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Detector requirements and R&D challenges at CLIC

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The results from the LHC experiments should give us an idea of the physics at the TeV scale. A lepton-collider at these energies will then be required to complement the information from the LHC, and to fully understand the new physics. The Compact Linear Collider (CLIC) with a center-of-mass energy of up to 3 TeV is a suitable concept for such a future e^+-e^--linear-collider. The detector requirements for precision measurements at multi-TeV energies in general and the special experimental conditions at the CLIC accelerator open a rich field of detector R&D opportunities. Some of these requirements go beyond those for a detector at the ILC. Nevertheless, the R&D work that is being performed for the ILC detectors is an excellent starting point for these studies.

The specific challenges are for example the use of dense calorimeter absorber materials for excellent jet energy resolutions up to the highest energies and low material silicon detectors with small pixel sizes. In addition, the high machine-induced-background levels in combination with the short time of only 0.5 ns between two bunch crossings at CLIC will require precise time-stamping capabilities for all sub-detectors.

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1. Introduction

A future linear collider like the Compact LInear Collider (CLIC) [1] will be complementary to the LHC by allowing precision measurements on previously discovered particles and probing the parameter space of models beyond the Standard Model (SM). The requirements for a detector at CLIC are inspired by typical measurements at the TeV scale. The jet energy resolution should be adequate to distinguish di-jet pairs originating from Z or W bosons as well as a light Higgs boson which translates to a resolution of $\sigma_E/E \approx 3.5-5\%$ for jet energies of 50 GeV up to 1 TeV. The momentum resolution requirement is driven by the precise measurement of leptonic final states like the Higgs mass measurement through Z recoil, where the Z decays into muons or electrons, or the determination of slepton masses. This leads to a required resolution of $\sigma_{p_\mathrm{T}}/p_\mathrm{T}^2 \approx 2\times10^{-5}\,\mathrm{GeV}^{-1}$ in order to not be the dominating uncertainty. The impact parameter resolution should allow for excellent flavor tagging through precise measurements of displaced vertices. The requirement is usually quoted as $\sigma_\mathrm{IP} \approx 5\,\mu\mathrm{m} \oplus 15\,\mu\mathrm{m}\cdot\mathrm{GeV}/(p\ \sin^{3/2}\theta)$, where p is the momentum and θ is the polar angle of the particle.

The International Large Detector concept (ILD) [2] and the Silicon Detector concept (SiD) [3] developed for the International Linear Collider (ILC) [4] both fulfill these requirements and are designed in view of the particle flow paradigm using highly granular calorimeters to identify the clusters of individual particles [5]. These concepts were used as a starting point for the CLIC detector studies and resulted in the CLIC_ILD [6] and CLIC_SiD [7] concepts presented and studied in the CLIC conceptual design report [8]. Some of the required modifications to the detector concepts, like a deeper hadronic calorimeter (HCal), are due to the higher jet energies resulting from the higher center of mass energy of 3 TeV at CLIC compared to 500 GeV at the ILC. Most of the challenges for the detector arise from the beam structure at CLIC, though. The high density of the beams required for high luminosity leads to beam-beam interactions and the creation of beamstrahlung [9] which results in a very large number of coherent and incoherent electron pairs of which 60 particles per bunch crossing are within the detector acceptance. Furthermore there are about 3 $\gamma\gamma \to$ hadrons interactions [10] per bunch crossing at CLIC resulting in 54 particles per bunch crossing within the detector acceptance. In addition, the time structure of the beam with only 0.5 ns bunch spacing, coming in trains of 312 bunches with a frequency of 50 Hz, means that the read-out will always integrate over several bunch crossings and thus accumulate considerable pile-up of beam-induced background.

As an example, the specific detector requirements at CLIC are discussed for the vertex detector and the HCal.

