CLD detector model overview of layout and performances

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CLD - detector model for FCC-ee derived from CLICdet model and optimized for FCC-ee experimental conditions

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**CLIC**

- Compact Linear Collider ($e^- e^+$)
- 3 energy stages: 380 GeV, 1.5 TeV, 3 TeV
- 156 ns long bunch trains; 20 ms distance between trains → Power Pulsing of electronics → Air cooling of Vertex detector
- CLICdet - proposed detector for CLIC

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**FCC-ee**

- Future Circular Collider ($e^- e^+$)
- 4 energy stages: 91 - 365 GeV → thinner calorimeter is sufficient
- Bunch spacing: 20 - 3396 ns

Both experiments demand state-of-the-art detectors with:

- low-material tracking system
- precise calorimetry
Detector constraints from the FCC-ee machine design

- In order to maximize luminosity final focusing quadrupole chosen to be at 2.2 m from IP - **inside the detector**

- Compensating solenoid to prevent emittance blow-up from detector magnetic field due to non-zero crossing angle is even closer to the IP → **forward region within 150 mrad is reserved for Machine-Detector Interface**

- Constrains the **maximum possible detector magnetic field to 2T** (while the CLIC proposal assumes 4T magnetic field)
CLD detector layout

→ Tracking system
→ Calorimetry
→ The magnet and muon system
- Full silicon tracking system - provides $\geq 12$ hits per track
- Fine-grained ECAL and HCAL optimised for particle flow reconstruction
- Superconducting solenoid is outside of the calorimeter
- Steel return yoke with muon chambers
- Forward detector region ($< 150$ mrad) is reserved for Machine-Detector Interface (accommodates LumiCal)
- Support structures, cables and services are included in the model
Tracking system

Vertex detector

- Silicon pixels: 25x25μm²
- Single-point resolution: 3 μm
- 3 double layers in barrel:
  - r = 17, 37, 57 mm
- 3 double endcap disks per side:
  - z = 160, 230, 300 mm
- Material budget: 0.6% X₀ per double layer

Tracker detector

- Silicon pixel and microstrips detector
- Inner Tracker:
  - 3 barrel layers, 7 disks per side
- Outer Tracker:
  - 3 barrel layers, 4 disks per side
- Single-point resolution:
  - 7 μm x 90 μm
  - except 1st IT disk: 5 μm x 5 μm
- Material: 1.1-1.6% X₀ per layer
**Electromagnetic Calorimeter**
- Si-W sampling calorimeter
- cell size 5x5 mm²
- 40 layers (1.9 mm thick W plates)
- Depth: 22 $X_0$, 1 $\lambda_I$, 20 cm

**Hadronic Calorimeter**
- Scintillator-steel sampling calorimeter
- cell size 30x30 mm²
- 44 layers (19 mm thick steel plates)
- Depth: 5.5 $\lambda_I$, 117 cm (inspired by ILD)
The magnet and muon system

The magnet system

- Superconducting coil outside calorimeter (90 mm aluminium thick coil)
- Return yoke (1.5 m thick steel)
- The simulation model assumes:
  - 2 T homogeneous field in the tracker region
  - 1 T field in the yoke barrel
  - no field in the yoke endcaps

The muon system

- 6 layers of muon chambers (RPC)
- Cell size: 30 x 30 mm$^2$
For performance study of the CLD detector for FCC-ee one can benefit from the fully functional and well tested 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**

Up-to-date geometry of detector model implemented in lcgeo package: **FCCee_o1_v02**

Tracking and calorimetry performances have been studied with full detector simulation
Tracking performance

- Momentum and $d_0$ resolutions
- Efficiency for single muons
- Efficiency in complex events
Momentum and $d_0$ resolutions

- Statistics used: 10k single muons at fixed energy and $\theta$ for each datapoint

- Achieved resolutions for 100 GeV muons in the barrel
  - momentum resolution: $4 \times 10^{-5}$ GeV$^{-1}$
  - transverse impact parameter resolution: $< 1 \mu m$
Tracking efficiency for single muons

- Efficiency = fraction of reconstructed particles out of the reconstructable MC particles
- Reconstructable particles: stable MC particles with $p_T > 0.1$ GeV/c and $|\cos(\theta)| < 0.99$ which left at least 4 unique hits in tracking system
- Statistics used: 2M single muons

Efficiency = fraction of reconstructed particles out of the reconstructable MC particles

Reconstructable particles: stable MC particles with $p_T > 0.1$ GeV/c and $|\cos(\theta)| < 0.99$ which left at least 4 unique hits in tracking system

Statistics used: 2M single muons

Fully efficient tracking from 700 MeV over the whole $\theta$ range
Efficiency = fraction of pure reconstructed particles out of the reconstructable MC particles
Pure reconstructed particles: $\geqslant 75\%$ of hits from track are associated to the simulated MC particle

Tracking efficiency for $Z$-like boson events decaying at rest into light quarks:

- $m_Z = 91$ GeV
- $m_Z = 380$ GeV

- Fully efficient tracking from 700 MeV

Selection cuts:
- $10 < \theta < 170$
- vertex $R < 50$ mm
Calorimetry performance

- Single particle identification efficiency
- Jet energy resolution
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 93-95% pion efficiency for $E > 10$ GeV
- Pion inefficiency due to misreconstruction of particle type
Photon merging procedure is used to recover inefficiency due to photon conversion and electron Bremsstrahlung.

