PROCEEDINGS OF SCIENCE

A novel high-granularity crystal calorimeter

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Future electron-positron colliders, or Higgs factories, impose stringent requirements on the energy resolutions of hadrons and jets for the precision physic programs of the Higgs, Z/W bosons and the top quark. Based on the particle-flow paradigm, a novel highly granular crystal electromagnetic calorimeter (ECAL) has been proposed to address major challenges from the jet reconstruction and to achieve the optimal electromagnetic energy resolution of around $2-3\ \%/\sqrt{E(\mathrm{GeV})}$ with the homogeneous structure. R&D efforts have been carried on to evaluate the requirements on the sensitive detector units and physics potentials of the crystal calorimeter concept within a full detector system. The requirements on crystals, photon sensors as well as readout electronics are parameterized and quantified in a full simulation model based on Geant4. Experiments including characterizations of crystals and silicon photomultipliers (SiPMs) have been followed to validate simulation results and optimize simulation parameters. Physics performance of the crystal ECAL has been studied with Higgs physics benchmarks using the particle-flow algorithm "ArborPFA". Progress has been made on optimizing the ArborPFA algorithm and parameters therein, leading to a significant improvement of the separation efficiency for close-by showers and jet reconstruction performance. For the new detector layout with long crystal bars arranged to be orthogonal to each other in two neighboring layers, a dedicated reconstruction software is also being developed to address major challenges on pattern recognition.

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1. Introduction

Following the demands from the precision measurements of the Higgs, Z/W bosons as well as searches for physics beyond the Standard Model, future electron–positron colliders including CEPC [1], FCC-ee [2], ILC [3] and CLIC [4] have been proposed. To fully exploit the physics potentials, the CEPC detector should achieve an unprecedented jet energy resolution and aim to reach the invariant mass resolution of 3–4% with the hadronic decays of Higgs and Z/W bosons [1], which poses stringent requirements on the detector design. In the light of the physics demand, high-granularity calorimetry concepts based on the particle flow algorithm (PFA) [5] have been proposed over the past two decades and are being developed within the CALICE Collaboration [6], aiming to measure each of the final-state particles with the optimal sub-detectors and achieve good separation of close-by particle showers.

For the existing PFA-oriented sampling electromagnetic calorimetry (ECAL), e.g., the silicon-tungsten (SiW) ECAL [7] and scintillator-tungsten ECAL [8], the major focus is on the pattern recognition and thus the energy resolution would be limited by the structures. Hereby, we propose a new conceptual design of the high granularity crystal ECAL with fine 3D segmentations to be compatible with the PFA, to reach an optimal EM resolution of $2\text{–}3\%/\sqrt{E\,(\text{GeV})}$, and to significantly improve the sensitivity to low-energy particles. The precision measurements of γ and π^0 can also be portals to further explore the new physics beyond the standard model [9]. There are two major designs of the high granularity crystal ECAL in the proposal, as shown in Figure 1. Design 1, with finely segmented crystals in both longitudinal and transversal dimensions, would be naturally compatible with PFA, but sets a stringent requirement on the electronics and mechanical structures. To address this challenge, Design 2, a new detector layout is proposed with long crystal bars arranged to be orthogonal to each other in two neighboring layers for a maximum longitudinal segmentation, minimum inactive materials in between and a significant reduction in readout channels. Each crystal bar is read out by 2 silicon photomultipliers (SiPMs) at two ends, which can also provide timing information for positioning reconstruction, clustering and particle identification.

In this proceeding, PFA studies will be presented in Section 2. Besides the highlights of physics performance studies and software development, preliminary results from hardware R&D activities on the key aspects of the calorimeter design are presented in Section 3, followed by the summary and prospects in Section 4.

