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Performance of particle flow calorimetry at CLIC

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ABSTRACT

The particle flow approach to calorimetry can provide unprecedented jet energy resolution at a future high energy collider, such as the International Linear Collider (ILC). However, the use of particle flow calorimetry at the proposed multi-TeV Compact Linear Collider (CLIC) poses a number of significant new challenges. At higher jet energies, detector occupancies increase, and it becomes increasingly difficult to resolve energy deposits from individual particles. The experimental conditions at CLIC are also significantly more challenging than those at previous electron–positron colliders, with increased levels of beam-induced backgrounds combined with a bunch spacing of only 0.5 ns. This paper describes the modifications made to the PandoraPFA particle flow algorithm to improve the jet energy reconstruction for jet energies above 250 GeV. It then introduces a combination of timing and p_T cuts that can be applied to reconstructed particles in order to significantly reduce the background. A systematic study is performed to understand the dependence of the jet energy resolution on the jet energy and angle, and the physics performance is assessed via a study of the energy and mass resolution of W and Z particles in the presence of background at CLIC. Finally, the missing transverse momentum resolution is presented, and the fake missing momentum is quantified. The results presented in this paper demonstrate that high granularity particle flow calorimetry leads to a robust and high resolution reconstruction of jet energies and di-jet masses at CLIC.

1. Introduction

CLIC [1] is a proposed linear collider designed to perform electron–positron collisions at centre-of-mass energies ranging from a few hundred GeV up to 3 TeV, with a luminosity of $5.9 \times 10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$ at the highest energy. The anticipated physics potential of such a collider is extremely broad. It ranges from precision tests of the Higgs and top sector, to detailed studies of new phenomena, through new particle spectroscopy, coupling measurements, threshold scans, measurement of spins and other quantum numbers. Accurate jet energy reconstruction will be crucial for this physics programme, driving the need for fine-grained calorimeters and the particle flow approach to calorimetry at CLIC.

This paper describes the performance of high granularity particle flow calorimetry at high energies and with the challenging background conditions present at CLIC. These studies build on those first reported in the context of the ILC [2]. The results presented here are based on full GEANT4 simulations of the CLIC_ILD [3] detector concept considered in the CLIC conceptual design report [1]. Results for the CLIC_SiD [4] detector concept were comparable [5].

2. The particle flow concept

Many of the interesting physics processes at CLIC will produce final states containing multiple jets, which may be accompanied by charged leptons and/or missing transverse momentum. In order to perform precision physics measurements, it is vital to be able to reconstruct the invariant masses of the jets; accurate jet mass measurements are a powerful tool for both reconstruction and identification of physics events. The goal for jet energy resolution at CLIC is that it should be sufficient to allow separation of the hadronic decays of W and Z bosons through the reconstruction of their di-jet invariant masses. This sets a challenging jet energy resolution goal of $\sigma_E/E \lesssim 5{-}3.5\%$ for 50 GeV–1 TeV jets, which is unlikely to be achievable with a traditional approach to calorimetry [2].

Measurements of jet fragmentation at LEP provide detailed information about the particle composition of jets [6,7]. In a typical jet, approximately 62% of the energy is carried by charged particles (mainly hadrons), whilst 27% is carried by photons, 10% by long-lived neutral hadrons and 1.5% by neutrinos. In a traditional approach to calorimetry, the jet energy would be obtained

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from the energies deposited in the electromagnetic and hadronic calorimeters (ECAL and HCAL respectively). This means that 72% of the energy of a typical jet would be measured with a precision limited by the relatively poor HCAL resolution of $\gtrsim 55\%/\sqrt{E/\mathrm{GeV}}$.

The particle flow approach to calorimetry aims to improve jet energy measurements by reconstructing the four-vectors of all visible particles in an event. The reconstructed jet energy is then the sum of the energies of the individual particles in the jet. At LEP, ALEPH used particle flow techniques [8] to improve the energy resolution for hadronic events. However, due to the relatively low granularity of the calorimeters, energy depositions from neutral hadrons still had to be identified as significant excesses of calorimetric energy compared to the associated charged particle tracks. Particle flow techniques are also being used by CMS [9] at the LHC.

The linear collider detector concepts extend the particle flow approach by using fine-granularity calorimeters and sophisticated software algorithms to accurately trace the individual paths of particles through the detector. The energy and momentum for each particle can then be determined from the detector subsystem in which the measurements are the most accurate. Charged particle momenta are measured in the inner detector tracker, whilst photon energy measurements are extracted from the energy deposited in the ECAL, with typical resolution $< 20\%/\sqrt{E/\mathrm{GeV}}$. The HCAL is used to measure only the 10% of jet energy carried by long-lived neutral hadrons. Particle flow calorimetry can therefore offer a significant improvement to jet energy measurements, compared to traditional calorimetry. For jet energies above about 100 GeV, the jet energy resolution is limited by the mistakes in the assignment of the energies to the different reconstructed particles, termed *confusion*, rather than the intrinsic resolution of the calorimeters.

