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Development of a novel highly granular hadronic calorimeter with scintillating glass tiles

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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. To address the challenges, one of the state-of-art calorimetry options is based on the particle flow algorithms (PFA) and requires fine longitudinal and transverse segmentations to achieve excellent separation capability to distinguish near-by particle showers. Among highly granular calorimetry options, a novel hadronic calorimetry (HCAL) with scintillating glass tiles is emerging.The scintillating glass HCAL design focuses on the significant improvement of hadronic energy resolution, especially in the low energy region (typically below 10 GeV for major jet components at Higgs factories), with a notable increase of the energy sampling fraction by using high-density scintillating glass tiles. Simulation studies have been done to quantify the hadronic energy resolution with single hadrons and physics potentials with jets using the ArborPFA. Developments of new scintillating glass materials are ongoing within a collaboration of research institutions and companies in China. Small-scale samples of scintillating glass have been characterised using dedicated experimental setups to extract key properties (e.g. intrinsic light yield, emission and transmission spectra, scintillation decay times, etc.) required by the HCAL design. An optical simulation model of a single scintillating glass tile has been established to provide guidance for the development of scintillating glass. In this contribution, highlights of the expected detector performance and latest scintillating glass developments will be presented.

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1. Introduction

Next-generation high energy electron-positron collider experiments have been proposed including the CEPC [1], FCC-ee [2], ILC [3] and CLIC [4] for precision measurements of the Higgs, Z/W bosons as well as searches for physics beyond the Standard Model. To fully exploit the physics potentials, the CEPC requires accurate particle identification and reconstruction of all final states from Higgs, W and Z bosons, which requires the jet energy resolution of the CEPC detector to achieve $\sim 30\%/\sqrt{\mathrm{E_{jet}(GeV)}}$ [1]. To address this challenge, the high granularity calorimetry based on the particle flow algorithm (PFA) [5] has been proposed and extensively studied within the CALICE collaboration [6] over the past two decades. PFA-oriented calorimetry utilises the optimal sub-detector to determine the energy-momentum of each particle within a jet, and is featured with high granularity to achieve an excellent three-dimensional spatial resolution for good separation capabilities of close-by showers.

As the majority of jet components at Higgs factories with the center-of-mass energy of 240 GeV are with relatively low energy i.e. mostly below 10 GeV [7], an even better hadronic energy resolution would be essential to further improve the jet energy resolution. Hereby we have proposed a new design of a highly granular hadronic calorimeter (HCAL) with high-density scintillating glass tiles, with a higher energy sampling fraction and PFA compatibility, to furthter improve the hadronic energy resolution. Besides, dense scintillating glass with a moderate light yield and adjustable ingredients is considered as a promising option and more cost effective for calorimetry applications compared with scintillating crystals. The general detector layout of scintillating glass HCAL is similar to the CALICE scintillator-steel hadronic calorimetry (AHCAL) technique, proposed in the CEPC Conceputal Design Report [1].

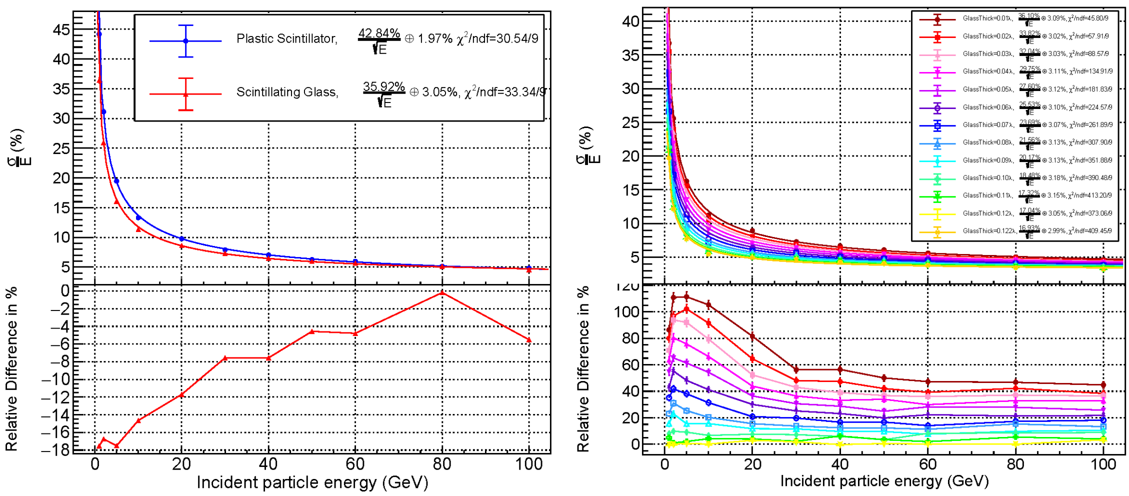
In this proceeding, Section 2 introduces the performance studies and physics potentials of scintillating glass HCAL. Recent progresses in high-density scintillating-glass R&D activities and characterisation of glass samples will be covered in Section 3, followed by simulation studies as well as measurements in Section 4 for an HCAL detector unit and summary in Section 5.