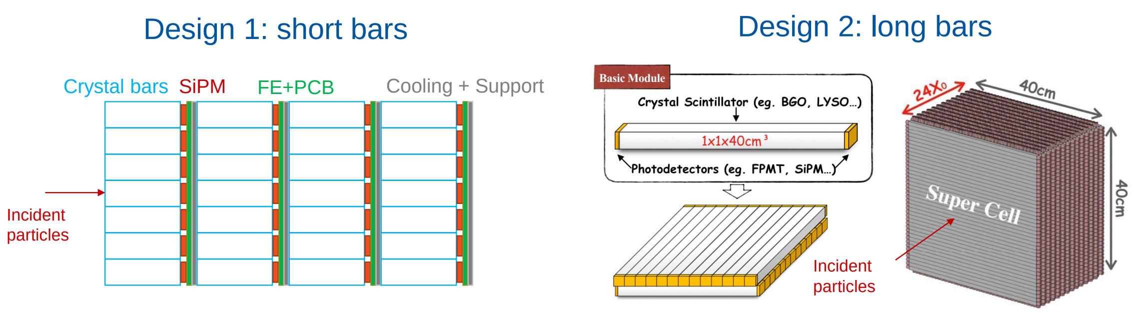


Figure 1: Two designs proposed for a high granularity crystal calorimeter: Design 1 with finely segmented crystals and single-ended readout; Design 2 with long crystal bars and two-ended readout.

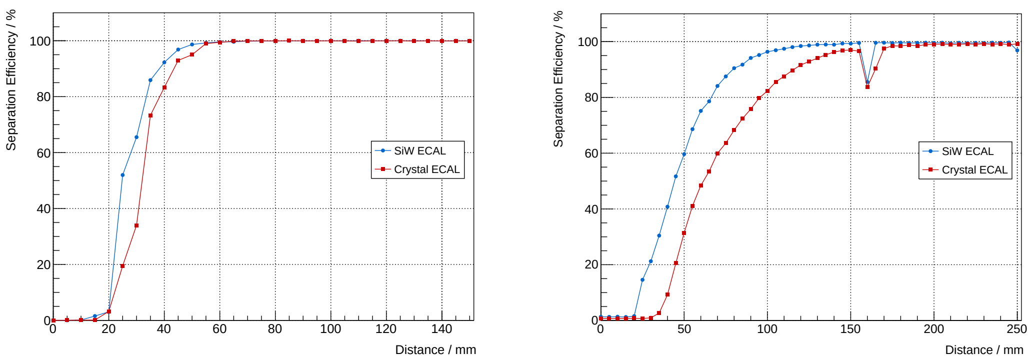
2. PFA Performance

For PFA performance studies and optimizations, the CEPC baseline detector [1] and the PFA software "ArborPFA" [10] were implemented in the CEPC software framework [11]. The CEPC CDR SiW-ECAL with the transverse cell size $1 \times 1 \times cm^2$ cells as well as Bismuth Germanate (BGO) crystal bars with the fine granularity of $1 \times 1 \times 2$ cm^3 are compared in the full simulation to evaluate the separation capability in Section 2.1 and the physics performance of Higgs benchmarks is presented in Section 2.2.

2.1 Separation Power of Close-By Showers

PFA calorimetry requires good separation of showers initiated by close-by particles. Considering typical jet components, key scenarios in ECAL are combinations of (1) two photons (denoted as $\gamma' s$) and (2) a charged pion ($\pi^{\pm}$) and a γ [12]. Since the ArborPFA was optimized for SiW-ECAL with smaller Molière radius (R_M), further optimizations is required for the crystal option. Key updates implemented in the ArborPFA include: (1) applying a relatively higher energy threshold to locate the cluster skeleton; and (2) re-clustering by absorbing low-energy hits with a relatively lower energy threshold to restore the response linearity.

As shown in Figure 2, the crystal ECAL with optimized ArborPFA parameters can reach a similar two-photon separation efficiency curve to the SiW-ECAL. But for the separation capability of hadronic clusters from EM ones, due to the more widely distributed hadronic showers, the crystal ECAL could not yet reach as good as the SiW option. Moreover, the complicated hadronic shower profiles lead to failures of matching the charged clusters in calorimeters with the tracking detector. There could be some room for calorimeter-tracker matching of hadronic clusters by further optimizing the particle-flow algorithm. It should be noted that the gaps between modules (e.g., around 160 mm in the plots) will degrade the separation efficiency.



