length). Each sampling layer is equipped with plastic scintillator strips ($45 \times 5 \times 2$ mm^3) and a copper-tungsten absorber plate (W:Cu = 85%:15%, 3.2 mm thick) to ensure compact EM shower profiles. Every two layers are arranged perpendicularly to each other to achieve an effective transverse granularity of 5×5 mm^2.

The analogue hadron calorimeter prototype (CEPC-AHCAL) was developed during 2018-2022 for the CEPC, with a total of 12,960 readout channels in 40 longitudinal layers. The total depth is around 4.8 λ_{I} (hereby λ_{I} denotes the nuclear interaction length). Each layer is instrumented with an array of 18×18 plastic scintillator tiles ($40 \times 40 \times 3$ mm^3) and a 20 mm thick iron plate as an absorber, with a total transverse size of 72×72 cm^2 (as shown in Fig. 2).

Both prototypes utilize the silicon photomultiplier (SiPM) readout, with front-end electronics chips (SPIROC2E) embedded on readout boards. Each scintillator strip/tile is directly coupled to a SiPM individually based on the CALICE SiPM-on-Tile design. Dedicated LED-based calibration system were embedded in both prototypes, enabling in-situ SiPM gain calibration of each channel.

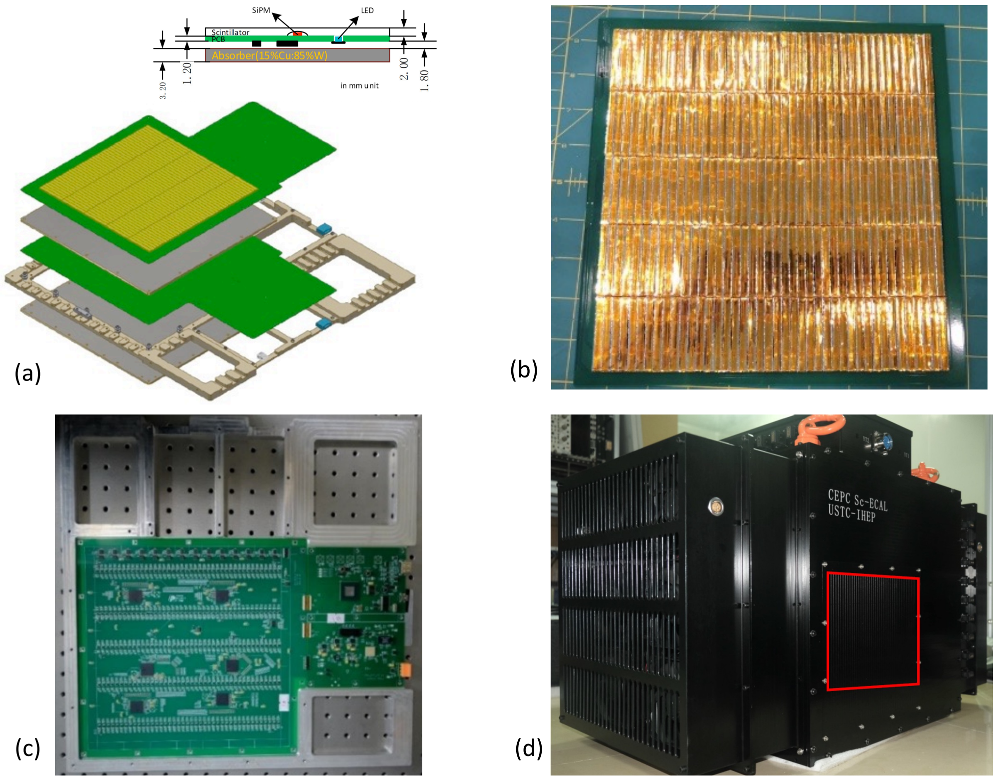

Figure 1: The ScW-ECAL prototype: (a) schematics of two sensitive layers mounted on a CuW absorber layer; (b) a sensitive layer equipped with 210 plastic scintillator strips (wrapped with ESR foil) and SiPMs (underneath scintillator strips, not shown); (c) the other side of a sensitive layer populated with electronics components, readout chips (OMEGA SPIROC2E) and an LED calibration system; (d) the ScW-ECAL prototype constructed in 2019 (with a red box indicating the transverse sensitive area).

