Detector technology R&D for CLIC

Eva Sicking (CERN)
on behalf of the CLICdp collaboration

CERN Academic Training Lectures on CLIC
5–9 March 2018
1. Physics potential of a high-energy $e^+e^-$ collider
2. Detector technology R&D for CLIC → today
3. The CLIC accelerator design and performance
4. Key technology developments for the CLIC accelerator
5. Overview of applications using high-gradient acceleration, from photon sources to medical physics
Content of today’s lecture

Introduction

Input for CLIC detector design
  Physics programme
  Backgrounds and beam structure at CLIC

CLIC detector concept

Detector R&D
  Vertex and tracking detectors
  Calorimetry

Detector performance from full detector simulations

Summary
Reminder: CLIC

- CLIC = Compact Linear Collider
- High-luminosity linear $e^+e^-$ collider at the energy frontier
- Energy from few hundred GeV up to 3 TeV
- Proposed for the post HL-LHC phase

- Staged construction
- Two-beam acceleration scheme
- High acceleration gradient of 100 MV/m

- Physics goals:
  - Precision measurements of SM processes (Higgs boson, top quark)
  - Precision measurements of new physics potentially discovered at LHC or CLIC
  - Search for new physics: unique sensitivity to particles with electroweak charge
Detector technology R&D for CLIC

CLIC detector layout and technology has to be optimised for:

- Physics programme at CLIC:
  - Precision measurements
  - Searches for new physics

- Experimental conditions at CLIC:
  - Colliding system $e^+e^-$
  - Collision energy and energy spread
  - Beam-induced backgrounds

Affordability, feasibility → already introduced yesterday → discussed today
Detector technology R&D for CLIC

- CLIC detector layout and technology has to be optimised for
  - Physics programme at CLIC:
    - Precision measurements
    - Searches for new physics
  - Experimental conditions at CLIC:
    - Colliding system $e^+e^-$
    - Collision energy and energy spread
    - Beam-induced backgrounds
  - Affordability, feasibility

→ already introduced yesterday

→ discussed today
Input for detector design
Reminder: CLIC physics programme

- CLIC energy reach: 350 GeV to 3 TeV, adjustable to new discoveries
- CLIC physics programme focusses on
  - Precision measurements of Higgs boson and top quark
  - Indirect and direct BSM searches
Reminder: pp and $e^+ e^-$ cross sections

In pp collisions, interesting events need to be found in huge number of collisions

- $e^+ e^-$ collisions more clean

**pp cross section**

<table>
<thead>
<tr>
<th>Energy [TeV]</th>
<th>Cross Section [$\sigma$ [nb]]</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 LHC</td>
<td>$10^9$</td>
</tr>
<tr>
<td>14 LHC</td>
<td>$10^7$</td>
</tr>
<tr>
<td>33 HE LHC</td>
<td>$10^5$</td>
</tr>
<tr>
<td>100 VLHC</td>
<td>$10^3$</td>
</tr>
</tbody>
</table>

**$e^+ e^-$ processes**

**Factor $> 10^8$**
Detectors for pp and e^+e^- collisions

- Detectors for hadron colliders
  - Large QCD backgrounds
  - Focus on radiation hardness of many sub-detectors
  - Complex triggers

- Detectors for linear e^+e^- colliders
  - Cleaner e^+e^- collisions
  - Beam-induced backgrounds constrain detector design
  - Radiation damage only relevant in very forward detectors
    \( \theta \sim 10 \text{ mrad} \Rightarrow \eta = 5.3 \)
  - Less/no need for triggers
Beam-induced backgrounds at CLIC

- Achieve high luminosities by using extremely small beam sizes
- 3 TeV CLIC: Bunch size: $\sigma_{x,y,z} = \{40 \text{ nm}; 1 \text{ nm}; 44 \mu\text{m}\}$
- → very high E-fields → beam-beam interactions:

\[ \gamma/\gamma^* \rightarrow \text{hadrons} \]
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  → very high E-fields → **beam-beam interactions:**

  \[\gamma/\gamma^* \rightarrow \text{hadrons}\]