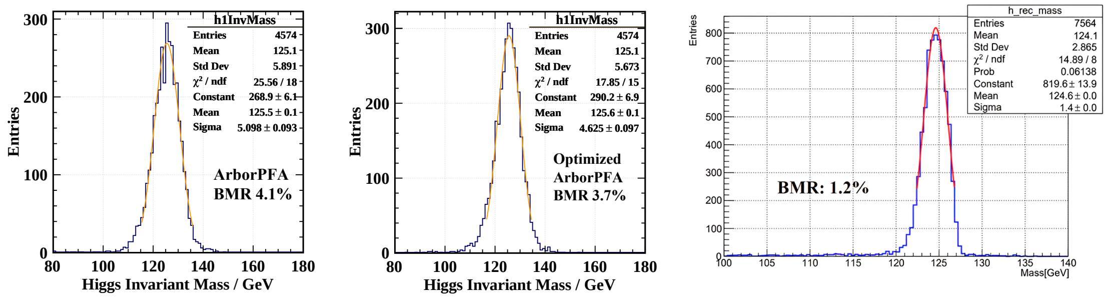
(a) **(b)**

Figure 2: Separation efficiency with varying distances between two incident particles: (**a**) γ/γ; (**b**) π^+/γ.

Furthermore, a new reconstruction algorithm dedicated to the long crystal bar layout is under development in the new software framework named "CEPCSW" [13], aiming to reach the fine granularity of $1 \times 1 \times 2$ cm^3. Key questions including pattern recognition and cluster-track matching need to be addressed.

2.2 Higgs Benchmarks

The Boson Mass Resolution (BMR) is a key parameter to evaluate the PFA performance of Z/W/Higgs decays. The BMRs of two gluon jets in $ZH \to \nu\nu gg$ as well as two photons in $ZH \to \nu\nu\gamma\gamma$ at 240 GeV have been evaluated with the CEPC baseline detector, where the SiW-ECAL is substituted by the crystal ECAL with the fine granularity of $1 \times 1 \times 1$ cm^3. The BMR is defined as the invariant mass of Higgs reconstructed by the ArborPFA. After implementing the key updates for the crystal option in ArborPFA as discussed in Section 2.1, there is a significant improvement in BMR for 2 gluon jets from 4.1% (Figure 3(a)) to 3.7% (Figure 3(b)). The Higgs BMR with two photons in the final states is also presented in Figure 3(c). Further optimizations and studies of impacts from granularity are ongoing.



(a) (b) (c)

Figure 3: Higgs boson mass resolution using the ArborPFA algorithm with the crystal ECAL. (**a**) Two gluon jets final-state BMR using the default ArborPFA. (**b**) Two gluon jets final-state BMR using the optimized ArborPFA. (**c**) Two photons final-state BMR using the default ArborPFA

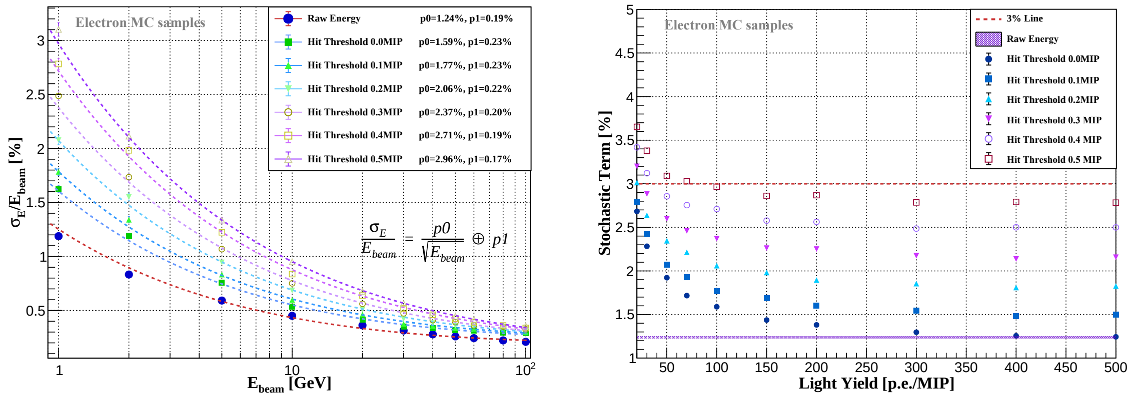
3. Detector Design and Characterizations

The quantitative requirements on crystal-SiPM unit are presented in this section, followed by the latest measurement results.

