Fine-grained calorimeters for experiments at CLIC and FCC-ee

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Abstract

We present optimisation studies for detectors being designed for future e^+e^- colliders such as CLIC and FCC-ee, using particle-flow calorimetry. Surrounding a large silicon tracker volume, a very fine-grained ECAL is envisaged, with 40 Si-W layers and a lateral segmentation of 5×5 mm^2. Beyond the ECAL, a steel-scintillator HCAL is placed, with 60 (44) active layers for CLIC (FCC-ee) consisting of 30×30 mm^2 scintillator tiles coupled to SiPMs. The newly developed software chain based on the DD4Hep detector description toolkit is used for the studies, together with the PANDORA particle flow algorithms. Results obtained for the jet energy resolution as well as particle identification efficiencies for the two detector models designed for CLIC and FCC-ee are presented in this contribution.

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Abstract. We present optimisation studies for detectors being designed for future e^+e^- colliders such as CLIC and FCC-ee, using particle-flow calorimetry. Surrounding a large silicon tracker volume, a very fine-grained ECAL is envisaged, with 40 Si-W layers and a lateral segmentation of 5×5 mm^2. Beyond the ECAL, a steel-scintillator HCAL is placed, with 60 (44) active layers for CLIC (FCC-ee) consisting of 30×30 mm^2 scintillator tiles coupled to SiPMs. The newly developed software chain based on the DD4Hep detector description toolkit is used for the studies, together with the PANDORA particle flow algorithms. Results obtained for the jet energy resolution as well as particle identification efficiencies for the two detector models designed for CLIC and FCC-ee are presented in this contribution.

1. Introduction

Future e^+e^- collider experiments require very precise reconstruction of the collision events in order to reach the desired measurement precision of SM processes as well as of possible direct or indirect observation of new physics. Among the major goals, precise reconstruction of hadronic signatures is important. One of the ways to achieve an excellent jet energy resolution is to exploit particle flow calorimetry, which requires fine-grained calorimeters and precise tracking.

In this note, we discuss and compare the calorimetry performance of two detector models, CLICdet [1] and CLD [2], which are proposed detector designs for the CLIC (centre-of-mass energies of 380 GeV to 3 TeV) and FCC-ee (centre-of-mass energies of 91.2 GeV to 365 GeV) colliders, respectively.

2. Overall detector layouts

Detectors for CLIC and FCC-ee share a common layout but have different parameters. For track reconstruction, a full silicon tracking system is used which provides at least 12 hits per track with a polar angle down to about 9°. Beyond the tracker, a fine-grained sampling electromagnetic calorimeter is placed with 40 Si-W layers of 5×5 mm^2 cell size and 1.9 mm thick W plates. The hadronic calorimeter consists of 60 steel-scintillator layers (in CLICdet) or 44 layers (in CLD) with segmentation of 30×30 mm^2. A superconducting solenoid outside of the calorimeters provides 4T and 2T magnetic field for CLICdet and CLD detectors, respectively. A steel return yoke is placed outside the solenoid using six layers of RPCs with 30×30 mm^2 cells for the purpose of muon identification.

The CLICdet model was adapted for FCC-ee experimental conditions which resulted in the CLD detector. One may highlight two major modifications: First, the outer radius of the

silicon tracker was increased from 1.5 m to 2.15 m to compensate for the lower magnetic field in the detector to reach comparable tracking performance. Second, the depth of the hadronic calorimeter was decreased from 7.5 λ_I to 5.5 λ_I due to the lower collision energy of FCC-ee.