3. Beamtest campaigns

The two prototypes were successfully tested at CERN SPS and PS beamlines (H8, H2, and T09, respectively) during 2022-2023 with beam particles in a wide momentum range of 1-350 GeV with sufficient statistics of data samples collected.

A crucial issue is the beam purity of data samples, which contain charged hadrons, electrons, and positrons. In particular, the beam purity was generally found to be significantly low in the 2022 SPS-H8 data. High-purity data samples are essential to detector performance studies. Cherenkov threshold detectors as part of the SPS beamline instrumentation could not provide sufficiently good particle identification (PID) performance, especially in the high-momentum region. Therefore, two dedicated PID techniques based on the high-granularity feature have been developed to address this issue. The first PID technique, named "fractal dimension" (FD) [11], utilizes the self-similarity information of shower transverse profiles while the second one is based on an Artificial Neural Network (ANN) [12]. Based on the cross check, the two PID techniques were found to be consistent within 1%. Fig. 3 shows preliminary results of the beam composition fractions at SPS-H2 based on the FD technique and the 2023 AHCAL data. The pion beam purity can achieve 90% or above when the momentum is equal to or above 30 GeV. Below 30 GeV, the pion purity significantly drops. For

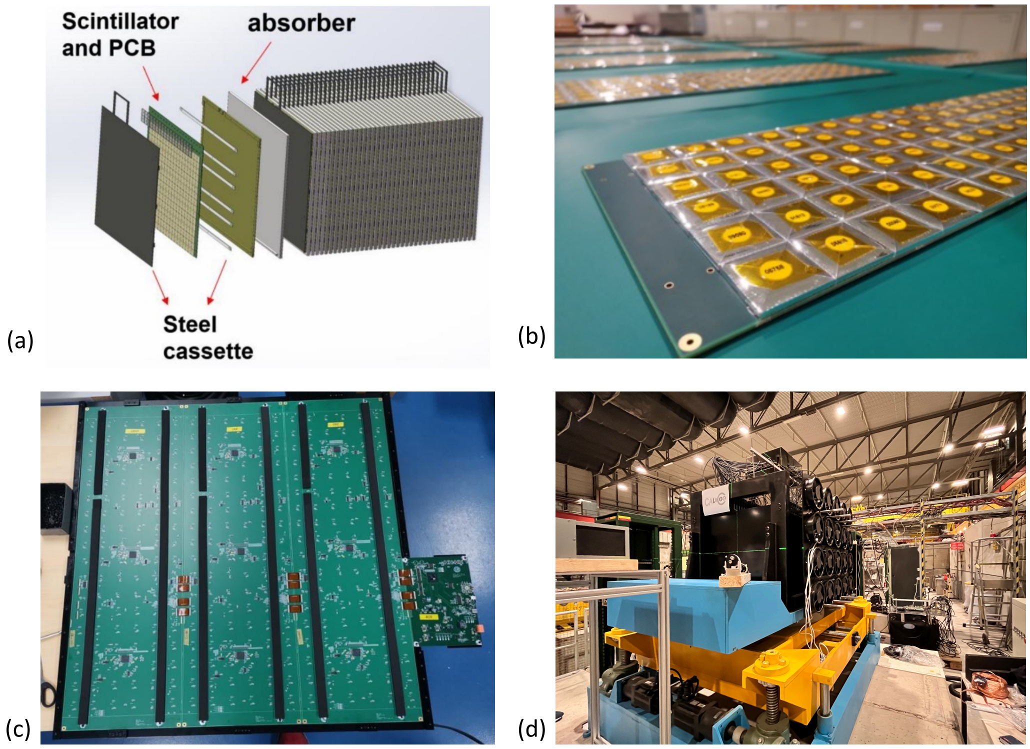

Figure 2: The CEPC-AHCAL prototype: (a) schematics of the sensitive and absorber layers; (b) plastic scintillator tiles wrapped with ESR foil and glued on a readout board; (c) a complete AHCAL sensitive layer, connected via flex-band connectors by three readout boards, each equipped with 3 SPIROC2E chips in the dimensions of 24×72 cm^2; (d) the prototype setup positioned in the SPS-H8 testbeam area.

the electron beam, the purity is above 94% in the entire available momentum range.

