PROCEEDINGS OF SCIENCE

Highly granular hadronic calorimeter with glass scintillator tiles: R&D overview and highlights

Dejing Du,[a,b] **Peng Hu,**[a] **Zhehao Hua,**[a,c,d] **Yong Liu,**[a,b,*] **Baohua Qi**[a,b] **and Sen Qian**[a,b]

[a] *Institute of High Energy Physics, Chinese Academy of Sciences, Yuquan Road 19B, 100049 Beijing, China*
[b] *University of Chinese Academy of Sciences, Yanqihu East Road 1, 101408 Beijing, China*
[c] *China Building Materials Academy, Fuxing Road 17, 100024 Beijing, China*
[d] *School of Materials Science and Engineering, Wuhan University of Technology, Luoshi Road 122, 430070 Wuhan, China*

E-mail: liuyong@ihep.ac.cn

A new hadronic calorimeter (HCAL) with glass scintillator tiles has been designed for future lepton collider experiments (e.g. the Circular Electron Positron Collider). Using a sampling structure (similar to the CALICE AHCAL technology), the new HCAL design aims for better hadron and jet performance, with a higher sampling fraction by using high-density glass scintillator instead of plastic scintillator. Full simulation studies were done on jet performance of Higgs hadronic decays using a Particle-Flow Algorithm (PFA). The HCAL design was optimised in terms of longitudinal depth, transverse granularity, glass density and effective light yield. Hardware activities focus on measurements of high-density glass tiles developed within the Glass Scintillator Collaboration. First two batches of glass tiles in the target dimensions of $40 \times 40 \times 10$ mm^3 were tested with beam particles at CERN and DESY. In the contribution highlights of R&D activities will be presented, including performance studies, design optimisations and latest beam test results.

42nd International Conference on High Energy Physics (ICHEP2024)
18-24 July 2024
Prague, Czech Republic

*Speaker

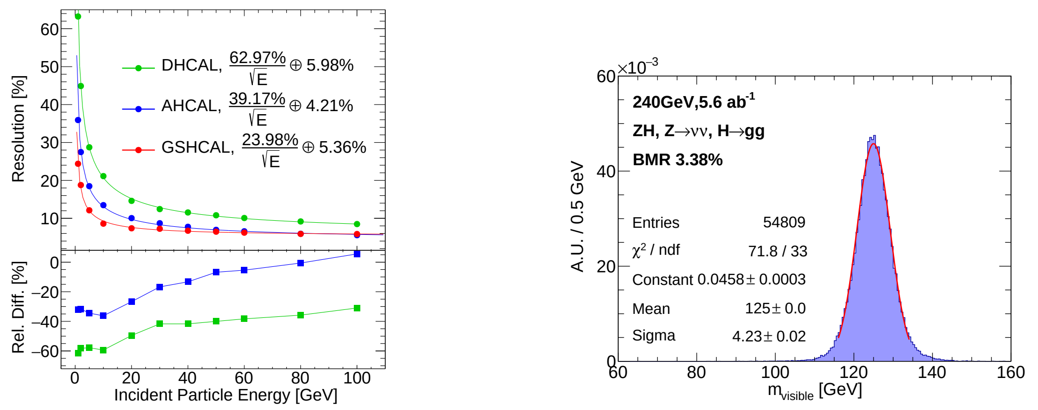
PoS(ICHEP2024)1144

1. Introduction

A new detector system based on the particle-flow algorithms with highly granular calorimeters has been proposed for the Circular Electron Positron Collider (CEPC) [1–3], including an electromagnetic calorimeter with crystal bars and a glass scintillator hadron calorimeter (GSHCAL) [4] [5]. With a higher energy sampling fraction compared with the plastic scintillator, the GSHCAL equipped with high-density glass scintillator tiles is expected to achieve a better hadronic energy resolution and thus to further improve the Boson Mass Resolution (BMR). To evaluate the performance of high-density glass scintillator tiles, particularly in terms of the response to a Minimum Ionising Particle (MIP) , we developed a dedicated test stand and conducted two beamtests at CERN and DESY, respectively. Section 2 focuses on the GSHCAL simulation studies, followed by Section 3 with beam test results. Conclusions will be covered in Section 4.

2. Simulation studies and design optimisations

To evaluate the performance potentials, the GSHCAL hadronic energy resolution was studied using a stand-alone Geant4 simulation model. Compared with two major HCAL options, i.e. the AHCAL with plastic scinitllator tiles and the DHCAL with resistive plate chambers [6–8], the GSHCAL is expected to have a better hadronic energy resolution due to a higher sampling fraction (i.e. the ratio between the energy deposition in sensitive layers and that in both sensitive and absorber layers), as shown in Figure 1(a). The jet performance of GSHCAL was investigated within a complete CEPC simulation and reconstruction framework (CEPCsoft) integrated with the Arbor PFA [9]. As shown in Figure 1(b), the BMR of the CEPC detector with GSHCAL can reach around 3.38% and shows an improvement of around 10% compared to the CEPC detector design with DHCAL. Therefore, GSHCAL emerges as a promising HCAL option to further improve the hadron and jet performance.