The layouts of the CLD and CLICdet detectors are shown in Figures 1 and 2, respectively.
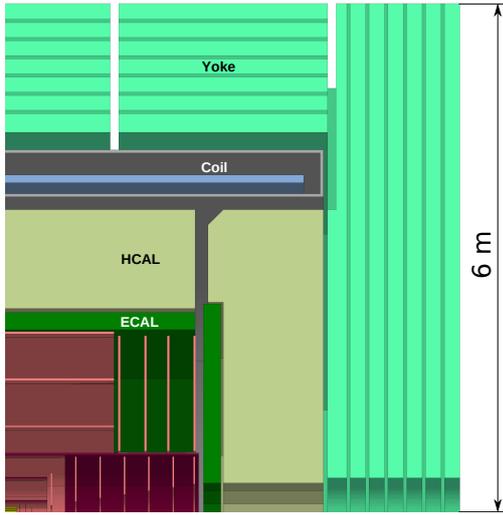
Figure 1. Vertical cross section showing the top right quadrant of the CLD detector. Details of the machine-detector interface region are not shown.
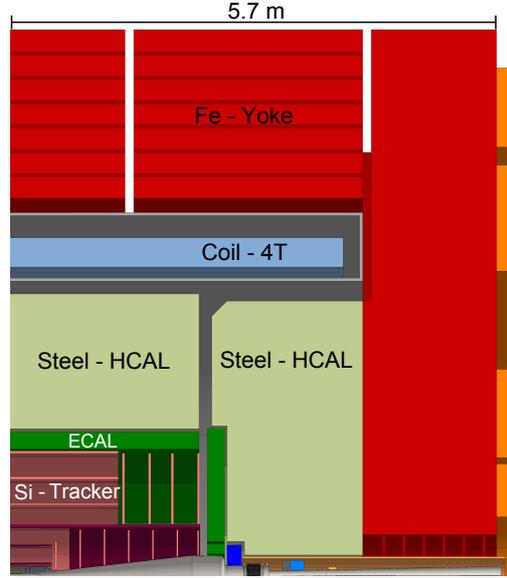
Figure 2. Vertical cross section showing the top right quadrant of the CLICdet detector. Details of the machine-detector interface region are shown.

3. Single particle identification efficiency

Particle flow algorithms aim to reconstruct each visible particle in the event using information from all subdetectors. Muons are identified using clusters of hits in the muon subdetector, tracks matched to these clusters and calorimeter clusters compatible with a minimum ionizing particle signature in ECAL and HCAL. Electron candidates consist of clusters largely contained within ECAL and tracks matched to them. Hadronic clusters in ECAL and HCAL matched to tracks are used for charged hadron determination. Non-matched hadronic clusters are assigned as neutrons, while non-matched electromagnetic clusters are considered to be photons.

The particle identification efficiency for both CLICdet and CLD detectors has been studied in single particle events separately for muons, electrons, photons and pions. The simulated particles in the events are produced with a flat angular distribution in $\cos\theta$.

To estimate particle identification efficiency, the following criteria have been used. The reconstructed type of the particle has to be the same as the "true" particle. It has to satisfy angular matching criteria $|\phi_{\text{reconstructed}} - \phi_{\text{true}}| < 2$ mrad and $|\theta_{\text{reconstructed}} - \theta_{\text{true}}| < 1$ mrad. The reconstructed transverse momentum of charged particles has to be within 5% of the transverse momentum of the "true" particle. The reconstructed energy of the photon has to be within 5 σ of the ECAL resolution.

The particle identification efficiency is studied for a few energy points. The muon efficiency is shown in Figure 3 and is larger than 99% for all energies for both detector models. The pion efficiency is shown in Figure 4 and is above 90% at low energies and reaching 93–96% at higher

energies. The pion efficiency for the CLD detector is lower by a few per cent compared to the CLICdet detector and degrades at energies above 50 GeV. This effect is caused by the thinner HCAL of the CLD detector which leads to more high momentum pions being mis-reconstructed as muons.
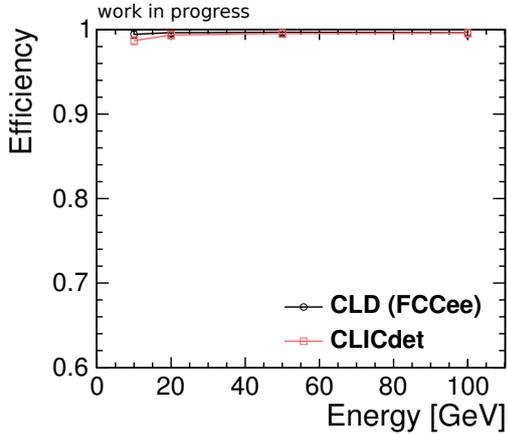
Figure 3. Muon identification efficiency as a function of energy.
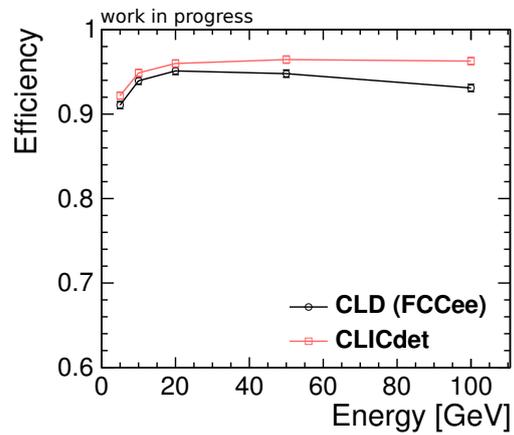
Figure 4. Pion identification efficiency as a function of energy.