4. Studies on simulation validation and detector performance

Simulation based on the Geant4 toolkit has been established for the beam test setup, including the detailed geometry and material descriptions, digitisation, beam profiles, and upstream materials. Digitisation generally converts raw hit information from Geant4 into digits the same as in prototype data (e.g., ADC for energy, TDC for timing). The digitisation model consists of three major parts: (a) a model of photo-statistics in the scintillator and SiPM, (b) SiPM non-linearity effects for large signals, and (c) a model of the SPIROC2E chip (e.g., auto-trigger threshold, high-gain and low-gain modes). Part (a) is validated based on LED single-photon calibration data and muon data for Minimum Ionizing Particle (MIP) calibration. Part (c) utilizes parameters extracted from the 2023 muon data and ASIC configuration values. It should be noted that Part (b) is still based on the assumption that all scintillation photons are detected by the SiPM simultaneously, without considering any pixel recovery effect, which is also correlated with the scintillation time and optical photon propagation time within the detector unit.

EM and hadronic shower performance of the AHCAL prototype have been studied based on high-purity electron and pion data samples, respectively, which were selected with the aforementioned FD-based PID technique. Fig. 4 shows that the EM response linearity is within ±10% and the

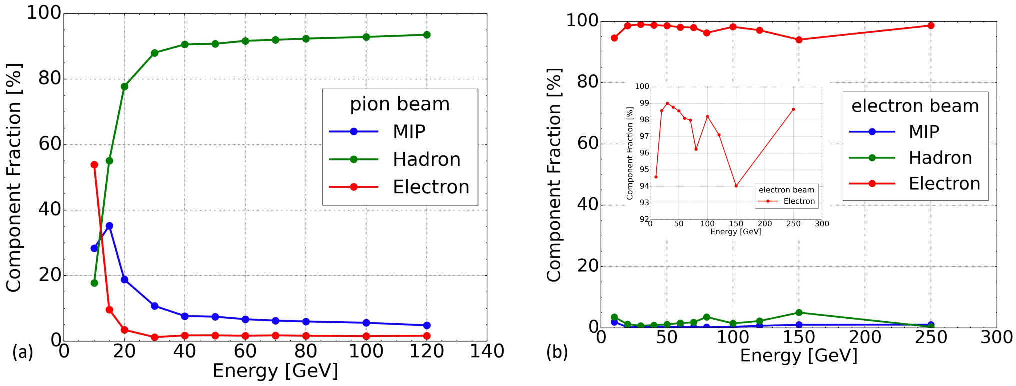

Figure 3: Preliminary results of the beam purity of the CERN SPS-H2 beamline based on the AHCAL-alone data in 2023: (a) component fractions of pion beams in the momentum range of 10 -120 GeV; (b) component fractions of electron beams in the range of 10 - 250 GeV.

EM energy resolution is approximately $22\%/\sqrt{\mathrm{E(GeV)}} \oplus 2\%$ in the range of 2 -50 GeV, including both 2023 PS-T09 and SPS-H2 electron data sets. Simulation with digitisation can generally reproduce key performance parameters in electron data. It should be noted that corrections for SiPM non-linearity effects have not yet been applied in these preliminary results, which is expected to be a major reason for the degraded performance of the EM response linearity.

Preliminary results on the AHCAL hadronic performance show that the response linearity is within $\pm 1.5\%$ and the hadronic energy resolution is $56\%/\sqrt{\mathrm{E(GeV)}} \oplus 2.5\%$, as illustrated in Fig. 5. This meets the requirements of the linearity within $\pm 3\%$ and the resolution better than $60\%/\sqrt{\mathrm{E(GeV)}} \oplus 3\%$.

