A detector for CLIC: performance optimisation and technology R&D

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CERN & JGU Mainz

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Outline

• Overview of the experimental conditions and the physics goals
• Main requirements on the detector
  □ Challenges and optimisation for each subsystem
  □ Status of the R&D on silicon technologies and calorimeters
→ Integration between different subsystems
→ Interplay between hardware and software reconstruction
Compact Linear Collider: where we stand

2013 - 2019 Development Phase
Development of a Project Plan for a staged CLIC implementation in line with LHC results; technical developments with industry, performance studies for accelerator parts and systems, detector technology demonstrators

2020 - 2025 Preparation Phase
Finalisation of implementation parameters, preparation for industrial procurement, Drive Beam Facility and other system verifications, Technical Proposal of the experiment, site authorisation

2026 - 2034 Construction Phase
Construction of the first CLIC accelerator stage compatible with implementation of further stages; construction of the experiment; hardware commissioning

2019 - 2020 Decisions
Update of the European Strategy for Particle Physics; decision towards a next CERN project at the energy frontier (e.g. CLIC, FCC)

2025 Construction Start
Ready for construction; start of excavations

2035 First Beams
Getting ready for data taking by the time the LHC programme reaches completion

• Documents supporting accelerator, detector and physics program
  - Detector note: http://cds.cern.ch/record/2254048?ln=en
  - Staging baseline: http://dx.doi.org/10.5170/CERN-2016-004
CLIC
Compact Linear Collider
High energy (high acceleration gradients),
High luminosity (small beam size),
Lepton collider
• High precision physics program: measurements + eventual discoveries
• Higgs, top, BSM

Strategy can be adapted to LHC discoveries

<table>
<thead>
<tr>
<th>Stage</th>
<th>$\sqrt{s}$ (GeV)</th>
<th>$L_{\text{int}}$ (fb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>380</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td>350</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>1500</td>
<td>1500</td>
</tr>
<tr>
<td>3</td>
<td>3000</td>
<td>3000</td>
</tr>
</tbody>
</table>

Dedicated for top mass threshold scan

Detector requirements driven by physics goals and experimental environment
Physics program

- High precision measurement of Higgs properties
  - Couplings: sub-% level (% level for rare decays)
  - Higgs width: 3.4%
- Model independent couplings determination
  - Mass recoil method in $ee \rightarrow Z(\mu\mu/ee/qq)H$ events

![Diagram of Higgsstrahlung](image)

- Top mass measurement
  - Precision for 1S mass scheme: 50 MeV (10x better than LHC)
- Top quark form factors looking at $A_{fb}$
  - Sub-percent level (10x better than HL-LHC)
- Exotic top decays e.g. $t \rightarrow cH, t \rightarrow c\gamma$

- Direct and indirect BSM searches ($SUSY, DM, Z', VV$ scattering, finite e size, hidden valley, ...)
  - More sensitive to electromagnetic processes
  - Discovery potential well beyond LEP and LHC
  - In case of discovery, precision measurement of new particles
Machine environment

- **Low duty cycle**
  - Power pulsing
- **High lumi → very small beam size at IP**
  - very strong e.m. field → Beamstrahlung
  - Beam induced background
  - Energy loss at IP (E spectrum)

Most physics processes are studied well above production threshold => profit from full luminosity

- **Luminosity spectrum**
  - At CLIC, this energy spread is expected to be 0.35% around the nominal beam energy of 1.5 TeV.
  - The mean beam energy is expected to fluctuate by approximately 0.1% [23].
  - The biggest effect on the center-of-mass energy at CLIC originates from the beamstrahlung introduced above.

   - For the nominal CLIC parameters, shown in Table 3.1, the fraction of collisions within the highest 1% of the nominal energy corresponds only to 35% of the total luminosity.
   - This mostly affects the measurement of processes with production thresholds close to the nominal center-of-mass energy.
   - On the other hand, processes which can be produced at lower $p_s$ will benefit from a significantly larger fraction of the total luminosity.