- **Main backgrounds** ($p_T > 20 \text{ MeV}, \theta > 7.3^\circ$)
  - **Incoherent $e^+e^-$ pairs:**
    - 19k particles / bunch train at 3 TeV
    - High occupancies → **Impact on detector granularity and design**
  - $\gamma\gamma \rightarrow \text{hadrons}$
    - 17k particles / bunch train at 3 TeV
    - Main background in calorimeters and trackers → **Impact on detector granularity, design and physics meas.**
**Beam-induced backgrounds at CLIC**

- Achieve high luminosities by using extremely small beam sizes
  - $3$ TeV CLIC: Bunch size: $\sigma_{x,y,z} = \{40 \text{ nm}; 1 \text{ nm}; 44 \mu\text{m}\}$
  - Very high E-fields $\rightarrow$ beam-beam interactions:

\[
\begin{align*}
\gamma/\gamma^* & \rightarrow q \\
\gamma/\gamma^* & \rightarrow \bar{q} \\
\gamma\gamma & \rightarrow \text{hadrons}
\end{align*}
\]

Main backgrounds ($p_T > 20 \text{ MeV}, \theta > 7.3^\circ$)

- **Incoherent $e^+e^-$ pairs:**
  - $19k$ particles / bunch train at $3$ TeV
  - High occupancies $\rightarrow$ Impact on detector granularity and design

- $\gamma\gamma \rightarrow \text{hadrons}$
  - $17k$ particles / bunch train at $3$ TeV
  - Main background in calorimeters and trackers $\rightarrow$ Impact on detector granularity, design and physics meas.
Beam energy spectrum at CLIC

Due to beamstrahlung, energy is lost right at the interaction point.

Collision energy is reduced by the amount lost in beamstrahlung before collision.

Example:

- Full luminosity at 3 TeV: $5.9 \cdot 10^{34} \text{ cm}^{-2} \text{s}^{-1}$
- 1% most energetic part: $2.0 \cdot 10^{34} \text{ cm}^{-2} \text{s}^{-1}$

Most physics processes are studied well above production threshold.

- Can profit from almost full luminosity

Impacts on feasibility of LEP-style kinematic fit → see next slide
Beamstrahlung and “kinematic fit”

  - $e^+e^-$ collider at CERN with $\sqrt{s} \leq 209$ GeV
  - Signal dominated, $e^+e^- \rightarrow Z$ and $e^+e^- \rightarrow W^+W^-$
  - Almost no background
  - Almost no beamstrahlung, $\sqrt{s}$ well known

- Possibility to do kinematic fit
  - Impose energy and momentum constraints on final state particles
    - $\sum_i E_i = \sqrt{s}$ and $\sum_i \vec{p}_i = 0$
  - In case of particles-pair production, use additional constraint of equal masses
    - e.g. $m_{W_1} = m_{W_2}$

- Advantage
  - Kinematic fit can significantly improve invariant mass resolution

At CLIC

- Kinematic fit can in some studies also be used
- For complex events with beamstrahlung and missing energy, an excellent jet energy resolution can only be reached with very good calorimeters
Linear colliders operate in bunch trains

1) Bunch separation drives timing requirement of detector
   - 10 ns hit time-stamping in tracking
   - 1 ns accuracy for calorimeter hits

<table>
<thead>
<tr>
<th>Property</th>
<th>√s 380 GeV</th>
<th>1.5 and 3 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Train repetition rate</td>
<td>50 Hz</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Bunches / train</td>
<td>356</td>
<td>312</td>
</tr>
<tr>
<td>Train duration</td>
<td>178 ns</td>
<td>156 ns</td>
</tr>
<tr>
<td>Bunch separation</td>
<td>0.5 ns</td>
<td>0.5 ns</td>
</tr>
<tr>
<td>Duty cycle</td>
<td>0.00089%</td>
<td>0.00078%</td>
</tr>
</tbody>
</table>

2) Low duty cycle → Possibility of power pulsing of detectors
CLIC detector requirements summary

- **Momentum resolution**
  - Higgs recoil mass, smuon endpoint, Higgs coupling to muons
  - \( \sigma_{p_T^2} / p_T^2 \sim 2 \times 10^{-5} \text{GeV}^{-1} \) above 100 GeV

- **Impact parameter resolution**
  - c/b-tagging, Higgs branching ratios
  - \( \sigma_{r\phi} \sim a \oplus b / (p[\text{GeV}] \sin^2 \theta) \mu \text{m} \)
  - \( a = 5 \mu \text{m}, \ b = 15 \mu \text{m} \)