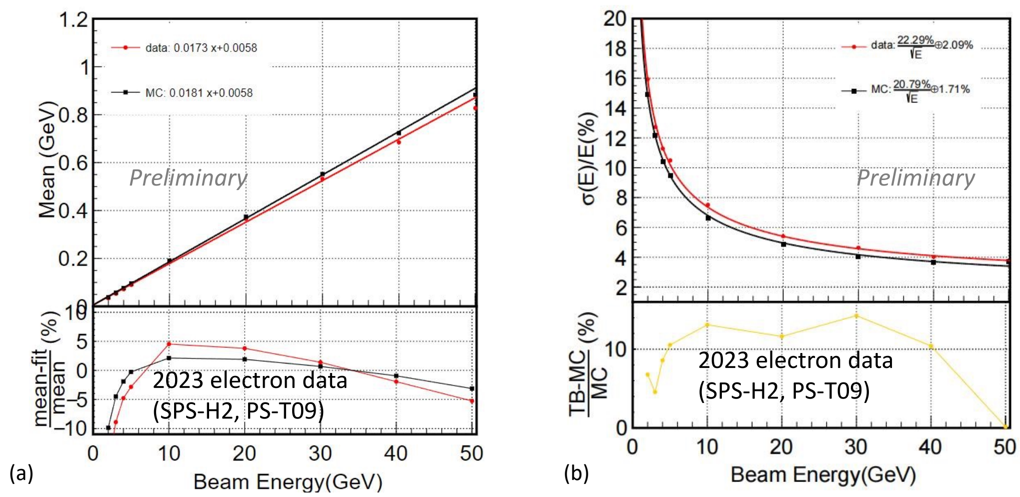

Figure 4: Preliminary results of AHCAL performance with electrons in the range of 2 - 50 GeV: (a) the EM response linearity; (b) the EM energy resolution.

Ongoing data analysis activities indicate that a more realistic model of SiPM non-linearity behaviour is essential for better descriptions of high-energy EM and hadronic showers in simulation. This model should accurately describe the SiPM pixel recovery effect, which is correlated with the scintillation time and the optical photon propagation time within the detector unit. After validation with beam test data, it can be applied to correct non-linearity effects in the data. Additionally, it was found that the SPIROC2E chip exhibits a noticeable non-linearity effect in its low-gain ADC mode. Dedicated laboratory measurements through charge injection are ongoing to quantify the response curve, which will be implemented in the simulation and further validated with beam test data.

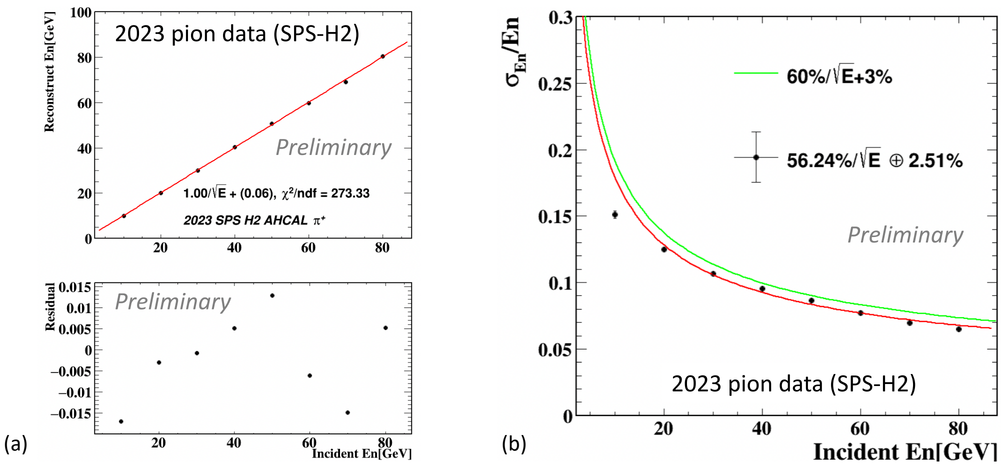

Figure 5: Preliminary results of AHCAL performance with pions in the range of 10 - 80 GeV: (a) the hadronic response linearity; (b) the hadronic energy resolution.

5. Summary and prospects

The CALICE scintillator-based calorimeter prototypes were developed between 2016-2022, followed by successful beam test campaigns at CERN during 2022-2023. Sufficient data have been collected over a broad energy range, enabling detailed performance evaluations and in-depth studies of both electromagnetic (EM) and hadronic showers in the 3D space and time domains.

Dedicated PID techniques were developed based on the its imaging capability, and the preliminary results are quite promising. Prototype simulation and digitisation have been established, and several key issues have been identified during validation studies, e.g. non-linearity effects of SiPMs and readout chips. Efforts are ongoing to address these critical issues and to improve the data-simulation consistency.

In the next phase, the ECFA DRD-on-Calorimetry (DRD6) collaboration will focus on state-of-art calorimetry developments for collider experiments and other applications. Within DRD6, it is expected that efforts on common software, data acquisition, and beam test campaigns will be more coherently coordinated. Meanwhile, the existing CALICE beam test data sets will continue to play a crucial role in the Geant4 validation and particle-flow performance studies.

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