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Design and performance studies of the calorimeter system for a FCC-hh experiment

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The physics reach and feasibility of the Future Circular Collider are currently being investigated in the form of a Conceptual Design Report. The ultimate goal is to collide protons with a centre-of-mass energies of 100 TeV, thus extending the reach of the current HEP facilities. This high-energy regime opens new opportunities for the discovery of physics beyond the standard model, but also new constraints on the detector design. As at 100 TeV a large fraction of the W, Z, H bosons and top quarks are produced with a significant boost, it implies an efficient reconstruction of high energetic objects. The reconstruction of those boosted objects sets the calorimeter performance requirements in terms of energy resolution, containment of highly energetic hadron showers, and high transverse granularity. The detectors designed for the FCC experiments need to tackle harsh conditions of the unprecedented collision energy and instantaneous luminosity. They also must be able to deal with a very high number of collisions per bunch crossings (pile-up). Excellent energy and angular resolution, also for low energetic particles, is therefore needed in order to meet the demands based on the physics benchmarks like Higgs self-couplings. We present the current baseline technologies for the calorimeter system of the FCC-hh reference detector and present first results of the performance studies with the combined calorimeters, meeting the energy resolution goal.

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1. Introduction

The Future Circular Collider (FCC) project [1] is an ambitious plan for a post-LHC era within the CERN complex. It includes studies of a pp circular collider with a centre-of-mass energy of 100 TeV (FCC-hh). An electron-positron collider (FCC-ee) is considered as a possible first step. Moreover, the option of an electron-proton collider is investigated (FCC-he). Given the topology of the CERN area, the maximum tunnel circumference that can be reached is almost 100 km[1]. The running scenario under consideration is 10 years with a peak luminosity of $5 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, followed by 15 years running with $30 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. This will result in $20\,\mathrm{ab}^{-1}$ per experiment. The outcome of the design studies is being summarised in the Conceptual Design Report, to be submitted for the European Strategy Update in 2020. This paper concentrates on the electromagnetic and hadronic calorimeter designs and performances of the FCC-hh experiment.

2. Requirements on the FCC-hh calorimeters

The new energy regime of a FCC-hh experiment allow for measurements of the Higgs production in vector boson fusion (VBF) processes, which give access to a range of Higgs properties and allows for dark matter searches in invisible Higgs decays [2]. However, the associated jets will carry low transverse momentum and thus appear at high pseudorapidities (η) in the detector. This sets the requirement for the detector to cover ranges up to $|\eta| = 6$. Sensitivity to coloured hadronic resonances up to 40 TeV, implies full containment for jets with transverse momenta of 20 TeV, which drives the calorimeter depth. The FCC-hh also has sensitivity to boosted resonances (e.g. $Z \to t\bar{t}$) up to masses of 20 TeV, where the decay products of a W jet with $p_T = 10$ TeV are separated by only $\Delta R \sim 0.02$, which in turn demands high granularity to resolve the substructures. However, one of the biggest challenges for the detector is the need to resolve up to $\langle\mu\rangle = 1000$ pile-up events. The additional vertices are on average expected to be separated by 170 μm in space and 0.5 ps in time, which motivates calorimeters with timing capabilities or dedicated timing layers. Additionally, most of the instruments have to withstand extreme radiation. The expected radiation levels for the Barrel calorimeters, in 1 MeV neutron equivalence fluence (neq), raise up to $4 \times 10^{15}\mathrm{cm}^{-2}$ in the ECal and up to $3 \times 10^{14}\,\mathrm{cm}^{-2}$ in the HCal.

3. FCC-hh reference calorimeter technologies

The FCC-hh reference calorimeter system consists of electromagnetic (EM) and hadronic (H) sections, in the Barrel and extended Barrel (B and EB) $|\eta| < 1.5$, Endcap (EC) $1.5 < |\eta| < 2.5$, and Forward (F) $|\eta| > 2.5$ regions. In the areas most strongly exposed to radiation, the detector is equipped with Liquid Argon (LAr) calorimeters. While the outer Barrel regions are covered by scintillator-Pb-Stainless Steel hadron calorimeters. This combined system has proven good performance in the ATLAS experiment [4], but the new energy frontier of the FCC requires further developments to provide the necessary jet reconstruction performance. Efficient reconstruction algorithms (like particle flow), particle shower separation, and pile-up rejection, demand higher transverse and longitudinal granularity.

The design of the LAr calorimeter at $|\eta| \leq 1.67$ (EMB) is shown in the bottom zoom in Fig. 1. Two millimetre thick Pb absorbers are inclined with a 50° angle, leading to an increase of the

[1]FCC-hh design study: fcc.web.cern.ch/

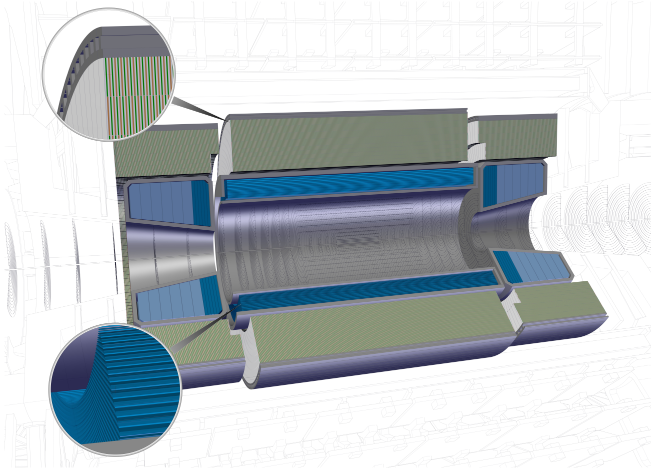


Figure 1: FCC-hh Barrel and Endcap calorimeter system.