   - In any case, this luminosity spectrum has to be taken into account when calculating production cross sections at CLIC.

   - We want to stress that the long tail in the luminosity spectrum is mostly caused by the beam-beam effects which cannot be avoided if a high total luminosity is desired.

   - A CLIC accelerator at lower center-of-mass energies of $p_s = 500$ GeV would have a much narrower luminosity spectrum with almost 75% of the luminosity within the highest 1% of the energy, but with a lower total luminosity of only $2.1 \times 10^{34}$ cm$^{-2}$s$^{-1}$ [23].

- **Staged Construction**
  - The configuration of the accelerator and especially the beam delivery system is chosen to optimize the available luminosity for the nominal center-of-mass energy.

  - Although the accelerator can also be operated at lower $p_s$, this will result in a significantly lower total luminosity.

  - For certain scenarios, e.g., a threshold scan, the accelerator will need to be operated far from its nominal energy.

  - It is thus beneficial to construct CLIC in several stages with increasing center-of-mass energies.

  - The chosen energy stages will depend strongly on the new physics scenarios discovered at the LHC.

  - One possible scenario involving three energy stages is investigated in [70].
Beam induced background

1. Pair-background
   - High occupancies
   - Extremely forward (mostly outside detector)

2. $\gamma\gamma$ to hadrons
   - Energy deposits
   - Main bkg in detector

- Full 156 ns train **triggerless** readout
  - Pairs: $3 \cdot 10^5$ per BX $\rightarrow$ $9.4 \cdot 10^7$ per train
  - $\gamma\gamma$ to had: $3.2$ per BX $\rightarrow$ $\sim 1000$ per train
    $\sim O(\text{TeV})$ energy in calorimeters
    $\rightarrow$ time cuts ($p_T$ and $\theta$ dependent)

- Small pixel and cell size, high B field
- Precise time stamping: 1-10 ns
- No issue from radiation damage:
  $< 10^{11} \text{n}_{eq}/\text{cm}^2/\text{y}$, except forward calos
  ($\sim 10^4 \text{n}_{eq}/\text{cm}^2/\text{y}$ less than LHC experiments)
Forward WW, no background

After time window: \(~1.2\text{ TeV}\)

After timing and \(p_T\) cuts: \(~100\text{ GeV}\)

*Precision physics in a harsh environment*
CLICdet

11.4 m

Return Yoke + muon ID
4T solenoid
Ultra light Vertex + Tracker
Fine grained calorimeters
Forward EM calorimeters

Detector optimised for 3 TeV

Final focusing (QD0) outside the detector
A technical note: simulation framework

- **Software framework extremely important for detector optimisation work**
- **DD4hep**: a flexible and easy to use geometry description
  - single source of information for simulation, reconstruction, analysis
  - supporting the entire experimental lifecycle
    
    *detector design, construction, operation, data taking*

- On the fly conversion to GEANT4 simulation
- Used by different experiments
  - *CLIC, ILC, FCC, CEPC, under investigation for LHCb*

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**Recent effort, not used for all the studies in this talk**
**Vertex detector**

- Higgs physics (hadronic Higgs decays separation), top physics, BSM
- Physics aim: excellent identification of secondary vertices for b/c-tagging → excellent impact parameter resolution

\[
\sigma(d_0) = 5 + \frac{15}{(p[GeV] \sin^{3/2}\theta)} \mu m
\]

- Affected by single point resolution → 3μm
- Multiple scattering → 0.2%\(X_0\) per detection layer

**Figures:**
- b) fit template: \(b\bar{b}\) ZH; \(Z \rightarrow q\bar{q}; H \rightarrow b\bar{b}\)
- CLICdp \(\sqrt{s} = 350\) GeV
- c) fit template: \(c\bar{c}\) ZH; \(Z \rightarrow q\bar{q}; H \rightarrow c\bar{c}\)
- f) fit template: SM background
**Vertex detector optimisation**

- **Single point resolution of 3µm**
  - 25x25µm² pixel $\rightarrow$ $\sim$1.5 billion channels
  - $\sim$ 24x finer than CMS
  - $\sim$ 10x less than CMS