2. Performance of Scintillating glass HCAL

The Boson Mass Resolution (BMR) is a key parameter to quantify physics performance for a given detector. The BMR has been factorised based on the PFA fast simulation, and it is found that the hadronic energy resolution (obtained with single hadrons), among several key factors, ranks the second-most important [7]. Therefore, it is expected to achieve a better BMR, when the hadronic energy resolution is improved with a new calorimetry technique.

To study the hadronic energy resolution of single hadrons, a Geant4 [8] full simulation (with the version 10.7.4 and the physics list “QGSP_BERT”) has been established, including all relevant physics processes for EM and hadronic showers. Hereby we use a large HCAL volume to minimise shower leakage effects. Each longitudinal layer consists of a steel plate as the absorber, a sensitive layer with scintillating glass tiles read out individually by silicon photomultipliers (SiPM) and a readout PCB. The transverse size of the glass tiles is set to 3×3 cm^2. The hadronic energy resolutions of the HCAL with plastic and glass were compared using the Geant4 simulation with the same sensitive layer thickness of 3 mm. The preliminary results in Figure 1(a) show that scintillating glass HCAL has a better hadronic energy resolution, especially for particles with low kinetic energies. It is fair to state that the plastic scintillator option provides an acceptable energy resolution, although the scintillating glass offers better performance.

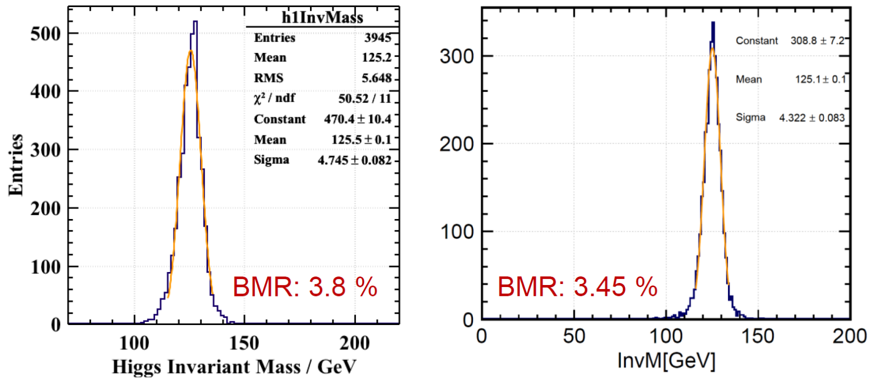
To study the impact of the scintillating glass thickness on the hadronic energy resolution, the thicknesses of the steel plate and the scintillator tiles are adjusted so as to give the same total with of 0.12 λ_I (λ_I denoted as the nuclear interaction length) as the AHCAL proposed in the CEPC CDR [1]. The λ_I of the scintillating glass (with the constituent recipe described in Section 3) and steel are 22.4 cm and 16.8 cm, respectively. As shown in Figure 1(b), the thickness of the scintillating glass can significantly affect the energy resolution, and thicker scintillating glass tiles would always be desirable for better hadronic energy resolution with the given energy threshold of 0.1 MIP.



