Overview of the CLD detector proposal

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on behalf of the FCC collaboration

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The CLD detector design:
• Overall dimensions and parameters
• Tracking system
• Calorimetry
• ECAL optimistion
• Beam-induced backgrounds

Physics performance:
• Track reconstruction
• Jet energy resolution
• Flavour tagging
Overall dimensions are parameters

Optimised for particle flow calorimetry, inspired by CLICdet design:

- **2 T** magnetic field (limited by luminosity goal)
- **Low-mass silicon** vertex and tracking detectors
- **High granularity calorimeters** (ECAL and HCAL) inside solenoid
- **Full detector simulation** (including support structures, cables and services)
Layout of the tracking system

Vertex detector:
- Silicon pixels (25 x 25 μm²), 3 μm single point resolution
- 3 double layers in barred (R = 17, 27, 57 mm)
- 3 double layers in endcap disks (Z = 160, 230, 300 mm)
- Material budget: 0.6% (0.7%) X₀ per double layer in barrel (endcaps)

Main tracker:
- Silicon pixels and microstips: 7 μm x 90 μm single point resolution, except 5 μm x 5 μm in 1st inner tracker disk
- Inner tracker: 3 barrel layers, 7 endcap disks
- Outer tracker: 3 barrel layers, 4 endcap disks
- Material budget: 1.1 - 1.5% X₀ per layer

NB: Estimates of material budget inspired by ALICE ITS upgrade
**ECAL:**
- Si-W sampling calorimeter
- Cell size: 5 x 5 mm$^2$
- 40 layers (1.9 mm W plates)
- 22 $\lambda_I$, 20 cm thickness

**HCAL:**
- Scintillator-steel sampling calorimeter
- Cell size: 30 x 30 mm$^2$
- 44 layers (19 mm steel plates)
- 5.5 $\lambda_I$, 117 cm thickness

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ECAL is the main cost driver of the detector → reduction of number of layers significantly reduces overall price of the detector

<table>
<thead>
<tr>
<th>Layer structure</th>
<th>Thickness tungsten alloy [mm]</th>
<th>Total thickness per layer [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 uniform</td>
<td>1.9</td>
<td>5.05</td>
</tr>
<tr>
<td>30 uniform</td>
<td>2.62</td>
<td>5.77</td>
</tr>
<tr>
<td>20 uniform</td>
<td>3.15</td>
<td>7.19</td>
</tr>
<tr>
<td>20 thin + 10 thick</td>
<td>1.9 + 3.8</td>
<td>5.05 + 6.95</td>
</tr>
</tbody>
</table>

ECAL options with different W layer thickness and 22 $X_0$ overall

<table>
<thead>
<tr>
<th>Cost [MCHF]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanics</td>
</tr>
<tr>
<td>Detectors and sensors</td>
</tr>
<tr>
<td>Power supplies</td>
</tr>
<tr>
<td>Integration and installation</td>
</tr>
<tr>
<td>DAQ</td>
</tr>
<tr>
<td><strong>ECAL Total</strong></td>
</tr>
</tbody>
</table>
Photon and jet energy resolutions

→ 40 layers best, 20 layers worst

→ 20+10 and 30 layer options similar (except at low energies)

→ 20+10 seems to be a good option for a new CLD baseline configuration

<table>
<thead>
<tr>
<th>Layer structure</th>
<th>JER [%] $\sqrt{s} = 365$ GeV</th>
<th>JER [%] $\sqrt{s} = 91.2$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 uniform</td>
<td>3.62 ± 0.05</td>
<td>4.52 ± 0.06</td>
</tr>
<tr>
<td>30 uniform</td>
<td>3.72 ± 0.05</td>
<td>4.45 ± 0.06</td>
</tr>
<tr>
<td>20 uniform</td>
<td>3.78 ± 0.05</td>
<td>4.82 ± 0.07</td>
</tr>
<tr>
<td>20 thin + 10 thick</td>
<td>3.67 ± 0.05</td>
<td>4.56 ± 0.06</td>
</tr>
</tbody>
</table>