LAr gap with radius from 1.15 to 3.09 mm. This changing sampling fraction with calorimeter depth is compensated for in calibrations. The calorimeter has 8 longitudinal layers, using the first one as a pre-sampler without absorber. The achieved granularity is $\Delta\eta \times \Delta\phi = 0.01 \times 0.009$ ($\Delta\eta$ of 0.0025 in 2nd layer). In simulations of single electrons, reconstructed using the sliding window algorithm [6](with a size of $\Delta\eta \times \Delta\phi = 0.07 \times 0.17$), an excellent energy resolution of $8.1\%/\sqrt{E} \oplus 0.2\%$ is achieved.

The hadronic calorimeters at $|\eta| \leq 1.81$ are divided into three sections, a central Barrel (HB) and two extended Barrels (HEB). The maximum dose of <8 kGy allows for an organic scintillating tile based calorimeter (TileCal). The calorimeter layout, shown in the top zoom of Fig. 1, uses tile scintillators (orange) oriented perpendicular to the beam axis, alternating with Pb (green) and Steel (grey) absorbers. The light is transported via wavelength shifting (WLS) fibres, and read out by silicon photomultipliers (SiPM) integrated in the outer Steel support. The granularity of the TileCal is chosen as $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$ with (8) 10 longitudinal layers for the (extended) Barrel. This calorimeter provides an excellent energy resolution for single pions of $42\%/\sqrt{E} \oplus 2.8\%$.

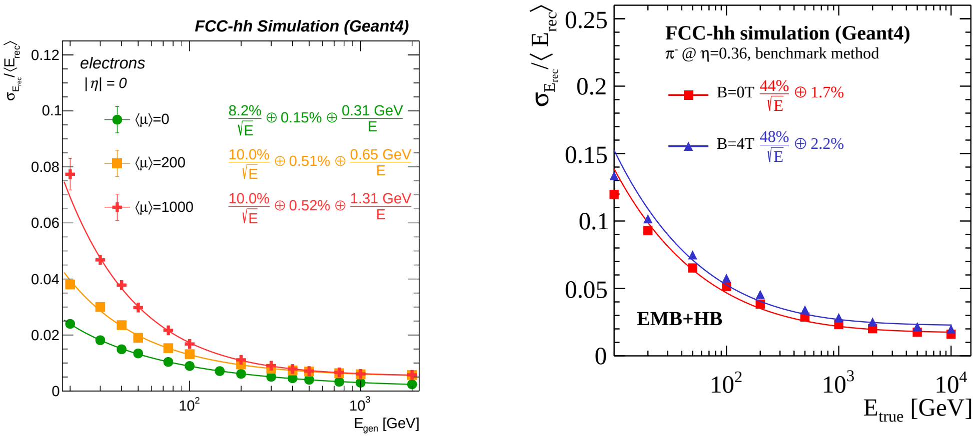
4. Performance and conclusion

The combined LAr and Tile calorimeter system achieves the performance goals with energy resolutions of $8\,\%/\sqrt{E} \oplus 0.2\,\%$ for electrons/photons, and $48\,\%/\sqrt{E} \oplus 2.2\,\%$ for single pions. The electron energy resolution and the effect of pile-up noise for $\langle\mu\rangle = 200$, and $1{,}000$, is shown in Fig. 2a. The electronics noise of the LAr calorimeter is approximately 0.3 GeV within a window of $\Delta\eta\times\Delta\phi$=0.07×0.17. When including pile-up noise, the window size was decreased to $\Delta\eta\times\Delta\phi$=0.03×0.08, and the out-of-time pile-up is neglected.

Fig. 2b shows the single pion energy resolution of the combined EMB+HB system and the effect of the magnetic field. An excellent resolution is achieved in absence of electronics noise and pile-up events, using a calibration method described in [7].

The combined EMB+HB system achieves a jet momentum resolution of $69\,\%/\sqrt{E} \oplus 1.6\,\% \oplus 1\,\mathrm{GeV}/E$ at $|\eta| < 0.5$. Where the jet finding is done using the anti-k$_T$ algorithm [9], that sums topological clusters [8] within cones of radius $R = 0.4$. Jet reconstructions within a 4 T magnetic field need to include the tracking information to recover the low momentum charged particles, which do not reach the calorimeters. Further development of more sophisticated algorithms are needed, to evaluate the combined performance of the tracking and calorimeter systems.

Additionally, the precision on the invariant mass for $H \to \gamma\gamma$ has been tested in full simulation, including electronics and pile-up noise. The in-time pile-up increases the resolution from 1.7 GeV to 2.8 GeV for $\langle \mu \rangle = 1000$.



(a) (b)

Figure 2: (a) The energy resolution of the EMB for single electrons at $\eta = 0$, for $\langle \mu \rangle = 0$, 200, and 1,000. (b) The single pion energy resolution for the combined EMB and HB system at $\eta = 0.36$.

In very high pile-up environments, the energy reconstruction becomes especially challenging for low energetic particles. First studies have started, where simplistic discrimination variables are used to reject pile-up jets, and deep neural nets are used to efficiently reconstruct single particles. The next steps will be to combine tracking information with the calorimeter clusters, to identify, recover, and correct the measured particle energies, and successfully remove pile-up events.

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