2. Vertex detector

The required impact parameter resolution can be achieved by a high single point resolution, i.e. small pixels of the order of $20\times20\,\mu\mathrm{m}^2$ with analog readout, combined with a very low material budget of less than 0.2% X_0 per layer. The pulsed beam structure allows for the use of power pulsing in the electronics to reduce the amount of material for cooling. An additional challenge for the design of the vertex detector at CLIC is the occupancy caused by the beam-induced backgrounds. Figure 1 (left) shows the angular distribution of the particles originating from the various back-

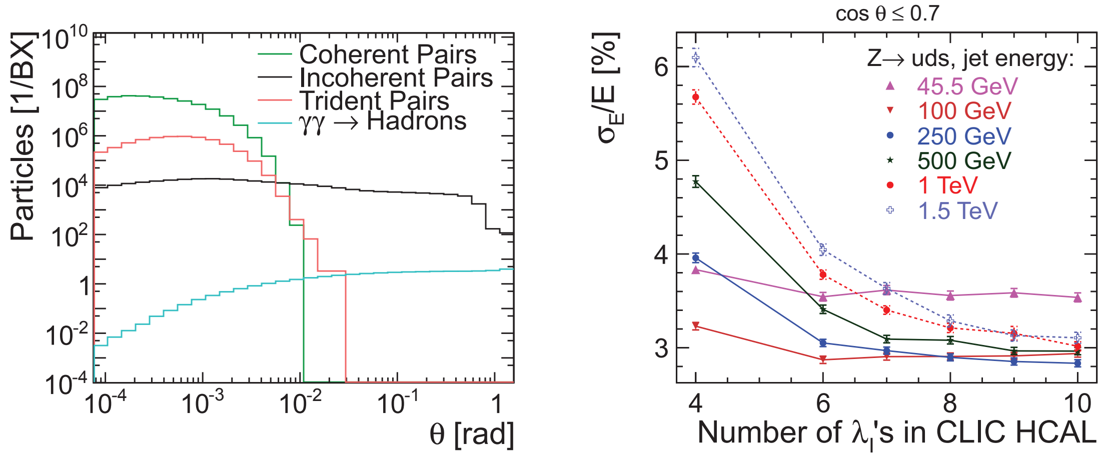

Figure 1: Distribution of the polar angle θ of the particles originating from pair and $\gamma\gamma \rightarrow$ hadrons background (left). Jet energy resolution achieved with PandoraPFA in di-jet decays from off-shell Z bosons decaying at rest using the ILD model with varying HCal thicknesses (right).

grounds at CLIC. The placement of the vertex detector layers has to be made carefully to avoid most of this background and to achieve a maximum occupancy of less than 2% per cell in one bunch train. Time stamping of the order of 10 ns will help the pattern recognition and background rejection.

The technology that will be chosen for CLIC will have to combine fast time stamping and small pixel sizes in a thin design, where the ability to use power pulsing is a key ingredient to achieve the material budget requirement. While no technology is currently available that would meet all these requirements, several options are being considered, like thinned hybrid pixels with through-silicon-via interconnects or fully 3D integrated pixels.

3. Calorimetry

Figure 1 (right) shows the jet energy resolution achieved with PandoraPFA [11] for different jet energies and varying HCal depths using di-jet events, simulated in a modified version of the ILD detector model. The jet energy resolution is improving for a deeper HCal as long as the leakage is dominating the energy resolution and approaches the intrinsic resolution determined by the sampling used in the calorimeter. For typical jet energies at CLIC of up to 1 TeV an HCal depth of at least 7.5 λ_I is desirable in order to avoid being dominated by leakage. This is considerably deeper than what has been foreseen by the ILC detector concepts for the HCal: 5.5 λ_I in the case of ILD and only 4.8 λ_I in the case of SiD.

A good energy measurement requires that both the electromagnetic calorimeter and the hadronic calorimeter are placed inside the solenoid coil to avoid a dead space of about 2 λ_I at the start of the shower development. On the other hand, for a high magnetic field a very large coil radius becomes prohibitive for technical reasons. An alternative to a larger coil radius is to use a denser material than steel to achieve sufficient HCal depth within the available space. One possibility is to use tungsten with a λ_I of about 10 cm, compared to 17 cm for steel.

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Choosing a different absorber material means that the absorber thickness has to be modified in order to optimize the sampling ratio. Simulation studies looking at different materials and sampling ratios concluded that for the given coil radii of the ILC detector models, assuming a gap size of 6.5 mm for each active layer, 1 cm thick tungsten absorber plates yield the best energy resolution for CLIC jet and provide the required 7.5 λ_I [12].