(a) (b)

Figure 1: The hadronic energy resolution of scintillating glass HCAL with the reasonable energy threshold of 0.1 MIP with single neutral kaons (K_L^0) in the kinetic energy range from 1 GeV to 100 GeV with the incidence perpendicular to the calorimeter front surface: (**a**) with different sensitive materials (plastic scintillator and scintillating glass); (**b**) with different thicknesses of scintillating glass tiles from 0.01 λ_I to 0.12 λ_I (dark red and orange for the minimum and maximum sampling fraction, respectively). The HCAL is set up with a transverse size of 540×540 cm^2 and 300 longitudinal layers.

The BMR of two gluon jets in $ZH \to \nu\nu gg$ at 240 GeV has been evaluated with the baseline CEPC detector and the HCAL instrumented with the scintillating glass design. As shown in Figure 2(a), the BMR with the CEPC CDR baseline detector is around 3.8%. In the scenario of a homogeneous HCAL with scintillating glass, the BMR is improved by around 10% to be 3.45%. A particle flow algorithm named “ArborPFA” [9] was used in the study, and the PFA parameters were still tuned with the CDR baseline HCAL. It is expected that the BMR can be further improved by optimizing the PFA for the scintillating glass HCAL. A low energy threshold (around 2.5% MIP) was implemented in the BMR simulation at this stage to illustrate the physics potentials. A range of realistic threshold values, considering possible constraints from photosensors, front-end electronics, the trigger, the DAQ, etc., will be further studied to evaluate the impacts on the BMR performance.



(a) (b)

Figure 2: BMR of $ZH \rightarrow \nu\nu gg$ at 240 GeV with the energy threshold of 0.1 MIP. (**a**) CEPC CDR baseline detector; (**b**) CEPC CDR baseline detector with the HCAL replaced by a homogeneous HCAL, which is 40 layers of $40 \times 40 \times 40$ mm^3 scintillating glass tiles (equipped with readout PCB and without any absorber). It needs to be noted that this setup configuration is not meant to be the final HCAL design, but is presented only to illustrate the physics potential of sufficient depth in the HCAL. Ongoing studies are being carried out with the exact same depth as the CDR requirement of around 4.8 λ_I as the total depth.

3. R&D of scintillating glass materials

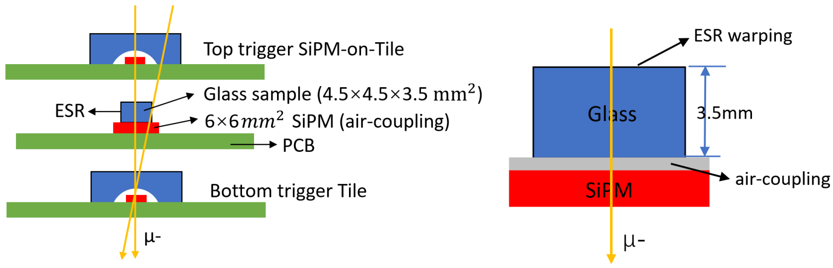
A scintillating glass collaboration was established in China in 2021 to develop scintillating glass materials for the PFA-oriented hadronic calorimeter. The major R&D goals include a high density ($6-7$ g/cm^3), a good visible-wavelength transparency (on average $\sim 75\%$), a high intrinsic light-yield (around 1000 photons/MeV), and cost-effectiveness. The collaboration has developed several sample-glass batches. To evaluate the glass performance (including the intrinsic light yield, energy resolutions, decay times, transmission spectra etc.), dedicated setups have been developed to measure the optical and scintillating characteristics of scintillating glass samples, and details about the instrumentation and results can be found in [10].

First batches of samples in the mm-scale (around 5×5 mm^2 large, 3 mm thick) have been measured. As shown in the characterization results of the optical and scintillating properties, one aluminoborosilicate glass sample with composition of $B_2O_3 - SiO_2 - Al_2O_3 - Gd_2O_3 - Ce_2O_3$ shows the best performance, with transmittance at visible wavelengths around 64%, light yield of 881 photons/MeV, and density of about 5 g/cm^3.