→ Jet energy resolution almost identical for the 4 ECAL options
Contributions studied in detail:
- Incoherent $e^+e^-$ pair production (dominant)
- $\gamma\gamma \rightarrow$ hadrons (small)
- Hits from synchrotron radiation (small)

→ see talk by Emmanuel Perez
Maximal energy deposit per bunch crossing:
• 0.1 GeV / 10 cells in ECAL
• 4 GeV / 50 mm in HCAL
Physics performance studies

Detector geometry: DD4hep
Event reconstruction framework: Marlin

Key event reconstruction steps:
• “Conformal tracking”: cellular automaton in conformal space for track finding
  \[ u = \frac{x}{x^2 + y^2} \]
  \[ v = \frac{y}{x^2 + y^2} \]
• Calorimeter clustering and particle flow analysis: PandoraPFA
• Flavour tagging: LCFIPlus


\[ e^+ e^- \rightarrow q \bar{q} \text{ event at } \sqrt{s} = 365 \text{ GeV} \]
(full detector simulation)
Single muons: tracking resolution

Transverse momentum resolution for 100 GeV muons in the barrel:

\[ \sigma(p_T) = 3.5 \times 10^{-5} \text{ GeV}^{-2} \]

Target impact parameter resolutions:

\[ \sigma(d_0) = \sqrt{a^2 + b^2 \cdot \text{GeV}^2 / (p^2 \sin^3(\theta))} \]

where:

- \( a = 5 \text{ \mu m} \)
- \( b = 15 \text{ \mu m} \)

(dashed lines)
Overview of the CLD detector proposal

Material and single point resolution

**Modifications to the vertex detector:**
- Impact parameter resolution with increased material (+50%)
- Worse single point resolution (3 μm → 5/7 μm)

→ Small effect of increased material budget
→ The single point resolution has a large impact on the impact parameter resolution at high $p_T$
**Single muons: efficiency**

**Tracking efficiency** = fraction of reconstructable MC particles that are reconstructed:
- Stable at generator level
- $p_T > 100$ MeV, $|\cos \theta| < 0.99$, at least 4 unique hits

→ Tracking fully efficient at $10^\circ$
→ Tracking efficient up to 40 cm radius (due to minimum number of hits required)
→ Drop by 15% efficiency at $p = 1$ GeV for $R > 38$ mm from particles losing too much energy to reach the minimum number of hits
**Tracking in complex events**

**Test case:** $e^+e^- \rightarrow b\bar{b}$ events at $\sqrt{s} = 365$ GeV

**Fake rate** = fraction of reconstructed tracks with purity < 75%
**Purity** = $\#$hits caused by MC particle / $\#$hits in reconstructed track

→ **High efficiency** over large $p_T$ range with $O(1\%)$ level fake rate
→ **Impact of beam-induced backgrounds is small**

**NB:** 10 μs detector integration time assumed, no timing cuts applied
Jet energy resolution

Test case: \( e^+e^- \rightarrow q\bar{q} \) \((q = u,d,s)\) events at \( \sqrt{s} = 91.2 \) and 365 GeV

Jet energy resolution = energy sum of all reconstructed particles
RMS\(_{90}\) = smallest range of reconstructed energy containing 90% of events

\[
\text{RMS}_{90} = \text{RMS} = \text{smallest range of reconstructed energy containing} \ 90\% \ \text{of events}
\]

\[
\text{Jet energy resolution} = \text{energy sum of all reconstructed particles}
\]

\[
\rightarrow 3 - 4\% \ \text{jet energy resolution at} \ 45.6 \ \text{GeV}, \ 4 - 5\% \ \text{at} \ 182.5 \ \text{GeV}
\]

\[
\rightarrow \text{Up to} \ 10\% \ \text{improvement from software compensation}
\]

EPJ C 77, 698 (2016)
Impact of beam-induced background

- Jets reconstructed using VLC algorithm (R = 1.1) in exclusive mode with 2 jets
- 400 ns time integration window assumed at both energies

\[ \sqrt{s} = 91.2 \text{ GeV} \]
\[ \approx 45.6 \text{ GeV} \]
\[ 400 \text{ ns} \]

\[ \sqrt{s} = 365 \text{ GeV} \]

\[ 400 \text{ ns} \]