Pandora parameters were retuned in order to recover some electron inefficiency due to Bremsstrahlung.

> 95% photons and 93-95% electron efficiency for E > 10 GeV
Z-like boson events decaying at rest into light quarks (two back-to-back jets)

Jet energy resolution in barrel region:
- 45.5 GeV jets: 4-4.5 %
- 190 GeV jets: 3-4 %

Total energy is reconstructed with 1% accuracy:
- 91 GeV: 90.2 GeV
- 380 GeV: 377.0 GeV

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

$$\text{RMS}_{90}(E_j) = \frac{\text{RMS}_{90}(E_{jj})}{\text{mean}_{90}(E_{jj})} \sqrt{2}$$
Summary

- The CLD detector design for the Conceptual Design Report has been presented.
- Tracking and calorimetry performance studies with full detector simulation demonstrates excellent overall detector performance.

Outlook

- Further detector performance simulation studies
  - flavour tagging performance
  - overlay of incoherent pairs (in progress) and synchrotron radiation backgrounds
- Full simulation studies of different physics processes
  - software framework and detector model available
- Engineering studies
  - cooling studies of all subdetectors (no power pulsing)
  - ECAL optimisation (technology choices, number of layers)
  - detector opening / maintenance scenarios, impact for detector layout

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 $X_0$</td>
<td>40 layers, 22 $X_0$</td>
</tr>
<tr>
<td>HCAL thickness</td>
<td>60 layers, 7.5 $\lambda_I$</td>
<td>44 layers, 5.5 $\lambda_I$</td>
</tr>
<tr>
<td>Yoke thickness</td>
<td>1989 mm</td>
<td>1521 mm</td>
</tr>
<tr>
<td>MDI (forward region)</td>
<td>$\Rightarrow$</td>
<td>$&lt; 150$ mrad</td>
</tr>
<tr>
<td>Solenoid field</td>
<td>4 Tesla</td>
<td>2 Tesla</td>
</tr>
</tbody>
</table>

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CLD detector model overview

20/18
Pion identification efficiency

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

- Efficiency

- 20 GeV pions

- 100 GeV pions

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

WORK IN PROGRESS
Electron identification efficiency

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

![20 GeV electrons](image1)

![100 GeV electrons](image2)

- 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”.

10 GeV electrons

**No charged PFOs**

**1 electron PFO**

**1 pion PFO**

**Other**

**Sum (validation)**

![Graph showing efficiency vs. cos(θ) for electron identification in Pandora track-cluster association algorithm.](image-url)
Conformal Tracking

Track fitting is done in the conformal space:

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

Cellular automaton is used to perform straight line search

Conformal tracking is used as the main track pattern recognition algorithm at CLIC

LCWS presentation about CLIC Conformal Tracking performance
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>
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<tr>
<td>Inner tracker support cylinder radius [m]</td>
<td>0.575</td>
<td>0.675</td>
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<tr>
<td>ECAL absorber</td>
<td>W</td>
<td>W</td>
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<tr>
<td>ECAL $X_0$</td>
<td>22</td>
<td>22</td>
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<tr>
<td>ECAL barrel $r_{\text{min}}$ [m]</td>
<td>1.5</td>
<td>2.15</td>
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<td>ECAL barrel $\Delta r$ [mm]</td>
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<td>202</td>
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<tr>
<td>ECAL endcap $z_{\text{min}}$ [m]</td>
<td>2.31</td>
<td>2.31</td>
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<tr>
<td>ECAL endcap $\Delta z$ [mm]</td>
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<td>202</td>
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<td>HCAL absorber</td>
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<td>HCAL $\lambda_l$</td>
<td>7.5</td>
<td>5.5</td>
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<td>HCAL barrel $r_{\text{min}}$ [m]</td>
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<td>HCAL barrel $\Delta r$ [mm]</td>
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<td>HCAL endcap $z_{\text{min}}$ [m]</td>
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<tr>
<td>HCAL endcap $\Delta z$ [mm]</td>
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<td>1166</td>
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<td>Solenoid field [T]</td>
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<td>Solenoid bore radius [m]</td>
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<td>Solenoid length [m]</td>
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<td>Overall height [m]</td>
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<td>12.0</td>
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<tr>
<td>Overall length [m]</td>
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<td>10.6</td>
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