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

Oleksandr Viazlo
on behalf of the CLICdp and FCC-ee collaborations

CERN

22 May 2018
Introduction

CLIC
- Compact Linear Collider ($e^- e^+$)
- 3 energy stages: 380 GeV, 1.5 TeV, 3 TeV
- bunch trains are 156 ns long and distance between trains is 20 ms → Power Pulsing of electronics

FCC-ee
- Future Circular Collider ($e^- e^+$)
- 4 energy stages: $Z$, $WW$, $HZ$, $t\bar{t}$
- Bunch spacing: 20 - 8533 ns

Both experiments demand state-of-the-art detectors with:
- low-material tracking system
- precise calorimetery

CLICdet - proposed detector model for CLIC with 4 Tesla magnetic field
CLD - detector model for FCC-ee derived from CLICdet and optimized for FCC-ee experimental conditions

Maximum possible detector magnetic field at FCCee is 2 Tesla (to preserve beam emittance)
CLD and CLICdet detector models

- Full silicon tracking system - provides $\geq 12$ hits per track
  - $R_{outer} = 1.5\, \text{m} - \text{CLICdet}$
  - $R_{outer} = 2.1\, \text{m} - \text{CLD}$
  
  increased material budget for 50% in VTX - CLD

- Fine-grained ECAL and HCAL optimised for particle flow reconstruction

- Superconducting solenoid is outside of the calorimeters
  - 4T field - CLICdet
  - 2T field - CLD

- Steel return yoke with muon chambers
  - 2 m thickness - CLICdet
  - 1.5 m thickness - CLD

- Support structures, cables and services are implemented in the simulation models
CLD and CLICdet detector models

- **Full silicon tracking system** - provides $\geq 12$ hits per track
  - $R_{outer} = 1.5\,\text{m}$ - CLICdet
  - $R_{outer} = 2.1\,\text{m}$ - CLD
  - increased material budget for 50% in VTX - CLD

- **Fine-grained ECAL and HCAL** optimised for particle flow reconstruction

- **Superconducting solenoid** is outside of the calorimeters
  - 4T field - CLICdet
  - 2T field - CLD

- **Steel return yoke with muon chambers**
  - 2 m thickness - CLICdet
  - 1.5 m thickness - CLD

- **Support structures, cables and services** are implemented in the simulation models
Electromagnetic Calorimeter
- Si-W sampling calorimeter
- cell size 5x5 mm$^2$
- 40 layers (1.9 mm thick W plates)
- Depth: 22 $\lambda_I$, 1 $\lambda_I$, 20 cm

Hadronic Calorimeter
- Scintillator-steel sampling calorimeter
- cell size 30x30 mm$^2$
- 60 layers (CLICdet) / 44 layers (CLD)
  (19 mm thick steel plates)
- Depth: 7.5 $\lambda_I$ (CLICdet) / 5.5 $\lambda_I$ (CLD)
Simulation and reconstruction software tools

- Performance studies of CLICdet and CLD detector models were done with iLCSoft software used by the CLIC and ILC community.

- Detector geometry description and event simulation: DD4hep

- Event Reconstruction: Marlin

- Track Pattern recognition: ConformalTracking

- Particle Flow Reconstruction: PandoraPFA
  - PandoraPFA is used both for jet and isolated particle ID studies

- Geometry of detector models are implemented in lgeo package:
  - CLIC_o3_v14
  - FCCee_o1_v03

Detector performances have been studied with full detector simulation
Transverse momentum resolution for single muons with CLICdet and CLD detector models as a function of $\theta$ for 1, 10 and 100 GeV energies

Overall comparable tracking performance of both detectors

Achieved momentum resolutions for 100 GeV muons at $\theta = 90^\circ$:
- $3 \times 10^{-5}$ GeV$^{-1}$ - CLICdet
- $4 \times 10^{-5}$ GeV$^{-1}$ - CLD
Particle ID efficiency

- Single isolated particles
- Leptons in $t\bar{t}$ events
Single particle identification efficiency

- Efficiency = fraction of matched reconstructed particles out of the simulated MC particles:
  - reconstructed particle of the same type as simulated MC particle
  - angular matching: $\Delta \theta < 1$ mrad and $\Delta \phi < 2$ mrad
  - energy matching:
    - charged particles: $|p_T^{\text{truth}} - p_T^{\text{PFO}}| < 5\% p_T^{\text{truth}}$
    - photons: $\Delta E < 5 \times \sigma(\text{ECal}) \approx 0.75 \times \sqrt{E}$

Sample: single particles with flat $\cos(\theta)$ distribution and fixed energy

- >99% muon efficiency and 93-96% pion efficiency for $E > 10$ GeV
- Inefficiency at high energies with CLD is caused by a larger rate of pions being mis-reconstructed as muons
Photon merging procedure is used to recover inefficiency due to photon conversion and electron Bremsstrahlung.