\( \text{no BG} \)
\( \text{with BG} \)

\rightarrow \text{Generally, the impact of beam-induced background is very small}
\rightarrow \text{Largest impact in the forward direction at 91.2 GeV}
\rightarrow \text{No timing cuts applied}

Test case: separation of hadronic W and Z boson decays in $WW \rightarrow q\bar{q}\mu\nu_\mu$ and $ZZ \rightarrow q\bar{q}\nu\nu$ events with $m_{WW/ZZ} = 250$ GeV (charged leptons excluded from jet reconstruction)
Mass separation $= \frac{m_Z - m_W}{\sigma_{av}}$ with $\sigma_{av} = \frac{(\sigma_Z + \sigma_W)}{2}$

Two methods compared:
• $W$ and $Z$ masses from mean of Gaussian fit
• Mass distribution scaled so that mean of fit is equal to the PDG values of the $W$ and $Z$ masses

<table>
<thead>
<tr>
<th>background overlay</th>
<th>$R$</th>
<th>$\sigma_{m(W)}/m(W)$ [%]</th>
<th>$\sigma_{m(Z)}/m(Z)$ [%]</th>
<th>Separation [$\sigma$]</th>
<th>Separation (fixed mean) [$\sigma$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>no BG</td>
<td>0.7</td>
<td>5.94</td>
<td>5.75</td>
<td>2.19</td>
<td>2.16</td>
</tr>
<tr>
<td>with BG</td>
<td>0.7</td>
<td>5.95</td>
<td>5.90</td>
<td>2.13</td>
<td>2.13</td>
</tr>
<tr>
<td>no BG</td>
<td>0.9</td>
<td>5.26</td>
<td>5.11</td>
<td>2.46</td>
<td>2.43</td>
</tr>
<tr>
<td>with BG</td>
<td>0.9</td>
<td>5.18</td>
<td>5.19</td>
<td>2.43</td>
<td>2.43</td>
</tr>
<tr>
<td>no BG</td>
<td>1.1</td>
<td>4.99</td>
<td>4.94</td>
<td>2.58</td>
<td>2.54</td>
</tr>
<tr>
<td>with BG</td>
<td>1.1</td>
<td>5.36</td>
<td>4.96</td>
<td>2.50</td>
<td>2.45</td>
</tr>
</tbody>
</table>

→ Effect of beam-induced background small
→ Separation on the level of 2.5 standard deviations possible
B-tagging performance

Test case: $e^+e^- \rightarrow q\bar{q}$ events with $\theta(q) = 80^\circ$

For 60% b-tagging efficiency:
- 0.1% (0.9%) fake rate from u/d/s (charm) at 91.2 GeV
- 0.4% (2%) fake rate from u/d/s (charm) at 365 GeV

Sizeable difference between “truth” and conformal tracking at 365 GeV understood: large fraction of B-hadrons decay after the first vertex layer (improvement in progress)

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C-tagging performance

Test case: $e^+e^- \rightarrow q\bar{q}$ events with $\theta(q) = 80^\circ$

For 60% c-tagging efficiency:
- 5% (1.2%) fake rate from u/d/s (beauty) at 91.2 GeV
- 4% (10%) fake rate from u/d/s (beauty) at 365 GeV

- Fraction of C-hadrons decaying after the first vertex layer smaller
- Higher energies benefit from larger boost
Treatment of secondary interactions in the detector material

- Secondary vertices with a position compatible with the vertex detector layers are removed → Sizeable reduction of the fake rates at 91.2 GeV
- Large contribution from beam pipe not yet excluded → Further improvement possible

![Graph showing misidentification efficiency vs beauty efficiency](image)

- **Beam pipe**
- **Radius of secondary vertices**

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Flavour tagging with smaller beam pipe

- Alternative FCC-ee interaction region with smaller beam pipe radius
- Innermost barrel layer moved from 17.5 mm to 12.5 mm, outer radius unchanged
- Vertex disks unchanged