Although for muons and pions the momentum is accurately reconstructed, for electrons the reconstructed energy has, due to Bremsstrahlung, a tail towards lower values compared to the true energy. A Bremsstrahlung recovery algorithm is applied which uses close-by photons (within $|\phi_{\mathrm{reconstructed}} - \phi_{\mathrm{true}}| < 20$ mrad and $|\theta_{\mathrm{reconstructed}} - \theta_{\mathrm{true}}| < 1$ mrad) to correct the electron energy by summing their energy deposits. Electrons corrected in this way have to satisfy energy matching requirements (reconstructed electron energy has to be within 5 σ of the ECAL resolution with respect to the energy of the "true" particle) instead of transverse momentum ones since part of their energy has been measured by the calorimeter only. Electrons without Bremsstrahlung have to fulfil the same requirements as muons and pions. The electron identification efficiency is shown in Figure 5 and reaches 97–98% for electrons with momentum above 50 GeV.

Photon reconstruction requires a separate treatment of events with photon conversions. If the conversion happens late in the tracking system the electron-positron pair will be reconstructed as two close-by photons since no tracks will be reconstructed in the tracker. In order to recover this kind of event the nearby electromagnetic clusters ($|\phi_{\mathrm{reconstructed}} - \phi_{\mathrm{true}}| < 20$ mrad and $|\theta_{\mathrm{reconstructed}} - \theta_{\mathrm{true}}| < 1$ mrad) are merged together and identification criteria are applied the final merged candidate. The fraction of converted photons is around 12% overall. However, merging close-by photons allows recovering the identification efficiency up to 98% for photons of 20 GeV and higher, as shown in Figure 6.

Since the CLIC collider is planned for operation up to 3 TeV centre-of-mass energy it is necessary to reconstruct leptons in the TeV range. Electron and muon efficiencies have been studied with $t\bar{t}$ events at 3 TeV with the CLICdet detector. Only direct leptons from W boson decays have been considered in the study. The reconstructed lepton has to be the same type as the "true" particle and to be matched with it in angle within $1°$. Muon and electron efficiencies as a function of energy are shown in Figures 7 and 8, respectively, for cases with and without $\gamma\gamma \rightarrow$ hadrons background, which is the dominant beam background source in the CLIC experiment. Overall good identification efficiency is observed for both high energy muons
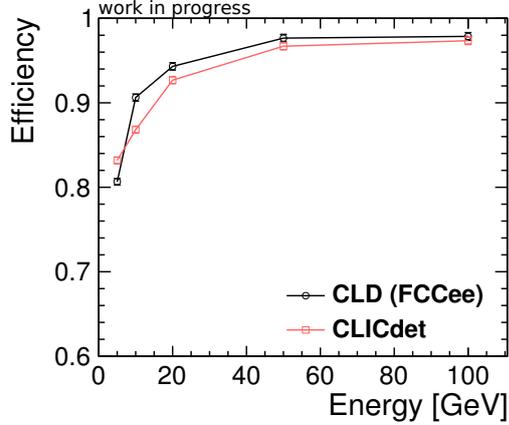
Figure 5. Electron identification efficiency as a function of energy.
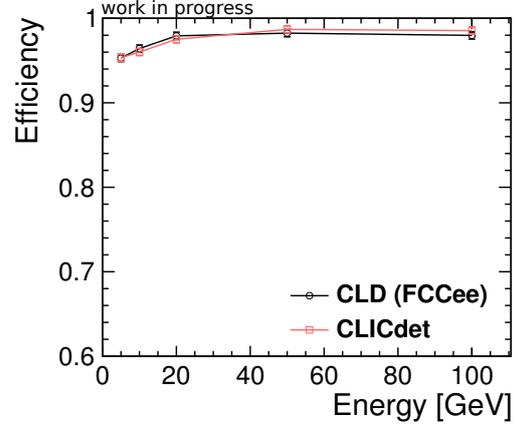
Figure 6. Photon identification efficiency as a function of energy.