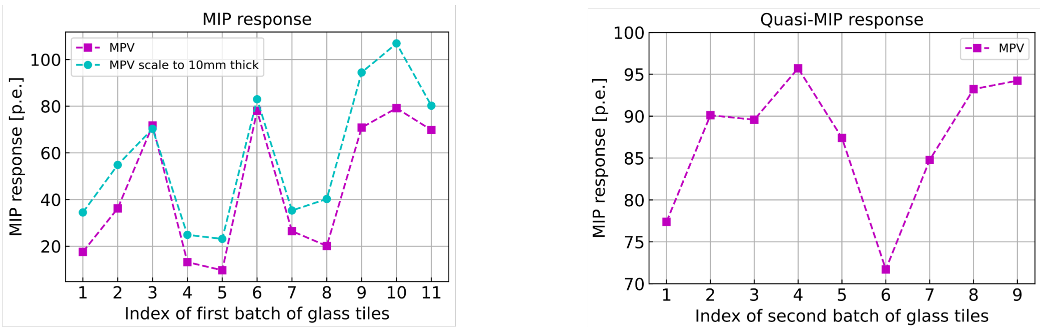
(a) (b)

Figure 1: (a) The hadronic energy resolution of the GSHCAL, compared with the DHCAL and AHCAL options; (b) the Higgs invariant mass distribution by reconstructing two gluon jets in the channel of $ZH \rightarrow \nu\bar{\nu}gg$, where the Z boson decays into a pair of neutrinos and the Higgs boson decays into a pair of gluon jets.

3. Beam test results of glass scintillator tiles

The first batch of 11 glass scintillator tiles in the cm-scale were successfully produced by the Glass Scintillator Collaboration [10] and later tested with 10 GeV muons [11] at the CERN PS-T09 in May 2023. All glass scintillator tiles were wrapped with Teflon reflector films, and read out individually by a silicon photomultiplier (SiPM) with a sensitive area of 6×6 mm^2. Clear MIP signals were observed in all glass scintillator tiles. The MIP response is defined as the most probable value (MPV) in terms of the number of photon equivalents (p.e.) detected by the SiPM. The MPV value is obtained by fitting the MIP energy spectrum with a convoluted Landau-Gaussian function. Figure 2(a) shows the MIP response of the first batch of glass scintillator tiles tested at CERN. The tile thickness varies in the range of 5.1-10.2 mm in the first batch. In order to facilitate the comparison of the MIP response of each tile, the MIP response was also scaled linearly to a thickness of 10 mm (i.e. the GSHCAL target design for the tile thickness), assuming the MIP response is proportional to the tile thickness in the ideal case. The data points in cyan indicate that the MIP response is in the range of 23 to 107 p.e./MIP for the baseline thickness of 10 mm. It should be noted that the transverse size of each tile also varies in the range of 27.8×25.6 mm^2 – 40.0×35.1mm^2, the MIP response may not scale exactly linearly with the thickness due to the self absorption of photons which could also be dependent on the tile transverse size. Significant variations of the MIP response were observed among the tiles, which could be due to different glass constituents and synthesising processes in the first production of glass scintillator tiles in the given dimensions.

The subsequent beam test was followed up at the DESY test beam facility in October 2023 with 5 GeV electrons for the second batch of glass scintillator tiles which were produced in the exact dimensions of $40 \times 40 \times 10$ mm^3 by the Glass Scintillator Collaboration. As observed in the data, the electron beam would start to initiate an electromagnetic showers in glass tiles, leading to a different energy spectrum compared with the muon beam. The energy deposition spectrum of electrons could be considered as a quasi-MIP response. Figure 2(b) shows the quasi-MIP response of the second batch of glass scintillator tiles, ranging from 72 to 96 p.e./MIP, which is very close to the GSHCAL requirement of around 100 p.e./MIP. In addition, the second batch also shows a significant improvement in the tile-wise uniformity compared with the first batch.



(a) (b)

Figure 2: (a) The MIP response distribution of the first batch of glass scintillator tiles measured at CERN with 10 GeV muons; (b) the quasi-MIP response distributions of the second batch of glass scintillator tiles in the dimensions of $40 \times 40 \times 10$ mm^3 measured at DESY with 5 GeV electrons.

4. Conclusions

A new hadron calorimeter option with high-density glass scintillator tiles has been proposed for future Higgs factories with a major aim to further improve the hadron and jet performance. The potentials have been studied with single hadrons in the Geant4 simulation and with jets using the PFA of Arbor. Dedicated beam tests were successfully performed to evaluate the performance of glass scintillator tiles produced in two batches. The preliminary results show that the high-density glass scintillator tiles are promising to achieve the GSHCAL requirement of 100 p.e./MIP, which would be crucial for the hadron performance.

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