**Ultra light detector: 0.2%$X_0$ per detection layer**

- Ultra thin sensor and readout: 0.1%$X_0$
- Low mass supports + cables: 0.1%$X_0$
- No liquid cooling $\rightarrow$ spiral geometry to allow forced air flow (combined with power pulsing)
- Double layers (3 + 3)
Vertex detector optimisation

- Single point resolution of 3µm
  - 25x25µm² pixel $\rightarrow$ $\sim$1.5 billion channels

\[ \sim 24x \text{ finer than CMS} \]

- 560 mm

Flavour tagging performance

Ultra light detector: 0.2%\(X_0\) per detection layer

- Ultra thin sensor and readout: 0.1%\(X_0\)
- Low mass supports + cables: 0.1%\(X_0\)
- No liquid cooling $\rightarrow$ spiral geometry to allow forced air flow (combined with power pulsing)
- Double layers (3 + 3)
Vertex occupancy

- Occupancy due to beam bkg < 3 %
  - $R_{in} = 31$ mm at 3 TeV (reduced $R$ for lower $\nu$s)
  - No multi-hits capability

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Conical and thick beampipe to shield backscattered particles from forward calos
Tracker detector

- Higgs and top leptonic decays, BSM program (i.e. smuon mass)
- Physics aim: excellent momentum resolution for high $p_T$ tracks (> 100 GeV)

$$\sigma_{p_T}/p_T^2 \sim 2 \times 10^{-5} \text{ GeV}^{-1}$$

0(10) better than LHC experiments

Position resolution

$$\frac{\delta p_T}{p_T} \propto \frac{\sigma \cdot p_T}{B \cdot L^2} \cdot \frac{1}{\sqrt{N + 4}}$$

Multiple scattering

$$\frac{\delta p_T}{p_T} \propto \frac{1}{B \cdot L} \cdot \sqrt{\frac{X_{tot}}{X_0}}$$

→ Large and light tracker with good single point resolution, high B field

$\sigma_{R\phi} \sim 7\mu m$

$\sim 1-2\% X_0$ per layer

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**Example:**

$H \rightarrow \mu \mu$

<table>
<thead>
<tr>
<th>Di-muon invariant mass [GeV]</th>
<th>Events / 0.05 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>116</td>
<td>10^4</td>
</tr>
<tr>
<td>118</td>
<td>10^3</td>
</tr>
<tr>
<td>120</td>
<td>10^2</td>
</tr>
<tr>
<td>122</td>
<td>10^1</td>
</tr>
<tr>
<td>124</td>
<td>10</td>
</tr>
</tbody>
</table>

$e^+e^- \rightarrow \tilde{\nu}_R \tilde{\nu}_R \rightarrow \mu^+ \mu^- \chi_1^0 \chi_1^0$

Endpoint to get $\mu^\sim$ mass
• Tracker overall size and B field
  - Acceptance $|\theta| > 7^\circ \Rightarrow |\eta| > 2.8$
  - $B = 4\ T$
  - $4.4\ m \times 3\ m$ tracker
Tracker material budget

- Realistic engineering model with cable routing, cooling and support structures
  - Very light: 1-1.5%\(X_0\) per layer
  - Air cooling not feasible \(\rightarrow\) liquid cooling
  - Space frame to have light and solid supports
    - So far deformation ok (Sag \(~\)50 \(\mu\)m)
• Realistic engineering model with cable routing, cooling and support structures
  - Very light: 1-1.5%$X_0$ per layer
  - Air cooling not feasible $\rightarrow$ liquid cooling
  - Space frame to have light and solid supports
    - So far deformation ok (Sag $\sim 50$ μm)
Tracker occupancy and cell size

- Elongated pixel / Short strips
  - Single point resolution of 7µm \( \rightarrow r\phi \)-pitch of \(~50\ \mu\text{m} \) (t.b.d.)
  - Occupancies from beam-beam interactions define readout granularity: 1-10 mm maximum strip lengths (increasing from in to out)
- Actual granularity will depend on the chosen technology
- No multi-hits capability
Number of layers optimisation

- Number of layers (3+3, 7+4) to minimise confusion in pattern recognition

- Tracker design is outcome of optimization studies in fast and full detector simulations

- Requirement on momentum resolution for high momentum tracks lead to $B = 4\, \text{T}$, $R = 1.5\, \text{m}$ and single point resolution $\sigma_r = 7\, \mu\text{m}$.