Pandora electron ID parameters were retuned in order to recover hard electron Bremsstrahlung (loosen maximum track-cluster distance requirement to recover events when a track is not associated to either of EM clusters).

- > 95% efficiency for >10 GeV photons and >20 GeV electrons
- Further optimization of electron Bremsstrahlung recovery procedure may improve electron efficiency (e.g. at lower energies)
Lepton identification efficiency in $t\bar{t}$ events at CLIC

- Lepton ID efficiency in $t\bar{t}$ events at 3 TeV at CLIC
- Only direct leptons from $W$ decays are considered
- Requirement of angular matching within $1^\circ$ is imposed.

![Graph showing muon and electron ID efficiency](image)

- Muons are identified with more than 98% efficiency for all energies
- Electrons are identified with 90-95% efficiency at energies of 20 GeV and higher
- Presence of beam background doesn’t affect muon ID while electron ID decreases by about 5%
Jet performance

- *Software compensation
- *Jet Energy Resolution
Software compensation:  
- Electromagnetic component of shower typically denser  
- Software compensation reweights hits in HCAL depending on the hit energy density  
- Weights are calculated by formula: \( \omega(\rho) = p_1 \exp(p_2 \rho) + p_3 \)  
  where each parameter is an energy dependent  
  \( \rightarrow \) 9 different parameters are used in total

Detector specific software compensation weights were obtained for CLICdet and CLD.
Software compensation weights derived using several fully simulated neutron and K0L single particle datasets

Mean and resolution after software compensation largely improved

Software compensation corrects for nonlinear response of hadrons on the fly
Dijet events of a Z-like particle decaying into pair of light quarks (u, d, s) at several centre-of-mass energies

- Ratio of total reconstructed energy to total simulated energy (excluding neutrinos)
- Software compensation provides reconstruction of total energy within 0.5% accuracy in light-quark dijet sample.
Dijet events of a Z-like particle decaying into pair of light quarks (u, d, s) at several centre-of-mass energies.

Comparing resolution for both detectors:
- Jet energy resolution in barrel region:
  - 45.5 GeV jets: 4-5 %
  - 190 GeV jets: 3-4 %

Jet energy ($E_j$) is measured as a half of total energy ($E_{jj}$) of $Z \rightarrow q\bar{q}$ (q=u,d,s) di-jet event

$$\frac{\text{RMS}_{90}(E_j)}{\text{mean}_{90}(E_j)} = \frac{\text{RMS}_{90}(E_{jj})}{\text{mean}_{90}(E_{jj})} \sqrt{2}$$
Default Software compensation are tuned for hadrons up to 100 GeV (optimized for ILD detector at ILC), at CLIC expect to reach higher hadron energies, at 3 TeV sometimes beyond 500 GeV → extend applicability range and retune for CLIC.

Excellent jet energy resolution (3.5-4.5 %) for most jet energies up to the endcaps (\(|\cos(\theta)| > 0.925\))

Conformal tracking is not yet fully efficient at 1500 GeV and work is ongoing → jet energy resolution is expected to become better.
Software compensation improves jet energy resolution within the whole $\theta$ range in all energies.

- Improvement reaches 10-25% in barrel region.
- Software compensation performs well even with high jet energies.
Performance of CLICdet and CLD detectors have been studied with PandoraPFA with isolated single particles and dijet events:

- Good single particle ID efficiency for both detectors (>95% from 20 GeV for charged particles)
- Excellent jet energy resolution (3.5-4.5 %) for most jet energies up to the endcaps

Overall calorimetry performance of CLD detector (FCCee) is similar to CLICdet

Software compensation:

- improves jet energy resolution by 10-25%
- provides reconstruction of total energy in dijet events with accuracy of 0.5%
- performs well even at high jet energies (tested up to 3 TeV centre-of-mass-energy)

Thank you for your attention!
### Overall dimensions of CLIC and FCC-ee detectors

<table>
<thead>
<tr>
<th></th>
<th>CLICdet</th>
<th>CLD</th>
</tr>
</thead>
<tbody>
<tr>
<td>VTX Barrel</td>
<td>31-60 mm</td>
<td>17-59 mm</td>
</tr>
<tr>
<td>VTX Endcap</td>
<td>Spirals</td>
<td>Disks</td>
</tr>
<tr>
<td>Tracker radius</td>
<td>1486 mm</td>
<td>2100 mm</td>
</tr>
<tr>
<td>ECAL thickness</td>
<td>40 layers, 22 X₀</td>
<td>40 layers, 22 X₀</td>
</tr>
<tr>
<td>HCAL thickness</td>
<td>60 layers, 7.5 λᵢ</td>
<td>44 layers, 5.5 λᵢ</td>
</tr>
<tr>
<td>Yoke thickness</td>
<td>1989 mm</td>
<td>1521 mm</td>
</tr>
<tr>
<td>MDI (forward region)</td>
<td></td>
<td>&lt; 150 mrad</td>
</tr>
<tr>
<td>Solenoid field</td>
<td>4 Tesla</td>
<td>2 Tesla</td>
</tr>
</tbody>
</table>
Pion identification efficiency