and electrons.
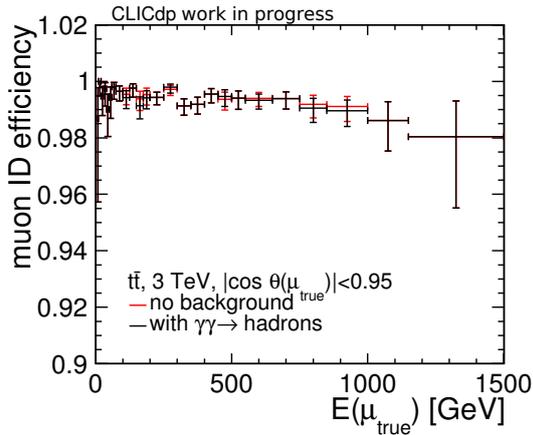
Figure 7. Muon identification efficiency in $t\bar{t}$ events at 3 TeV, with and without $\gamma\gamma \to$ hadrons background as a function of energy for $|\cos\theta(\mu_{\text{true}})| < 0.95$ with the CLICdet detector.
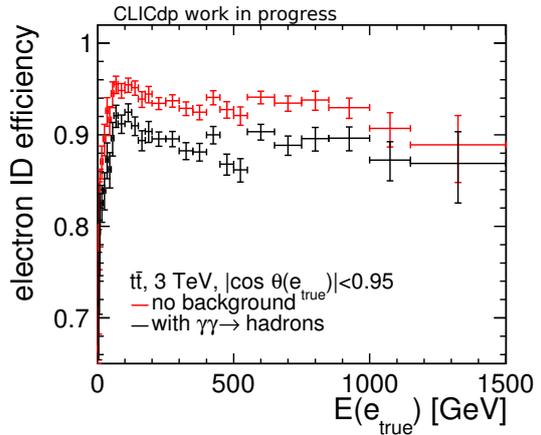
Figure 8. Electron identification efficiency in $t\bar{t}$ events at 3 TeV, with and without $\gamma\gamma \to$ hadrons background as a function of energy for $|\cos\theta(e_{\text{true}})| < 0.95$ with the CLICdet detector.

4. Jet performance

Fine-grained calorimeters and particle flow algorithms provide precise jet energy measurements that allow separation between jets originating from W and Z boson decays. The PANDORA particle flow algorithms [3, 4] use information from tracks, calorimeter clusters and hits in the muon system to reconstruct each particle within the jet. The jet performance in CLICdet and CLD is studied in dijet $e^+e^- \to q\bar{q}$ $(q = uds)$ events at different centre-of-mass energies.

To improve the energy reconstruction of hadrons a software compensation correction is applied using local energy density information provided by the high granularity of the calorimeter

system [5]. The jet energy resolution is determined by comparison the energy sum of all reconstructed particles with the sum of all stable visible particles (excluding neutrinos) on MC truth level [6].

RMS_{90} is defined as the RMS in the smallest range of the reconstructed energy containing 90% of the events [4]. This measure characterises the energy resolution of the bulk of events and is relatively insensitive to the presence of tails. Figure 9 shows that applying software compensation improves the energy resolution of jets by about 10% for most jet energies.
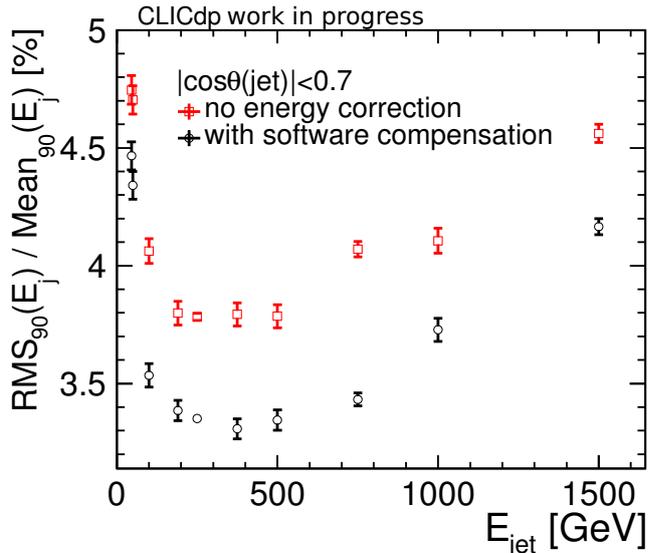
Figure 9. Jet energy resolution studied with CLICdet for jets with $|\cos\theta| < 0.7$ as a function of jet energy for $e^+e^- \to q\bar{q}$ ($q = uds$) events at different energies. Cluster reconstruction without energy correction (red) is compared to cluster reconstruction applying software compensation (black).