- Good agreement between fast and full simulation.

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**Position and granularity of first disk**

- Short strips for all disks
- Pixels for all disks
- Pixels only for 1st disk

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**Momentum resolution result**

- $\Delta p_T / p_{T,\text{true}}$ for $B^+$ decay

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**Need to reconstruct vertices in tracker**

- Decay after last vertex barrel layer

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**Distance [mm]**

**Area of the ellipse track errors [mm$^2$]**

**N particles per train per area**
Calorimeters

- Higgs, top, BSM hadronic decays or photon final state
- Good photon energy resolution $O(10-1000 \text{ GeV})$
  $$\frac{\sigma_E}{E} \sim 4 - 0.4\%$$
  Similar to ATLAS
- Excellent jet energy resolution $O(10-1000 \text{ GeV})$
  $$\frac{\sigma_E}{E} \sim 5 - 3.5\%$$
  @ ATLAS JER $\lesssim 5\%$ for $p_{T,\text{jet}} > 1 \text{ TeV}$
- Large coverage

From the perspective of the likely physics measurements at CLIC, the requirements are:

1. Slepton masses

Detector Requirements

Towards a new CLIC detector model

Calorimeters

Towards a new CLIC detector model

Detector Requirements

- Calorimeters
- Calorimeters

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Detector Requirements
Particle Flow Calorimeters

Classical approach

\[ E_{\text{JET}} = E_{\text{ECAL}} + E_{\text{HCAL}} \]

Particle flow approach

\[ E_{\text{JET}} = E_{\text{TRACK}} + E_\gamma + E_n \]

Typical jet composition:
- 60% charged particles
- 30% photons
- 10% neutrons

Always use the best info you have:
- 60% => tracker
- 30% => ECAL
- 10% => HCAL

Requires high granularity calorimeters to resolve deposits from different particles and sophisticated software to make correct associations.

\[ \pi^+ \rightarrow u d s \]
1. Multiple tracks associated to single cluster – split cluster.

2. Cluster energy much greater than track momentum – split cluster.

- Exploit calorimeter granularity to gradually build-up picture of events
- More than 70 algorithms to address specific event topologies, with very few mistakes, and to avoid accidental merging of separate particles
Calorimeter optimisation

- **ECAL**
  - 40 layers SiW (Sc investigated but Si allows for higher granularity)
  - 22 $X_0$ ($1 \lambda_i$)
- **HCAL**
  - 60 layers FeSc
  - 7.5 $\lambda_i$
  - Acceptance down to $\sim 5^\circ \rightarrow |\eta| \sim 3.1$

Cos $\theta \leq 0.7$

- $Z \rightarrow uds$, jet energy:
  - $45.5$ GeV
  - $100$ GeV
  - $250$ GeV
  - $500$ GeV
  - $1$ TeV
  - $1.5$ TeV

Photon energy resolution

Entries/2 GeV

<table>
<thead>
<tr>
<th>$R_{in}$</th>
<th>ZZ events</th>
</tr>
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<tbody>
<tr>
<td>$120$ mm</td>
<td></td>
</tr>
<tr>
<td>$240$ mm</td>
<td></td>
</tr>
<tr>
<td>$360$ mm</td>
<td></td>
</tr>
</tbody>
</table>

$|\eta| = 0$

Table 9: Energy [GeV] (10, 50, 200, 500, 1000, 1500)