- **Jet energy resolution**
  - Separation of W/Z/H di-jets
  - \( \sigma_{E^2} / E \sim 5\% - 3.5\% \) for jets at 50 GeV – 1000 GeV

- **Angular coverage**
  - Very forward electron and photon tagging
  - Down to \( \theta = 10 \text{ mrad} (\eta = 5.3) \)

- **Requirements from beam time structure** and beam-induced background
CLIC detector requirements summary

- Momentum resolution
  - Higgs recoil mass, smuon endpoint, Higgs coupling to muons
  - $\sigma_{p_T}/p_T^2 \sim 2 \times 10^{-5}\text{GeV}^{-1}$ above 100 GeV

- Impact parameter resolution
  - c/b-tagging, Higgs branching ratios
  - $\sigma_{r\phi} \sim a \oplus b/(p[\text{GeV}]\sin^2\theta)\mu\text{m}$
  - $a = 5\,\mu\text{m}$, $b = 15\,\mu\text{m}$

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  \[ \text{Down to } \theta = 10 \text{ mrad (} \eta = 5.3 \) \]

- Requirements from beam time structure and beam-induced background
CLIC detector concept
CLIC detector: CLICdet

Inspired by ILC detector concepts SiD and ILD and optimised for CLIC environment

- Large silicon tracker $R=1.5 \text{ m}$
- ECAL with 40 layers ($22 \ X_0$)
- HCAL with 60 layers ($7.5 \ \lambda_I$)
- B-field of 4 T
- Last focussing magnet QD0 outside detector: increased HCAL forward acceptance

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11.4 m

12.8 m
CLICdet: position in cavern

- Last focussing magnet QD0 in accelerator tunnel: $L^* = 6\, \text{m}$

- Assembly and maintenance in dedicated cavern
Detector R&D

- Feasibility studies of most challenging detector technologies
- Selection of recent developments
Vertex and tracking detectors
Challenges in vertex detector R&D

- **Flavour tagging** capabilities drive the design of the vertex detector
  - Precise determination of displaced vertices necessary input for tagging of heavy quarks
    → Extremely accurate
    → Extremely light

**Secondary vertex at r=5 mm: B-hadron**

- Inner radius limited by occupancy from beam-induced backgrounds
  → $r = 31 \text{ mm}$

**CLIC vertex detector**

- Surface area of $\sim 0.84 \text{ m}^2$
- Single point resolution: $\sigma < 3 \mu\text{m}$
  → Small pixels $\lesssim 25 \times 25 \mu\text{m}^2$, analog readout → $\sim 1.3$ billion channels
- Low power dissipation: $\leq 50 \text{ mW/cm}^2$
- Low Material budget: $\lesssim 0.2 \%X_0$ per layer
  - Thin sensors and ASICs
  - Low-mass support
  - Power pulsing and air cooling
- Time stamping $< 10 \text{ ns}$
Challenges in tracking detector R&D

- Very good momentum resolution drive the design of the tracker
  - Requires large $B \cdot R^2$
  - Many layers

CLIC all-silicon tracker
4.6 m

- Large surface area of $O(100 \text{ m}^2)$
- 7 $\mu$m single-point resolution
- Few % maximum occupancy from beam-induced backgrounds
- Time stamping $< 10 \text{ ns}$
  - Large pixels/strips: 50 $\mu$m short side 50 $\mu$m–1 mm – 10 mm long side 
    $\sim 600$ million channels
  - Use integrated sensors
- Maintain efficiency and good timing despite large pixel area
- Mechanical stiffness vs. little material budget
  - Light-weight support structure and cooling concepts
  - Material budget: $\lesssim 1 – 2\% X_0$ per layer
Occupancies from beam-induced bkg.

- Beam-induced backgrounds produce charged particles
- Study background-related occupancies of vertex and tracking detectors
- Choice of detector granularity
Occupancies from beam-induced bkg.