3. Particle flow implementation

The CLIC_ILD detector concept represents a possible configuration for a detector suitable for particle flow calorimetry, with calorimeters designed to provide longitudinal and transverse granularity rather than energy resolution alone. The main tracking detector is a time projection chamber (TPC) with inner and outer radii of 0.33 m and 1.80 m respectively and a half-length of 2.30 m. The ECAL is a silicon–tungsten sampling calorimeter consisting of 29 layers, with the silicon divided into $5 \times 5\ \mathrm{mm}^2$ pixels. At normal incidence, the ECAL corresponds to 23 radiation lengths (X_0) and approximately one nuclear interaction length (λ_I). The HCAL consists of 75 barrel-layers and 60 endcap-layers of absorber material and polystyrene scintillator, divided into $30 \times 30\ \mathrm{mm}^2$ tiles. The absorber material in the endcap is iron, whilst tungsten is used in the barrel to provide a more compact calorimeter. At normal incidence, the HCAL corresponds to approximately $8\lambda_I$. The calorimeter barrel is surrounded by a solenoid, providing a 4 T magnetic field, and the entire detector is surrounded by an iron return yoke, which is instrumented to allow muon identification.

Fig. 1 shows the typical topology of a simulated 250 GeV jet in CLIC_ILD, with labels identifying a number of the constituent particles. The figure shows inner detector tracks, representing the paths of charged particles in the TPC. These tracks can be extrapolated by eye and associated with clusters of calorimeter energy deposits in the fine granularity ECAL and HCAL. Photons produce energy deposits with characteristic longitudinal and transverse profiles in the ECAL and can be cleanly resolved by eye, due to their small transverse spread. HCAL clusters that cannot be associated with TPC tracks represent neutral hadrons. The challenge is to develop software algorithms to automate the reconstruction of the individual particles from the tracks and energy deposits in the calorimeters.

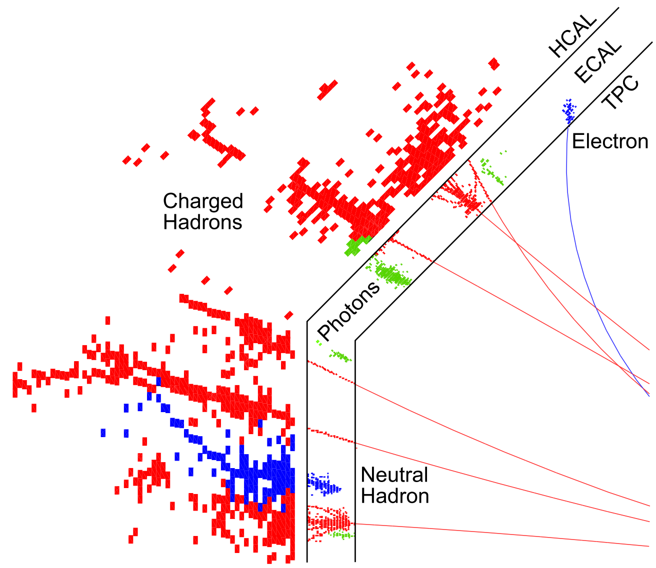

Fig. 1. A typical simulated 250 GeV jet in CLIC_ILD, with labels identifying constituent particles.

Particle flow calorimetry demands high performance software. The final jet energy resolution is strongly dependent on both the detector granularity and the quality of the particle flow reconstruction algorithms. These algorithms must be able to exploit the granularity to merge together energy deposits from individual particles, with minimal confusion. A logical approach is to implement a series of decoupled pattern-recognition algorithms, each designed to carefully reconstruct a specific particle topology. The implementation of a large number of efficient pattern-recognition algorithms drives the need for a central software framework, which can take care of memory-management and book-keeping issues. Such a framework helps to keep each algorithm simple and focused on its specific pattern-recognition task.

The PandoraPFA C++ Software Development Kit (SDK) [10] for particle flow calorimetry is a robust and efficient framework for developing and running algorithms for particle flow reconstruction. It consists of a single framework library and a number of carefully designed Application Programming Interfaces (APIs). It was designed with the twin aims of simplifying the development of efficient pattern-recognition algorithms and allowing easy application of existing algorithms to different detectors, different software environments or even different pattern-recognition tasks. Using the PandoraPFA SDK means that the pattern-recognition reconstruction is divided into three distinct sections, which communicate via the PandoraPFA APIs.

A PandoraPFA client application uses the APIs to pass details of the tracks and calorimeter cells in an event to the PandoraPFA framework. The framework then creates and manages its own lists of self-describing PandoraPFA tracks and cells. These objects are then accessed, in a controlled manner, by the PandoraPFA algorithms. The algorithms control the pattern-recognition reconstruction and determine how the tracks and cells are used to build clusters and, finally, reconstructed particles (termed particle flow objects, or PFOs). Importantly, the algorithms can only access or manipulate the PandoraPFA objects by using APIs to request services from the framework. Typical requests would be to create or delete clusters, merge multiple clusters, split clusters or associate tracks with clusters. This software engineering approach means that the framework can provide all memory-management and book-keeping operations in an efficient and well-tested manner.