<table>
<thead>
<tr>
<th>Energy [GeV]</th>
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<tbody>
<tr>
<td>10</td>
<td>±0.03 0.981 1.077 1.230 1.46 1.64</td>
</tr>
<tr>
<td>50</td>
<td>±0.02 1.230 1.46 1.70 1.94 2.11</td>
</tr>
<tr>
<td>200</td>
<td>±0.01 1.64 1.94 2.24 2.54 2.83</td>
</tr>
<tr>
<td>500</td>
<td>±0.009 0.790 0.981 1.17 1.36 1.55</td>
</tr>
<tr>
<td>1000</td>
<td>±0.008 1.36 1.55 1.74 1.93 2.12</td>
</tr>
<tr>
<td>1500</td>
<td>±0.007 1.93 2.12 2.31 2.50 2.68</td>
</tr>
</tbody>
</table>

**Figure 20**: Photon energy resolution

**Table 8**: Energy [GeV] (10, 50, 200, 500, 1000, 1500)

<table>
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Calorimeter cell size

- Small cell size to minimize confusion and to cope with bkg occupancy

ECAL cell size: $5 \times 5 \text{mm}^2$

$\Rightarrow \Delta \eta \Delta \phi = 0.003 \times 0.003$

HCAL cell size: $30 \times 30 \text{mm}^2$

$\Rightarrow \Delta \eta \Delta \phi = 0.0015 \times 0.0015$

- Further improvements could be achieved with software compensation

Plot not produced with the CLIC calo parameters → similar result expected

\[ \sigma_{\text{jet}} = \sqrt{\sigma_{\text{trk}}^2 + \sigma_{\text{ECAL}}^2 + \sigma_{\text{HCAL}}^2 + \sigma_{\text{conf}}^2} \]
A calorimeter for boosted objects?

*Example: boosted event topology*

- Excellent calorimeter granularity
- At $\sqrt{s} = 1.4$ TeV boosted top topology
  - Johns Hopkins top tagger
    - $W$-decays contributions tagged thanks to finer calorimeter granularity
- Explore more cluster based variables
Forward calorimeters

- **LumiCal** for luminosity measurement (per mille accuracy)
- **BeamCal** for very forward tagging of high E electromagnetic objects
  - No track information $\rightarrow$ no $e/\gamma$ identification
  - Centered at outgoing beamline (rotation of 10 mrad)
- R&D on compact sampling calorimeters within FCAL collaboration
  - Radiation hardness (maximum dose $\sim$100 MRad/yr)

suppress bkg with very forward electrons, i.e.:
- **Mono-\(\gamma\):**
  - sig: \(e^+e^-\rightarrow E_{T}^{\text{miss}}\gamma\)
  - bkg: \(e^+e^-\rightarrow e^+e^-\gamma\)
- **HH:**
  - sig: \(e^+e^-\rightarrow bbbb\nu\nu\)
  - bkg: \(qqqq\nu / qqqq\pm\)
  $\rightarrow$ $\sim$65% rejection
Silicon R&D overview

- CLICpix first pixel chip in 65 nm technology at CERN
  - Synergy with LHC upgrades
- Two lines of hybridization studied
  1. Bump bonded to planar sensor
  2. Capacitively coupled to active sensor (HV-CMOS)
- For tracker less strict requirements: larger pixel, more material budget
- Monolithic technology promising:
  1. HR-CMOS chips
  2. Silicon on Insulator (SoI)
Hybrid pixels

CLICpix chip (25μm pitch) bump bonded to 200-50 μm thick planar sensors or glued to active sensors

Planar sensors

σ_{SP} ~ 3-4 μm, 200 μm thick → Satisfy σ_{SP} but not m.b.