CLIC vertex detector at 3 TeV

- Beam-induced backgrounds produce charged particles
- Study background-related occupancies of vertex and tracking detectors
- Choice of detector granularity

CLIC tracking detector at 3 TeV
Silicon pixel technologies: Hybrid

Hybrid: Planar Si sensor + ASIC (65 nm)
Bump bonding

Hybrid: HV-CMOS sensor + ASIC (65 nm)
Capacitive coupling (glue)

- Hybrid technologies:
  interesting for small feature sizes, small pixel sizes
Silicon pixel technologies: Monolithic

- Monolithic: High-Resistivity CMOS
- Monolithic: Silicon on Insulator
- Monolithic: High-Voltage CMOS

▶ Monolithic technologies:
有趣的是，大规模生产，低厚度
Telescope for beam tests

- Reference system for pixel-detector tests: beam telescope
- EP-LCD Timepix3 telescope operated in CERN SPS H6 beamline
  - 7 planes of pixel detectors for reference tracking:
    Timepix3 assemblies with 55 \( \mu \)m pixel pitch
  - Resolutions on Device Under Test (DUT):
    Spatial resolution: \( \lesssim \) 2 \( \mu \)m,
    Timing resolution: \( \lesssim \) 1 ns
- High rate: 10M particles/s
- Automatic stage for x/y movement + rotation of DUT
Hybrid: planar-sensor assemblies

- 65 nm demonstrator CLICpix r/o ASIC
  - 64 × 64 pixel matrix
  - 25 µm pixel pitch
  - Simultaneous 4-bit time (TOA) and energy (TOT) measurement per pixel
- Indium bump-bonding
- Assemblies with 50 – 200 µm thick sensors
- Residuals at 3.5 µm for 200 µm sensors, ~ 8 µm for 50 µm sensors
- More charge sharing in thicker sensors → better resolution
Hybrid: capacitively coupled assemblies

- 65 nm CLICpix2 r/o ASIC
  - Increased matrix with 128 × 128 pixels
  - 25 µm pixel pitch
  - 8-bit time (TOA) and 5-bit energy (TOT) measurement per pixel
  - Reduced noise, cross-talk, improved I/O, added test pulse

- Glue assemblies with active HV-CMOS sensors with resistivities 20 and 80 Ωcm

- Tests planned also with planar sensors

- Beam tests with several 20 Ωcm assemblies

- Expect improved performance for high-resistivity substrates

Cluster size

Position resolution

Hit time residuals
Monolithic Active Pixel Sensor (MAPS)

- Monolithic pixel detectors based on **fully integrated CMOS technology**
- **180 nm HR-CMOS process**
  - High-Resistance epitaxial layer (15 – 40 µm, 1 – 8k Ωcm)
  - CMOS circuitry shielded by deep P-well
  - Standard and modified process (additional low-dose N-implant for full lateral depletion → improved radiation hardness)

- ALICE Investigator test chip
  - 134 mini-matrices with 8 x 8 pixels with various pixel sizes (20 x 20 µm to 50 x 50 µm) and collection electrode geometries
  - Beam tests using chips with 25 µm epitaxial layer and resistivity of 8k Ωcm
  - Spatial resolution down to 3.5 µm for 28 µm pixel pitch
  - Standard process: more charge sharing → better resolution

Resolution for matrix with 28 µm pitch
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Modified process

Resolution for matrix with 28 μm pitch

CLICdp Work in progress

CERN Academic Training
Eva Sicking: Detector technology R&D for CLIC
Monolithic Active Pixel Sensor (MAPS)

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ALICE investigator

Resolution for matrix with 28 µm pitch

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Eva Sicking: Detector technology R&D for CLIC
Monolithic SOI sensors

- Monolithic pixel detectors in SOI (Silicon on Insulator)
  - Thin SOI CMOS (200 nm feature size) and thick sensor bulk
  - High-resistive fully depleted sensor → Large S/N and high speed
  - Pixel pitch down to 30 µm achieved
  - Target thickness of 100 µm for CLIC

- Test results for 500 µm thickness, 30 × 30 µm² pitch, rolling-shutter r/o:
  > 99% efficiency, σ_{SP} \lesssim 2 µm

Cracow SOI test chip

SOI clustersize

[Graph showing SOI cluster size vs. back bias voltage]
Monolithic SOI sensors

- Monolithic pixel detectors in SOI (Silicon on Insulator)
  - Thin SOI CMOS (200 nm feature size) and thick sensor bulk
  - High-resistive fully depleted sensor → Large S/N and high speed
  - Pixel pitch down to 30 \( \mu \text{m} \) achieved
  - Target thickness of 100 \( \mu \text{m} \) for CLIC
- Test results for 500 \( \mu \text{m} \) thickness, 30 \( \times \) 30 \( \mu \text{m}^2 \) pitch, rolling-shutter r/o: > 99% efficiency, \( \sigma_{SP} \lesssim 2 \mu \text{m} \)