- Pion ID efficiency and inefficiency as function of $\cos(\theta)$

- High momentum pions more often are misreconstructed as muons in barrel
Electron identification efficiency

- Electron ID efficiency and inefficiency as function of $\cos(\theta)$

- Inefficiency for high-momentum electrons can be recovered by better Bremsstrahlung recovery algorithm
Electron identification efficiency (Pandora track-cluster association algorithm)

- in 10-13% of events no charged PFO is reconstructed in the event
- track-cluster association algorithm fails to attach track to cluster (as shown on the right)
- in 3-6% of events fake “pion” is reconstructed
- in calorimeter transition region a small fraction of electrons is reconstructed as “pions”
Conformal tracking is used as the main track pattern recognition algorithm at CLIC.

Cellular automaton is used to perform straight line search.

\[ u = \frac{x}{x^2 + y^2} \]
\[ v = \frac{y}{x^2 + y^2} \]

Track fitting is done in the conformal space.

Hits from the Vertex

Hits from the Tracker
CLD detector layout: x-y view
## CLD vs CLICdet overall dimensions

<table>
<thead>
<tr>
<th>Concept</th>
<th>CLICdet</th>
<th>CLD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertex inner radius [mm]</td>
<td>31</td>
<td>17</td>
</tr>
<tr>
<td>Tracker technology</td>
<td>Silicon</td>
<td>Silicon</td>
</tr>
<tr>
<td>Tracker half length [m]</td>
<td>2.2</td>
<td>2.2</td>
</tr>
<tr>
<td>Tracker outer radius [m]</td>
<td>1.5</td>
<td>2.1</td>
</tr>
<tr>
<td>Inner tracker support cylinder radius [m]</td>
<td>0.575</td>
<td>0.675</td>
</tr>
<tr>
<td>ECAL absorber</td>
<td>W</td>
<td>W</td>
</tr>
<tr>
<td>ECAL $X_0$</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>ECAL barrel $r_{\text{min}}$ [m]</td>
<td>1.5</td>
<td>2.15</td>
</tr>
<tr>
<td>ECAL barrel $\Delta r$ [mm]</td>
<td>202</td>
<td>202</td>
</tr>
<tr>
<td>ECAL endcap $z_{\text{min}}$ [m]</td>
<td>2.31</td>
<td>2.31</td>
</tr>
<tr>
<td>ECAL endcap $\Delta z$ [mm]</td>
<td>202</td>
<td>202</td>
</tr>
<tr>
<td>HCAL absorber</td>
<td>Fe</td>
<td>Fe</td>
</tr>
<tr>
<td>HCAL $\lambda_l$</td>
<td>7.5</td>
<td>5.5</td>
</tr>
<tr>
<td>HCAL barrel $r_{\text{min}}$ [m]</td>
<td>1.74</td>
<td>2.40</td>
</tr>
<tr>
<td>HCAL barrel $\Delta r$ [mm]</td>
<td>1590</td>
<td>1166</td>
</tr>
<tr>
<td>HCAL endcap $z_{\text{min}}$ [m]</td>
<td>2.4</td>
<td>2.4</td>
</tr>
<tr>
<td>HCAL endcap $\Delta z$ [mm]</td>
<td>1590</td>
<td>1166</td>
</tr>
<tr>
<td>Solenoid field [T]</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Solenoid bore radius [m]</td>
<td>3.5</td>
<td>3.7</td>
</tr>
<tr>
<td>Solenoid length [m]</td>
<td>8.3</td>
<td>7.4</td>
</tr>
<tr>
<td>Overall height [m]</td>
<td>12.9</td>
<td>12.0</td>
</tr>
<tr>
<td>Overall length [m]</td>
<td>11.4</td>
<td>10.6</td>
</tr>
</tbody>
</table>
Jet energy resolution: CLIC specific SWC weights

- Comparable performance for jets up to 190 GeV
- Improvement of jet energy resolutions by around 10% for larger jet energies
- Achieve jet energy resolution between 3.1 % and 4.5 % with CLIC tuned weights
Increasing magnetic field of detector significantly improves jet energy resolution
There are three main sources of beam related backgrounds at CLIC:

- $e^+ e^-$ pairs which are predominantly produced with low transverse momenta $p_T$
- $\gamma\gamma \rightarrow$ hadrons (from the interaction of real and virtual photons from the colliding beams) which result in pile-up of low energy particles with $p_T < 5$ GeV
- beam halo muons