Comparisons of jet energy resolution as a function of $|\cos\theta|$ for CLD and CLICdet for dijets produced at 91 GeV and 380 GeV centre-of-mass energies are shown in Figures 10 and 11 respectively. The detectors have comparable performance and the jet energy resolution is 4-5% at 91 GeV and 3-4% at 380 GeV centre-of-mass energies.

The jet energy performance also has been studied at larger jet energies (up to 1.5 TeV jets) with CLICdet. The jet energy resolution as a function of $|\cos\theta|$ is shown in Figure 12. At jet energies from 190 GeV onwards the resolution is less dependent on energy. The only exception is the case of 1.5 TeV jets which has a worse resolution due to a problem in the conformal tracking algorithm. Currently work is ongoing and the jet energy resolution is expected to improve.

5. Summary
We have presented detector layouts and full simulation performance studies with single particles and dijet events of the CLICdet and CLD detectors for experiments at CLIC and FCC-ee. Both detectors demonstrate comparable performance with a particle identification efficiency above 95% for particles with momenta above 20 GeV as well as outstanding jet energy resolution of 3.5–4.5% for jet energies in the range 45–1500 GeV including the endcap region of the detectors.
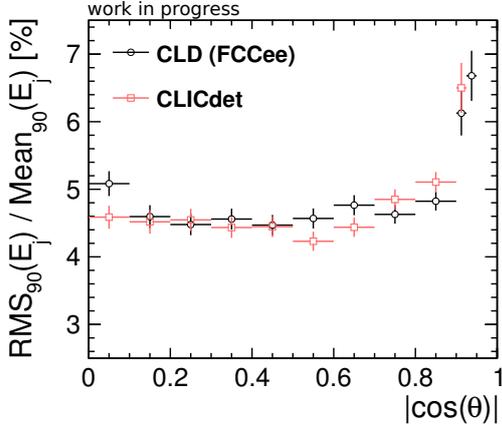
Figure 10. Jet energy resolution as a function of $|\cos\theta|$ for $e^+e^- \rightarrow q\bar{q}$ ($q = uds$) events at 91 GeV energy with CLD (black) and CLICdet (red) detectors.
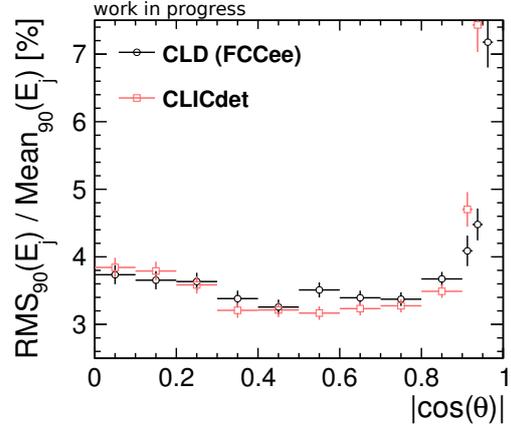
Figure 11. Jet energy resolution as a function of $|\cos\theta|$ for $e^+e^- \rightarrow q\bar{q}$ ($q = uds$) events at 380 GeV energy with CLD (black) and CLICdet (red) detectors.
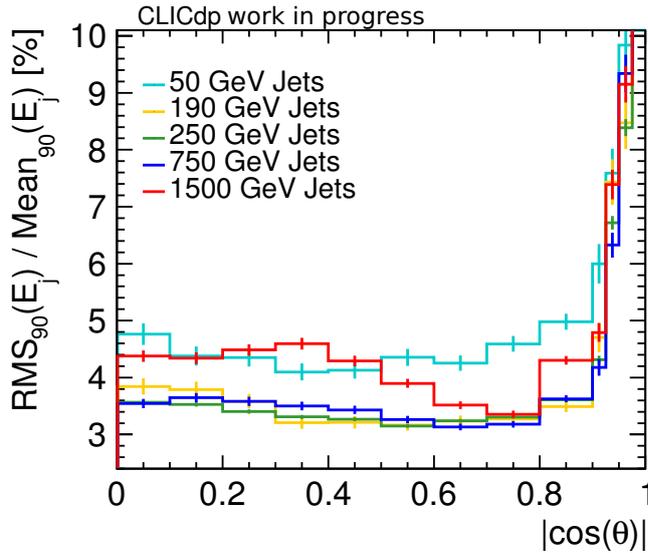
Figure 12. Jet energy resolution as a function of $|\cos\theta|$ for $e^+e^- \rightarrow q\bar{q}$ ($q = uds$) events with the CLICdet detector.

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