Recently, the glass scintillator collaboration has made great progress. The measurements of latest glass samples show that one sample achieves a density of 6 g/cm^3 and an intrinsic light yield of 1076 ph/MeV, but its size is still in the mm-scale. On the development of large-scale scintillating glass, a new glass sample reaches $42 \times 51 \times 10$ mm^3 in dimensions and its properties are to be measured. Future R&D efforts would focus on the development of cm-scale scintillating glass tiles with both high density and high light-yield.

4. Performance of an HCAL detector unit

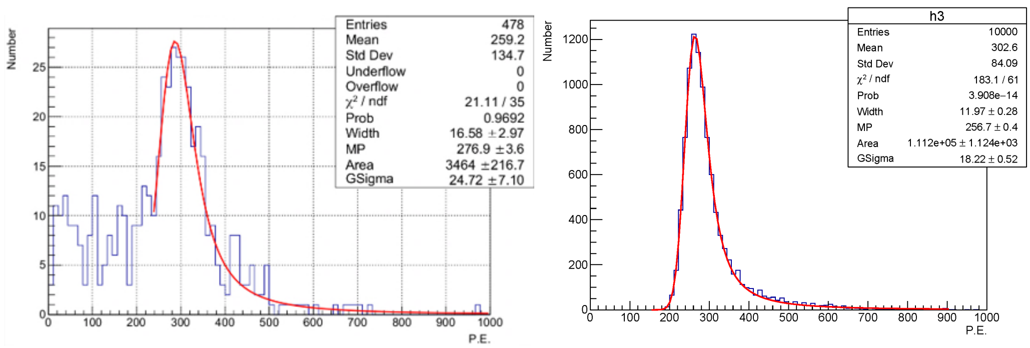
A basic HCAL detector unit consists of a scintillating glass tile and a silicon photomultiplier (SiPM). The response of an individual detector unit to a Minimum Ionizing Particle (MIP) provides the energy scale for the energy reconstruction of the highly granular HCAL. Hereby the response to MIPs is defined as the number of photons detected at the SiPM placed in the tile center of the transverse plane and is studied in both measurements and simulation.



(a) (b)

Figure 3: The schematic of the geometry setup: (**a**) cosmic ray test and (**b**) optical simulation.

A dedicated cosmic-ray test stand was developed to measure the response to MIPs of scintillating glass samples. As shown in Figure 3(a), the scintillating glass sample (wrapped with an ESR foil) is directly air-coupled with a SiPM and placed between two trigger scintillator tiles as coincidence. As the trigger tiles are larger than the glass sample, there were still a part of the cosmic muons that do not pass through the glass volume or oblique incident on the glass surface. The best glass sample ($4.5 \times 4.5 \times 3.5\ mm^3$) of the first batch was used for measurements with a SiPM (Hamamatsu S13360-6025PE). Figure 4(a) shows the response to MIPs of the small scintillating glass tile with the most probable value (MPV) of 277 detected photons at the SiPM.



(a) (b)

Figure 4: The MIP response of a scintillating glass tile: (**a**) cosmic ray test and (**b**) optical simulation.

The Geant4 optical simulation has been established for the HCAL detector unit, as shown in Figure 3(b). According to the simulation shown in Figure 4(b), the MPV of the number of photons detected at the SiPM is 257 p.e./MIP. As the muon's incidence in the simulation is exactly perpendicular to the tile surface, it is reasonable that the simulation expects a slightly smaller response to MIPs than the measurements. This study demonstrated that the Geant4 optical simulation can reasonably reproduce the measurements.

5. Summary and prospects

A new high-granularity HCAL concept with high-density scintillating glass tiles has been proposed to further improve the energy resolution and the BMR. Compared with the plastic scintillator, the scintillating glass HCAL option is expected to achieve a better hadronic energy resolution, especially in low energy regions, and would have better BMR performance. The software compensation technique [11] in high-granularity calorimeters can be applied to significantly improve the energy resolution. The joint efforts of glass scintillator collaboration are in steady progress in the development of scintillating glass tiles with high density, good light yield and cost-effectiveness.

Acknowledgments

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