Resolution in y-direction:

![Cracow SOI test chip](image)

![Graph showing resolution in y-direction](image)
Vertex detector: power-delivery + pulsing

- Small duty cycle of CLIC machine: 0.00078% @ 3 TeV
  - Turn off front end in gaps between bunch trains, to reduce average power
  - Power-delivery and power-pulsing concept optimised for low material budget

- Power pulsing with local energy storage in silicon capacitors and voltage regulation with Low-Dropout Regulators

- FPGA-controlled current source provides small continuous current
- Low-mass Al-Kapton cables

Power-delivery and power-pulsing design for low mass

Corresponding test setup

Zoom: Analog dummy load PCB
Vertex detector: air cooling

- Vertex-detector heat load of $\leq 50 \text{ mW/cm}^2$
- Extractable using air flow $\rightarrow$ low material budget

- Spiral vertex disks allow air flow through detector
  - Simulation studies of air velocity, temperature, study of potential vibrations
  - Experimental verification with 1:1 thermo-mechanical mockup

1:1 scale thermo-mechanical mockup of vertex detector

Simulation results:
- Temperature
- Air velocity

<table>
<thead>
<tr>
<th>Mass Flow: 20.1 g/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average velocity</td>
</tr>
<tr>
<td>@ inlet 11.0 m/s</td>
</tr>
<tr>
<td>@ center 5.2 m/s</td>
</tr>
<tr>
<td>@ outlet 6.3 m/s</td>
</tr>
</tbody>
</table>
Proof-of-concept prototype of light tracking-detector mechanics

- Confirm stability and material budget assumptions
- Off-the-shelf carbon fibre tubes
- Node developed and fabricated
- Compare finite element calculations with measurements

Stiffness achieved with low mass structure

Total weight 926 g (70% tubes, 26% nodes, 4% glue)
**Proof-of-concept prototype of light tracking-detector mechanics**

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**Synergies with ALICE ITS outer barrel stave**
Mechanical integration studies

- Integration: low-mass supports, services and assembly scenarios
  - Taking into account constraints from powering and cooling
  - Material-budget calculations, comparison with simulation models
  - Example: assembly of vertex and inner tracking detector around beam pipe

Beam-pipe, vertex detector and inner tracker in support cylinder (CLIC_ILD)
Dimensions: 4.6 m length, outer diameter of 0.6 m
Mechanical integration studies

- Integration: low-mass supports, services and assembly scenarios
  - Taking into account constraints from powering and cooling
  - Material-budget calculations, comparison with simulation models
  - Example: assembly of vertex and inner tracking detector around beam pipe
Calorimetry
Challenges in PFA calorimeter R&D

- Jet energy resolution of $\sigma_E/E \approx 5 - 3.5\% \rightarrow$ Highly granular calorimeters

- **Si-W-ECAL**
  - 2 mm thick tungsten plates interleaved with 500 $\mu$m thick silicon sensors
  - 40 layers 22 $X_0$ or 1 $\lambda_I$
  - 5 x 5 mm$^2$ silicon cell size
  - $\rightarrow \sim 2500$ m$^2$ silicon
  - $\rightarrow \sim 100$ million channels

- **Scint-Fe-HCAL**
  - 19 mm thick steel plates interleaved with 3 mm thick plastic scintillator + SiPMs
  - 60 layers: 7.5 $\lambda_I$
  - 30 x 30 mm$^2$ scintillator cell size
  - $\rightarrow \sim 9000$ m$^2$ scintillator
  - $\rightarrow \sim 10$ million channels / SiPMs

- Compact design of all components
- Calibration of channels
- Time stamping $< 1$ ns
Particle flow calorimeters

Idea:

- Average jet composition
  - 60% charged particles
  - 30% photons
  - 10% neutral hadrons

- Always use the best information
  - 60% → tracker
  - 30% → ECAL
  - 10% → HCAL

Particle Flow Analysis: Hardware + Software

- Hardware: Resolve energy deposits from different particles
  → High granularity calorimeters

- Software: Identify energy deposits from each individual particle
  → Sophisticated reco. software

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

\[ E_{\text{jet}} = E_{\text{track}} + E_{\gamma} + E_{n} \]
Calorimeter optimised for particle flow

- Jet energy resolution (JER) requirements depend on physics goals
- Starting point for LC detector design
  → Ability to separate hadronic W and Z decays

Perfect → 3.1σ sep.  2% JER → 2.9σ sep.  3% JER → 2.6σ sep.  6% JER → 1.8σ sep.