σ_{SP} ~ 7.7 μm, 50 μm thick → Satisfy m.b. but not σ_{SP}

From simulation (50μm thick): 15μm pitch → challenging for chip design

Expected improvements with CLICpix2, e.g. better noise isolation
Monolithic technology

- foreseen for large area tracker
- can satisfy: $\sigma_{SP} < 7 \, \mu m$, time stamping < 10 ns

Investigator analog test chip in 180 nm HR-CMOS process

- Developed for ALICE ITS upgrade
- Pitch 28 $\mu$m, 15-40 $\mu$m thick epitaxial
- Readout with external sampling ADCs

Test chip with integrated readout in 200 nm SoI process
- 30 $\mu$m pitch
- 500 $\mu$m thickness

- $\sigma \sim 6 \, \mu m$
- $\sigma \sim 5 \, ns$
- $\sigma = 4.6 \, \mu m$
Calorimeter R&D

Many technologies pursued by CALICE

- Collaboration between Linear Colliders
- Recent: collaboration with CMS upgrade

See CALICE seminar: [https://indico.cern.ch/event/563768/](https://indico.cern.ch/event/563768/)
• Finalizing analyses for data with 1\textsuperscript{st} generation prototypes ("physics")
  - comprehensive comparison of the various technologies
• 2\textsuperscript{nd} generation prototypes ("technology") under construction:
  - improved r/o technologies
  - establish scalability (embedded electronics)
  - system tests with other sub-detectors
  \textit{\textbf{→ first beam tests of full prototypes foreseen in 2017}}
Conclusions

- The CLIC accelerator provides
  - unique potential for precision and discovery physics at the TeV scale
  - challenging requirements for the detector
- Developed detector concept optimised for physics performance and taking into account constraints from engineering studies
- Ongoing broad R&D program on detector technologies meeting the requirements
Thank you!
BACK-UP
**Test beam results**

- Test beam experiments in 2006–2015 at DESY, CERN, FNAL
- First physics prototypes of up to ~1m$^3$, ~2m$^3$ with Tail Catcher Muon Tracker

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**Figure 1:** 50 GeV hadronic shower illustrating that connection between clusters could be done with the reconstructed tracks.

**Figure 4:** Time of first hit distribution of muon data with steel absorbers and hadron data with steel and tungsten.

**Figure 3:** Energy per layer [a.u.] for W-AHCAL 2011, protons at 61 GeV. Linearity of detector response and energy resolution.

**Table 1:** Comparison of data and Geant4 simulation of hadron showers with steel absorbers.

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**CALICE Preliminary**

- Fe-SDHCAL, 1x1cm$^2$, pions 10-80 GeV, CAN-047

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**Y (cm)**

Fe-SDHCAL, 1x1cm$^2$, pions 10-80 GeV, CAN-047

**SDHCAL Layer**

**N$_{vis}$ / 0.8 ns**

- $f(t) = A_{fast} e^{t / \tau_{fast}} + A_{slow} e^{t / \tau_{slow}} + c$
- 60 GeV hadrons - tungsten, $\tau_{fast} = 8.7$ ns, $\tau_{slow} = 480$ ns, $c = 5.5E^{-06}$
- 60 GeV hadrons - steel, $\tau_{fast} = 7.7$ ns, $\tau_{slow} = 75$ ns, $c = 3.1E^{-06}$
- 180 GeV muons, $c = 1.2E^{-06}$

**Time of First Hit [ns]**

**CALICE T3B**

**$\langle E_{vis} \rangle$ [MIPS]**

- Data
  - $\pi^+$
  - $p$
  - $K^+$
  - $e^+$

**$\langle E_{rec} \rangle - E_{available}$ vs $E_{available}$ [GeV]**

- Linearity

---

**Analysis Note CAN-037, 30th November 2012**

- Tracks of low energy that stop inside the calorimeter may have hits of second or third threshold. This may bias the energy estimation. Therefore giving the same weight for all the hits belonging to these tracks should improve on the energy reconstruction.

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**CALICE Collaboration**

References
QD0 and return yoke

- **Final focusing (QD0) outside the detector** → $L^* = 6m$
  - Acceptable L reduction w.r.t. $L^* = 4.5m$ (QD0 inside the detector)
  - Space to increase calorimeter acceptance
  - Shallow yoke endcap of 1.4m
  - Add (copper) ring coils to reduce the stray field
    - Power of ring coils: 2 x 2260 kW
Power pulsing and air flow

- Power pulse CLICpix ASIC for dissipation < 50 mW/cm² in the sensor area
  - Analog electronics turned off
  - Digital electronics in idle except during readout

- Tested in 1.5T magnetic field
  - Electronics keep working
  - Forces due to power pulsing too small to be seen

- Air flow
  - Total heat load after power-pulsing ~470 W
  - Blow dry air cooling at 0°C at 5-10 m/s
  - Vibrations: 1-2 μm RMS amplitude

→ Tested in real size thermal mock-up
A calorimeter for boosted objects?