<table>
<thead>
<tr>
<th>Vertex barrel layer</th>
<th>Radius for the default model [mm]</th>
<th>Radius for the new model [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer 1</td>
<td>17.5</td>
<td>12.5</td>
</tr>
<tr>
<td>Layer 2</td>
<td>18.5</td>
<td>13.5</td>
</tr>
<tr>
<td>Layer 3</td>
<td>37</td>
<td>35</td>
</tr>
<tr>
<td>Layer 4</td>
<td>38</td>
<td>36</td>
</tr>
<tr>
<td>Layer 5</td>
<td>57</td>
<td>57</td>
</tr>
<tr>
<td>Layer 6</td>
<td>58</td>
<td>58</td>
</tr>
</tbody>
</table>

![Histogram showing default model](image)
Smaller beam pipe: barrel

- $e^+e^- \rightarrow q \bar{q}$ events with $\theta(q) = 80^\circ$
- "Truth" tracking

→ Sizeable improvement for charm at both energies and beauty at 91.2 GeV

\[ \sqrt{s} = 91.2 \text{ GeV} \]

\[ \sqrt{s} = 365 \text{ GeV} \]
Smaller beam pipe: forward

- $e^+e^- \rightarrow q\bar{q}$ events with $\theta(q) = 20^\circ$
- “Truth” tracking
  
  $\rightarrow$ Larger impact compared to the barrel region
Summary and conclusions

• The CLD detector concept is based on the mature design of the CLIC detector model (CLICdet)

• Full simulation studies show promising performances for key aspects: track reconstruction, jet energy measurement, flavour tagging

• Recent developments include: ECAL optimisation, flavour tagging studies (impact of smaller beam pipe, rejection secondary interactions in the detector material)
Backup slides
Comparison to CLICdet

<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>17.5</td>
</tr>
<tr>
<td>Vertex outer radius [mm]</td>
<td>60</td>
<td>58</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 inner radius [m]</td>
<td>0.127</td>
<td>0.127</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 $r_{\min}$ [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 $\varepsilon_{\min}$ [m]</td>
<td>2.31</td>
<td>2.31</td>
</tr>
<tr>
<td>ECAL endcap $\Delta \varepsilon$ [mm]</td>
<td>202</td>
<td>202</td>
</tr>
<tr>
<td>HCAL absorber</td>
<td>Fe</td>
<td>Fe</td>
</tr>
<tr>
<td>HCAL $\lambda_{\parallel}$</td>
<td>7.5</td>
<td>5.5</td>
</tr>
<tr>
<td>HCAL barrel $r_{\min}$ [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 $\varepsilon_{\min}$ [m]</td>
<td>2.54</td>
<td>2.54</td>
</tr>
<tr>
<td>HCAL endcap $\varepsilon_{\max}$ [m]</td>
<td>4.13</td>
<td>3.71</td>
</tr>
<tr>
<td>HCAL endcap $r_{\min}$ [mm]</td>
<td>250</td>
<td>340</td>
</tr>
<tr>
<td>HCAL endcap $r_{\max}$ [m]</td>
<td>3.25</td>
<td>3.57</td>
</tr>
<tr>
<td>HCAL ring $\varepsilon_{\min}$ [m]</td>
<td>2.36</td>
<td>2.35</td>
</tr>
<tr>
<td>HCAL ring $\varepsilon_{\max}$ [m]</td>
<td>2.54</td>
<td>2.54</td>
</tr>
<tr>
<td>HCAL ring $r_{\min}$ [m]</td>
<td>1.73</td>
<td>2.48</td>
</tr>
<tr>
<td>HCAL ring $r_{\max}$ [m]</td>
<td>3.25</td>
<td>3.57</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>
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<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>

Mayor modifications:

- Outer radius of silicon tracker:
  $1.5 \text{ m} \rightarrow 2.15 \text{ m}$
  (reduced magnetic field)

- Depth of HCAL:
  $7.5 \lambda_{\parallel} \rightarrow 5.5 \lambda_{\parallel}$
  (lower centre-of-mass energy)