- 3%–4% jet energy resolution gives \( \sim 2.6 - 2.3\sigma \) W/Z separation
Optimise calorimeter for particle flow

- High granularity of calorimeters
  → Separate overlapping showers to reduce confusion
  \[
  \sigma_{\text{jet}} = \sqrt{\sigma_{\text{track}}^2 + \sigma_{\text{el.-m.}}^2 + \sigma_{\text{had.}}^2 + \sigma_{\text{confusion}}^2}
  \]

- JER of 3%–4% when using
  → ECAL cell size: $\sim 5 \times 5 \text{ mm}^2$
  → HCAL cell size: $\sim 30 \times 30 \text{ mm}^2$

$rms_{90}$ and $mean_{90}$ $\equiv$ rms and mean in smallest range of $E_{\text{rec}}$ dist. containing 90% of events
Calorimetry: technologies for active layers

- Hardware R&D by CALICE and FCAL collaborations
  - Build prototypes of highly granular calorimeters
  - Use different absorbers and different active layer technologies
  - Compare results to Geant4 simulations → validate Geant4
  - Optimise detector geometry in simulations for physics performance

CALICE silicon PIN diodes
1 × 1 cm² in 6 × 6 matrices

CALICE scint. tiles + SiPMs
3 × 3 cm²

FCAL silicon sensor petal
1.8 mm wide strips, diff. lengths
CALICE physics prototypes

- Test beam experiments in 2006–2018
- Evolution of prototypes: Proof of principle → Engineering challenges
- Prototypes of up to $\sim 1\, \text{m}^3$
- 10k-500k readout cells in $\sim 1\, \text{m}^3$ (depending on readout technology)

Physics prototype: W-AHCAL: 38 layers, $\sim 8000$ readout channels

- Detector challenges:
  - Compact design of calorimeters
  - Calibration of all channels
CALICE technology prototypes: scalability

- AHCAL technology prototype under construction for beam tests in 2018
  - 40 layers, 23,000 tiles and SiPMs
  - Automated production, quality assurance
  - LED calibration, active temperature compensation

- Smaller AHCAL stacks already used in stand-alone beam tests and as backing HCAL in combined CMS HGCal + AHCAL beam tests

15 full layers of $12 \times 12$ tiles (without absorber)
Stack tested with electron beams

Beam tests with CMS HGCal

Tile-board assembly: $3 \times 3 \text{ cm}^2$ tiles
CALICE technology prototypes: scalability

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Layer with $24 \times 24$ tiles of $3 \times 3\, \text{cm}^2$ size

15 full layers of $12 \times 12$ tiles (without absorber)
Stack tested with electron beams

Beam tests with CMS HGCal

- CE-E
- CE-H (front)
- CE-H (back)
- CALICE

- e, π, μ beams
CALICE event displays

- Study shower shapes substructure and time structure for various particle types and energies
- Example: Identify track segments within shower
CALICE example results

Response to different particles

Improving energy reconstruction with software compensation

Time structure: W vs. Fe HCAL

Shower substructure: Si-W-ECAL
Forward CALorimetry: FCAL

- Very forward e.m. calorimeters
  - LumiCal for luminosity measurement (< ±1% accuracy)
  - BeamCal for very forward electron tagging
- e and γ acceptance to small angles
- Very compact design (sensors, read-out, absorber) → small Molière radius
- BeamCal: GaAs, LumiCal: silicon

LumiCal $R_{out} = 34\,\text{cm}$, BeamCal $R_{out} = 15\,\text{cm}$

Tracker ECAL HCAL Muon system

LumiCal Energy Response

Stack used in test beam

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CLICdet performance from full detector simulations
Full detector simulations at CLIC