3.1 Energy Resolution and Requirements

The EM energy resolution of the crystal calorimeter has been studied with the Geant4 [14] simulation. A digitization tool has been developed to take into account the important factors related to photon detection, and parameters were tuned based on the cosmic-ray and radioactive test results. The photon statistics are primarily evaluated in terms of the MIP (minimum ionising particle) response.

As shown in Figure 4, the EM energy resolution is dominated by the energy threshold and MIP response per readout channel. Generally, a low threshold and a moderately high MIP response would be desirable and need to be balanced with the SiPM noises. To achieve the aim of $< 3\%/\sqrt{E(\mathrm{GeV})}$ for the EM energy resolution, the MIP light yield is required to be between 100 and 200 p.e.. As for the critical issue of the SiPM dynamic range, laser tests of SiPMs with a larger pixel density is ongoing.



(a) **(b)**

Figure 4: Energy resolution under different energy thresholds and crystal light yields. (**a**) The EM energy resolution when different energy thresholds are implemented on calorimeter hits. The light yield is set to 100 detected photons per MIP. (**b**) The stochastic term of the EM energy resolution with varying light yields (number of detected photons per MIP) and energy thresholds for hits.

3.2 Response Uniformity of Long BGO Crystal Bar

The characterizations of a $1\times1\times40$ cm^3 long BGO crystal bar (manufactured by the Shanghai Institute of Ceramics [15]) were carried out to evaluate the performance and the results are also used to validate the digitization tool. The response uniformity along the crystal bar was measured with a radioactive source test-stand. Experiments were performed with a 40 cm BGO crystal bar and signals were read out by two SiPMs (Hamamatsu S13360-6025PE [16]) directly air-coupled with each end. A radioactive source of Cs-137 was placed on a 1D movable rail to scan along the crystal length direction. It should be noted that the source collimation diameter is around 8 mm. The results from measurements and Geant4 optical simulation are shown in Figure 5(a),(b). Preliminary results show that the response uniformity in measurements is better than the simulation, but features an asymmetrical pattern. For better consistency of simulation and data, there are several subtle parts to be studied, such as optical model parameters and the modeling of defects on the crystal surface, guided by the measurements. On the other hand, more crystals will be tested to evaluate repetitive precision.

With the same Geant4 simulation model, a 2D uniformity map is obtained with muons perpendicularly passing through a basic crystal module with the detector layout of crossed long crystal bars. As shown in Figure 5(c),(d), the 2D non-uniformity effect will lead to position dependence for the energy reconstruction. Monte Carlo samples of high-energy electrons were used to evaluate the impacts on energy resolution, dependent on different levels of non-uniformity. Therefore, the crystal-SiPM response uniformity needs to be well-controlled and carefully calibrated.

4. Summary and Prospects

High-granularity calorimetry options enable an excellent jet reconstruction capability for future high-energy experiments. A highly granular crystal calorimeter was proposed to aim at a superior