- Excellent calorimeter granularity
- Boosted top at 1.4 TeV ($R_{\text{large jet}} = 1.0-1.5$)
  - Trimming as first step to reduce beam bkg contamination ($R_{\text{subjet}} = 0.2$)
  - Johns Hopkins top tagger $\rightarrow W$-decays contributions tagged thanks to finer calorimeter granularity
- In $Z/W$ events, exploit full granularity with use of $D_2/C_2$ variables? (make use of clusters instead of subjets)
BEFORE TRIMMING

AFTER TRIMMING

1) Trimming technique

Drawing by I. Garcia

• ee_genkt_algorithm
• $R_{\text{subjets}} = 0.4$
• $E_{\text{threshold}} = 5 \text{ GeV}$

Remove background.

Inclusive reconstruction of subjets with high activity removing the soft stuff.

Clustering the subjets into a big boosted jet.

• VLC algorithm.
A successful test: the CLIC Test Facility 3

Image credit: Maximilien Brice

- CTF3 successfully demonstrated:
  - drive beam generation
  - RF power extraction
  - two-beam acceleration up to a gradient of 145 MeV/m
Background rejection

- Triggerless readout

- Find the $t_0$ physics event offline and pass a window around $t_0$ to the reconstruction
  - Compromise between calorimeter integration time and bkg minimisation $\rightarrow$ 10 ns (100 ns for W)
  - Energy in calorimeters: from \(~19\) TeV to \(~1.2\) TeV

- Apply $p_T$ and timing cuts on PFOs (loose, default and tight selections available)
  - Calorimeter time stamp resolution: 1 ns
  - Time corrected for shower development and TOF
  - Cuts depend on particle type, $p_T$ and $\theta$
    - Allow to protect high $p_T$ object
  - Energy in calorimeters: from \(~1.2\) TeV to \(~100\) GeV
Decay after last vertex barrel layer

$B^+$ decay length [m]

- p(b-jet) = 100 GeV
- p(b-jet) = 200 GeV
- p(b-jet) = 500 GeV
- p(b-jet) = 1 TeV
- p(b-jet) = 1.5 TeV
Tracker optimization

Tracker design is outcome of optimization studies in fast and full detector simulations.

Requirement on momentum resolution for high momentum tracks lead to $B = 4T$, $R = 1.5\text{ m}$ and single point resolution $\sigma_r = 7\mu\text{m}$.

Good agreement between fast and full simulation.

<table>
<thead>
<tr>
<th>$p$ [GeV]</th>
<th>$\sigma(\Delta p_T/p_T,\text{true})$ [GeV$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^1$</td>
<td>$10^{-5}$</td>
</tr>
<tr>
<td>$10^2$</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>$10^3$</td>
<td>$10^{-3}$</td>
</tr>
</tbody>
</table>

$\theta = 90^\circ$

Performance goal
Figure 26: Overlap, in percent, of $m_W$ and $m_Z$ measurements from the invariant mass of the two jets in $WW \to \nu\nu jj$ and $ZZ \to \nu\nu jj$ events, respectively, as a function of the typical energy of the jets in the events. Solid lines show results without background events, dashed lines results with 60 bunch-crossings of $gg \to \gamma\gamma$ hadrons background overlaid.