- Full Geant4 detector simulation including overlay of beam induced backgrounds
- Full reconstruction chain including reconstruction of tracks and clusters → particle flow objects → jets → flavour tagging

\[ e^+ e^- \rightarrow t\bar{t} \ @ 380 \text{ GeV} \]

\[ e^+ e^- \rightarrow H\nu_e \nu_e \rightarrow b\bar{b}\nu_e \nu_e \ @ 1.4 \text{ TeV} \]

\[ e^+ e^- \rightarrow t\bar{t} \ @ 3 \text{ TeV} \]
Beam-induced backgrounds at CLIC

- Use combined $p_T$ and timing cuts to reduce out-of-time background
  - Cuts optimised for detector regions
  - Cluster timing by combining hit timing information
    → tighter cuts possible on cluster timing
- Example: $e^+e^- \rightarrow t\bar{t}H \rightarrow Wb\bar{Wb}H \rightarrow q\bar{q}b\tau\nu b\bar{b}$ at 1.4 TeV

Before $p_T$ and timing cuts
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After $p_T$ and timing cuts
Detector optimisation

- Optimisation of CLIC detector model in full detector simulations
  - Ensure that detector performance meets requirements
  - Validate full software chain

Tracker radius and B-Field ↔ momentum resolution

ECAL configuration ↔ Photon energy reco.

![ECAL configuration graph](image)

![Background overlay graph](image)
CLICdet performance: Examples 1

- Jet energy resolution using particle flow analysis and software compensation
- Requires detailed calibration and tuning for all detector regions

Transverse momentum resolution of $2 \times 10^{-5}$ GeV$^{-1}$ achieved for high-energy tracks in the barrel

Jet energy resolution

\[
\sigma(p_T/p_T^{\text{true}}) \text{ [GeV}^{-1}] = \begin{cases} 
10^{-1} & \text{for } p \leq 1 \text{ GeV} \\
10^{-2} & \text{for } 1 < p \leq 10 \text{ GeV} \\
10^{-3} & \text{for } 10 < p \leq 100 \text{ GeV} \\
10^{-4} & \text{for } p > 100 \text{ GeV}
\end{cases}
\]

CLICdp Work in progress

\[
\text{RMS}_{\text{90}}(E_j)/\text{Mean}(E_j) \text{ [%]} = \begin{cases} 
5 & \text{for } 50 \text{ GeV Jets} \\
3.5 & \text{for } 190 \text{ GeV Jets} \\
3 & \text{for } 250 \text{ GeV Jets} \\
2.5 & \text{for } 750 \text{ GeV Jets} \\
2 & \text{for } 1500 \text{ GeV Jets}
\end{cases}
\]
CLICdet performance: Examples 2

- **Vertex** finder reconstructs primary and secondary vertices
- **Jet** reconstruction using jet clustering algorithm
- Feed information into multi-variate analysis → flavourness of each jet

**Example: c-tagging**

- c-tagging performances in $e^+e^- \to q\bar{q}$ events
CLICdet performance: Examples 2

- **Vertex** finder reconstructs primary and secondary vertices
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---

**Example: c-tagging**

![c-tagging performance graph]

- c-tagging performances in \( e^+ e^- \rightarrow q\bar{q} \) events
Summary
CLIC is a precision machine with a unique physics potential
- Precision measurements and searches for physics beyond the Standard Model at the TeV scale

CLIC machine environment and physics goals lead to challenging requirements for detector and software
- Ultra-light vertex and tracking detectors
- Fine-grained calorimeters and Particle Flow Analysis
- Take into account CLIC beam structure and background in detector design

Integrated detector R&D for CLIC
- Full detector simulation studies for detector optimisation
- Proof-of-concepts of most-challenging detector concepts
- Study engineering challenges with realistic constraints

Synergies with already approved experiments and other collider proposals

Thanks to everyone who provided input to this talk!
Sources used in this presentation

- CDR: 10.5170/CERN-2012-007, 10.5170/CERN-2012-003, 10.5170/CERN-2012-005
- Staging baseline document: DOI: 10.5170/CERN-2016-004
- CLIC detector note 2017: CLICdp-Note-2017-001
- More details in:
  - Vertex detector geometry: CLICdp-Note-2014-002
  - Mechanical integration of vertex and tracking detectors: CLICdp-Note-2015-002
  - Power pulsing for vertex detector: CLICdp-Note-2015-004
  - CLIC tracker readout: CLICdp-Note-2017-002
- CLIC website: http://clic.cern
1. Physics potential of a high-energy $e^+e^-$ collider
2. Detector technology R&D for CLIC
3. The CLIC accelerator design and performance → tomorrow
4. Key technology developments for the CLIC accelerator
5. Overview of applications using high-gradient acceleration, from photon sources to medical physics
Backup
Hadron vs. lepton colliders