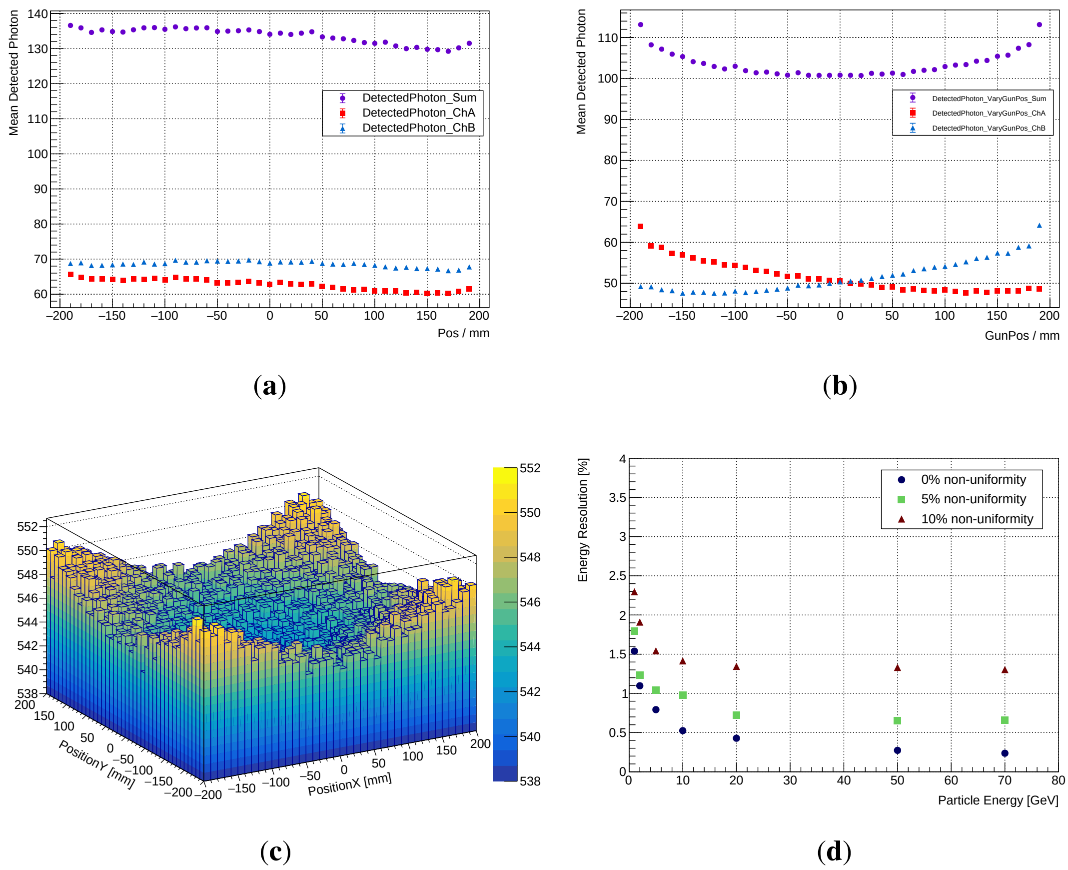


Figure 5: Simulations of uniformity of the crystal ECAL. (**a**) Measured response uniformity of a BGO crystal bar. (**b**) Simulated response uniformity of a BGO crystal bar, the surface roughness was considered. (**c**) 2D response uniformity of the ECAL module, 1 GeV muons are used for scanning. (**d**) Energy resolution under certain non-uniformity. Nine modules are placed in the simulation to prevent energy leakage.

EM energy resolution and PFA performance for future Higgs factories. Physics potentials were presented using the CEPC detector with a high-granularity crystal calorimeter, including the PFA performance on separation power and the Higgs benchmarks. A dedicated reconstruction algorithm is under development for the detector layout with long crystal bars arranged to be orthogonal in adjacent layers. It should be noted that the pattern recognition of jet components in crystals would be a challenging topic.

Hardware activities focus on the crystal–SiPM readout unit to address key questions of the detector requirements were studied. Characterizations of BGO crystals and SiPMs were carried out and the results were used to validate the simulation. Key specifications of the crystal ECAL extracted from simulations and experiments are listed in Table 1. In the near future, small-scale ECAL modules will be developed to evaluate the EM shower performance in beam tests, to gain experience in the large-scale module design, and to deliver reliable inputs to evaluate the whole detector performance.

Table 1: Key specifications of the crystal ECAL.

Key Parameters	Value/Range	Remarks
MIP light yield	100~200 p.e./MIP	8.9 MeV/MIP in 1 cm BGO
Dynamic range	0.1~10^3 MIP	Energy range from ~1 MeV to ~10 GeV
Energy threshold	0.1 MIP	Equivalent to ~1 MeV energy deposition
Timing resolution	~400 ps	Limits from G4 simulation (validation needed)
Crystal non-uniformity	<1%	After calibration
Temperature stability	Stable at ~0.05 °C	Reference of CMS ECAL
Gap tolerance	~100 μm	TBD via module development

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