Hadronic showers in tungsten have a larger neutron content compared to steel which might lead to a larger fraction of late energy deposits, depending on the active material used. Considering the time structure of the CLIC beams it is important to verify the time structure of the showers assumed by simulation models with test beam data. Thus, a tungsten HCal prototype corresponding to an HCal depth of about 4.8 λ_I has been built within CALICE [13]. The first test beam campaigns at the CERN PS and at the CERN SPS using scintillators with silicon photo multipliers as active layers have been successfully completed in 2010 and 2011.

4. Event reconstruction in presence of backgrounds

The $\gamma\gamma \to$ hadrons background events create, due to the duration of the read-out, a large amount of pile-up throughout the detector, especially in the forward region, and require special attention in order to be suppressed during event reconstruction. Even when assuming a short read-out window of 10 ns throughout the detector, the reconstructed energy from this pile-up amounts to about 1.4 TeV. This will not only affect analyses looking for missing energy but also degrade the jet energy resolution in general. While a cut on the transverse momentum may remove many of the particles originating from $\gamma\gamma \to$ hadrons, it can also cut away significant parts of the interesting physics event. Instead, the mean time of the reconstructed clusters can be used to reject individual clusters that are not in time with the signal event. Assuming a time resolution of 1 ns for the calorimeter hits will yield a sub-ns resolution for the mean cluster time which allows an efficient removal of reconstructed particles from $\gamma\gamma \to$ hadrons. Figure 2 shows the effect of applying these timing cuts in case of an event with two charged heavy Higgs bosons produced at a center-of-mass energy of 3 TeV.

This background rejection method is only possible in highly granular calorimeters which allow to identify clusters of individual particles, like the particle flow calorimeters proposed for the CLIC detector concepts. In addition, the readout technology for the calorimeter has to provide time stamping of the order of 1 ns and multi-hit capabilities in the endcaps, where the occupancy is highest due to the beam-induced background.

5. Conclusion

The high center-of-mass energy and the beam conditions at CLIC impose several very stringent detector requirements. They require dedicated R&D for the pixel detectors as well as the calorimeters to accommodate the time stamping requirements to mitigate the effect of the beam-induced backgrounds. In addition, denser absorber materials need to be explored for the hadronic calorimeters to keep the coil design feasible.

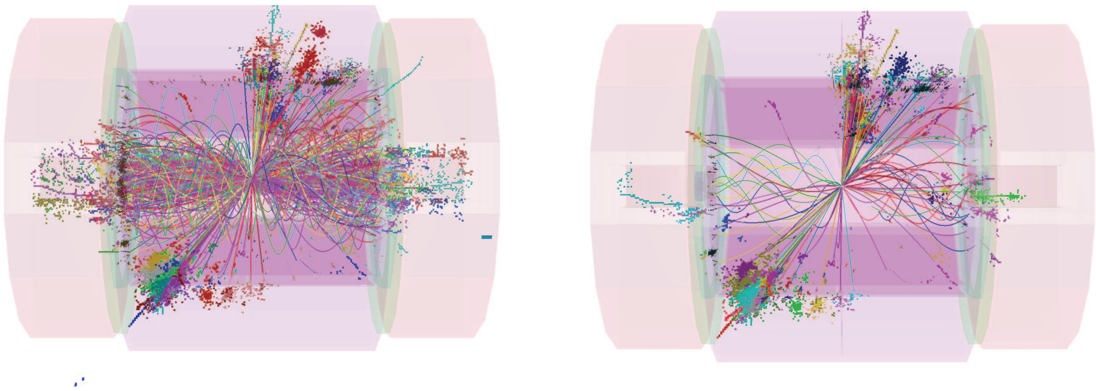

Figure 2: Reconstructed particles in a simulated $e^+e^- \rightarrow H^+H^- \rightarrow t\bar{b}b\bar{t}$ event at 3 TeV in the CLIC_ILD detector concept with background from $\gamma\gamma \rightarrow$ hadrons overlaid corresponding to 10 ns before (left) and after applying selection cuts based on the reconstructed cluster times (right).

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