1) Proton is compound object
   - Initial state unknown
   - Limits achievable precision

2) High rates of QCD backgrounds
   - Complex triggers
   - High levels of radiation

3) Very high-energy circular colliders feasible

1) $e^{\pm}$ are point-like
   - Initial state well-defined (energy, opt.: polarisation)
   - High-precision measurements

2) Clean experimental environment
   - Less/no need for triggers
   - Lower radiation levels

3) Very high energies require linear colliders
Circular vs. linear $e^+ e^-$ colliders

- **Circular colliders (CC)**
  - Can accelerate beam in many turns
  - Can collide beam many times
  - Possibility of several interaction regions
  - Limited energy due to synchrotron radiation
    - Synchrotron radiation per turn
      \[ \sim \frac{\text{Energy}^4}{(\text{Mass}^4 \cdot \text{Radius})} \]
    - $\text{Mass}_{\text{proton}} / \text{Mass}_{\text{electron}} \approx 2000$
    - E.g. 2.75 GeV/turn lost at LEP for $E = 105$ GeV
  - Shield detector against synchrotron radiation

- **Linear colliders (LC)**
  - Very little synchrotron radiation in a linac
  - Can reach high energies
  - Have to achieve energy in a single pass
    → High acceleration gradients needed
  - One interaction region
  - Have to achieve luminosity in single pass
    → Small beam size and high beam power
    → Beamstrahlung, energy spread
Landscape of high-energy $e^+e^-\ colliders$

Circular Electron Positron Collider (CEPC)
$e^+e^-, \sqrt{s} = 240-250\ GeV;\ SPPC\ pp,$
Circumference: 54-100 km

Future Circular Collider (FCC)
$e^+e^+, \sqrt{s} = 90-350\ GeV;$
pp, $\sqrt{s}: \sim 100\ TeV$
Circumference: 90-100 km

International Linear Collider (ILC)
$e^+e^+, \sqrt{s} = 250-500\ GeV\ (1\ TeV)$
Length: 31 km (50 km)

Compact Linear Collider (CLIC)
$e^+e^+, \sqrt{s} = 380\ GeV,\ 1.5\ TeV,\ 3\ TeV$
Length: 11 km, 29 km, 50 km
Reminder: Particle detection (1)

- Particles make small changes in the material they traverse
  - Ionisation, nuclear effect, ... ← all very small
- Particles differ in the way they interact with material
  - Identify particle types

![Diagram showing particle detection]

- **Tracker**
  - Photon $\gamma$
  - Electron $e^\pm$
  - Muon $\mu^\pm$
  - Proton $p^\pm$ / Pion $\pi^\pm$
  - Neutron $n$
  - Neutrino $\nu$

- **Calorimeters**

- **Hadronic**

- **Muon Detector**

**Very Light** | **Very Heavy**
Reminder: Particle detection (2)

- Elementary particles have very short life times
  - W, Z, Higgs and many more
- We only see the products of their decay
- Reconstruct the properties of the mother particle using decay patterns and properties of the daughter particles

Quarks hadronise to jets

- Cannot observe quarks directly, as they hadronise into jets of particles

Secondary vertex at $r=5\,\text{mm}$: b-quark

- Identify quark type via secondary vertex reconstruction
Full detector simulations

Forward WW, no background

+ background in reco. time window

After tight timing and $p_T$ cuts

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td><strong>Photons</strong></td>
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<tr>
<td>Central</td>
<td>$0.75 \leq p_T &lt; 4.0$</td>
<td>$t &lt; 2.0$</td>
<td>$1.0 \leq p_T &lt; 4.0$</td>
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<td>\leq 0.975$</td>
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<tr>
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<td>&gt; 0.975$</td>
<td>$0 \leq p_T &lt; 0.75$</td>
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<tr>
<td><strong>Neutral hadrons</strong></td>
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<td><strong>Charged particles</strong></td>
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<td>All</td>
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Installation and maintenance

- Study feasibility of installation and maintenance
- Here, CLICdet in assembly cavern
- Remove endcap to access forward calorimeters and tracker
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