At a later stage, smaller sensor cell sizes in the forward HCAL, possibly combined with shielding, may have to be introduced.
8 Variations of the HCal endcap tile size

Besides variations of the support tube geometry, the scintillating tile size in the HCal endcap also influences the occupancy. Here it is studied how much the occupancy can additionally be reduced by a reduction of the tile size. In the CDR design of the HCal endcap, the tile size is $30 \times 30$ mm$^2$. The occupancy is here additionally estimated for square tiles with sides of 10 mm, 15 mm, 20 mm and 25 mm, with the standard polyethylene–tungsten support tube. The results are shown in Figure 18. The relation between the maximum occupancy in the inner radius of the HCal endcap and the tile area is approximately linear. Accordingly there is no saturation reached in this case. A reduction of the tile size from $30 \times 30$ mm$^2$ to $10 \times 10$ mm$^2$ thus yield a factor 9 reduction, proportional to the decrease in area per tile.

Figure 18: The occupancy in the inner radius of the HCal endcap, averaged over azimuthal angle and layers 20 to 30 for the standard polyethylene–tungsten support tube, versus the length of the tile sides. The x-axis is quadratic.
Details of the presently envisaged design can be found in [19]. The main support tube, in its preliminary design, amounts to 1.25%\(\times 10^0\). The interlink structure for the outer barrel layers is estimated to contribute 0.3%\(\times 10^0\), while the inner interlink amounts to 0.5%\(\times 10^0\). Cables from the vertex detector, which are to be routed outwards along ITB1 and further out along the conical vacuum tube, are represented by an additional 0.47%\(\times 10^0\) (deemed to be a conservative estimate).

The total material budget for the vertex plus tracker region as a function of polar angle is shown in Figure 16. Preliminary results of a first validation of the tracking in CLICdet are shown in Figure 17.

Figure 13: XZ-view of the tracker as implemented in the simulation model. The black lines indicate the tracker support structures including cooling and cables, the green lines represent the tracker sensor layers. The blue lines show the main support tube and the interlink structures. The orange line indicates the vacuum tube. The vertex detector is shown in the centre (in red). Cables going outwards from the vertex detector are represented in magenta.
Top Physics

\[ \Gamma_{\mu}^{ttV}(k^2, q, q') = -i e \left\{ \gamma_{\mu} \left( F_{1V}^V(k^2) + \gamma_5 F_{1A}^V(k^2) \right) + \frac{\sigma_{\mu\nu}}{2m_t} (q + q')^\nu \left( i F_{2V}^V(k^2) + \gamma_5 F_{2A}^V(k^2) \right) \right\} \]

"4-fermion" operators

"vertex" operators

from Marcel Vos' talk 'Top quark physics' at ECFA LC2016, Santander
Pandora LC algorithms

from J. Marshall’s talk at LCWS15
Comparison of different options

Linear colliders:
- Can reach the highest energies
- Luminosity rises with energy
- Beam polarisation at all energies

Circular colliders:
- Large luminosity at lower energies
- Luminosity decreases with energy
decays have been studied for two $t\bar{t}$ pair, an Higgs boson is produced in association with a top quark determined from the production rate in the process where a $W$ boson decays leptonically, giving a $t\bar{t}$ final state of six jets (four b jets), one lepton and one neutrino, or electro-weakly, giving a $t\bar{t}$ final state of eight jets, including two charged leptons; and the invariant mass of the two jets associated with the Higgs decay; the c-tag value corresponding to the same jet; and the b-c-separation returned by the tagger.

The likelihood, normalised to the number of events with Higgs decay jets. Requiring a high signal likelihood, reduces the non-Higgs backgrounds to 4700 events, but leaves only 90 events from other Higgs decays, while setting a limit of 3000 events at 4 TeV using the CLIC_SiD detector model. The momenta of the reconstructed electrons, and background: the opening between the reconstructed electrons is fitted by signal and background components (where the normalisation is allowed to vary), giving:

\[ \hat{L} = L_{\text{signal}}(x_{\text{bkg}}, x_{\text{bkg}}) = L_{\text{bkg}}(x_{\text{bkg}}, x_{\text{bkg}}) \]

where the bkg distribution is fitted by signal and background components.

Finally, to separate the signal from all backgrounds, a further relative likelihood classifier, adjusting signal and rejects 80% of the remaining background.

The vertical arrows show the detector acceptance.