CLIC Detectors and Physics
Jan Strube
CERN
on behalf of the CLIC Detector and Physics study group
Outline

- The CLIC Accelerator
- Challenges for Detector Design
- The CLIC Detector and Physics Program
  - Simulation Studies
  - Detector Development
- Future Plans
- Summary
CLIC Layout at 500 GeV

- **e⁻ main linac**: 12 GHz, 80 MV/m, 4.4 km
- **e⁺ main linac**: 12 GHz, 80 MV/m, 4.4 km
- **drive beam accelerator**: 2.75 GeV, 1.0 GHz
- **circumferences delay loop**: 73 m
  - CR1: 293 m
  - CR2: 439 m
- **delay loop**: 2.5 km
- **decelerator**: 5 sectors of 878 m
- **booster linac**: 2.86 to 9 GeV
- **e⁻ injector**: 2.86 GeV
- **e⁺ injector**: 2.86 GeV
- **beam delivery system (BDS)**
- **time delay line**
- **combiner ring (CR)**
- **turnaround (TA)**
- **damping ring (DR)**
- **predamping ring (PDR)**
- **bunch compressor (BC)**
- **interaction point (IP)**
- **radius (TA)**

Legend:
- Red: electron (e⁻)
- Green: positron (e⁺)
CLIC two-beam scheme compatible with energy staging to provide the optimal machine for a large energy range. Lower energy machine can run most of the time during the construction of the next stage. Physics results will determine the energies of the stages.
Tunnel implementations (laser straight)
The CLIC Beams

Parameter | CLIC at 3 TeV
--- | ---
L (cm$^{-2}$s$^{-1}$) | 5.9×10$^{34}$
BX separation | 0.5 ns
#BX / train | 312
Train duration (ns) | 156
Rep. rate | 50 Hz
$\sigma_x / \sigma_y$ (nm) | ≈ 45 / 1
$\sigma_z$ (μm) | 44

Finite spread of beam energy
Reduction of luminosity
(small effect for processes far from threshold)

Systematic effect on reconstruction,
for example, slepton reconstruction

<table>
<thead>
<tr>
<th>$\sqrt{s'} / \sqrt{s}$</th>
<th>0.5 TeV</th>
<th>3 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 99 %</td>
<td>62 %</td>
<td>35 %</td>
</tr>
<tr>
<td>&gt; 90 %</td>
<td>89 %</td>
<td>54 %</td>
</tr>
<tr>
<td>&gt; 70 %</td>
<td>99 %</td>
<td>76 %</td>
</tr>
<tr>
<td>&gt; 50 %</td>
<td>~100 %</td>
<td>88 %</td>
</tr>
</tbody>
</table>
Background to Physics studies

Incoherent pair production:
Increases occupancy in inner tracker layers and forward region → impact on detector segmentation and pattern recognition

γγ → hadrons (at 3 TeV):
Deposit up to 19 TeV of energy in the calorimeters
~ 5000 Tracks with 7.3 TeV
Impact is minimized by using advanced reconstruction techniques

<table>
<thead>
<tr>
<th>√s (GeV)</th>
<th>N(γγ→hadrons) per BX</th>
</tr>
</thead>
<tbody>
<tr>
<td>350</td>
<td>0.05</td>
</tr>
<tr>
<td>500</td>
<td>0.3</td>
</tr>
<tr>
<td>1400</td>
<td>1.3</td>
</tr>
<tr>
<td>3000</td>
<td>3.2</td>
</tr>
</tbody>
</table>

Coherent e⁺e⁻ pairs:
7 x 10⁸ per BX, very forward

Incoherent e⁺e⁻ pairs:
3 x 10⁵ per BX, rather forward
Physics Goals Drive Detector Requirements

Momentum resolution
Higgs Recoil, $h \rightarrow \mu^+\mu^-$
$\sigma(p_T)/p_T^2 \sim 2 \times 10^{-5}$ GeV$^{-1}$

Jet Energy Resolution
Separation of heavy bosons, Gaugino, Triple Gauge Coupling
$\sigma(E)/E = 3.5\%-5\%$

Flavor Tagging
$\sigma_{r\phi} \approx 5 \mu m \oplus 15 \mu m/(p[GeV] \sin^{3/2} \theta)$
Challenges for Detector Design

**PFA calorimetry**
Calorimeters inside coil (track-shower matching)
Full shower containment for operation at 3 TeV

**Tracking**
Low material budget
Excellent impact parameter resolution

**Forward region**
QD0 inside detector ↔ compact design ↔ $4\pi$ coverage
Detector Concepts for CLIC

CLIC_ILD

- Fe Yoke
- Coil - 4T
- W-HCAL
- ECAL
- Steel HCAL
- TPC

Gaseous Tracking
4 T Field

CLIC_SiD

- Fe Yoke
- Coil - 5T
- W - HCAL
- Steel - HCAL

All- Silicon Tracker
5 T Field
Cost-constrained Design
CLIC detector concepts

- **Return yoke with Instrumentation for muon ID**
- **Strong solenoids** 4 T and 5 T
- **Fine grained calorimetry**, $1 + 7.5 \lambda$
  - 30 + 60/75 layers
- **Main trackers**: TPC+silicon (CLIC_ILD), all-silicon (CLIC_SiD)
- **Ultra low-mass vertex detector** with $\sim 25 \mu m$ pixels
- **Complex forward region with final beam focusing**
- **6.5 m**
# CLIC Detector Concepts Summary

<table>
<thead>
<tr>
<th></th>
<th><strong>CLIC_ILD</strong></th>
<th><strong>CLIC_SiD</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertex Tracker</td>
<td>3 double layers ( r_i = 31 \text{ mm} )</td>
<td>5 layers ( r_i = 27 \text{ mm} )</td>
</tr>
<tr>
<td>Tracker</td>
<td>TPC, ( r_o = 1.8 \text{ m} ) Silicon envelope</td>
<td>Silicon, ( r_o = 1.2 \text{ m} )</td>
</tr>
<tr>
<td>B-field</td>
<td>4 T</td>
<td>5 T</td>
</tr>
<tr>
<td>ECAL</td>
<td>SiW 23 ( X_0 )</td>
<td>SiW 26 ( X_0 )</td>
</tr>
<tr>
<td>HCAL barrel</td>
<td>W-Scint, 3x3 ( \text{mm}^2 ) 7.5 ( \lambda )</td>
<td>W-Scint, 3x3 ( \text{mm}^2 ) 7.5 ( \lambda )</td>
</tr>
<tr>
<td>HCAL endcap</td>
<td>Steel-Scint ( 7.5 \lambda )</td>
<td>Steel-Scint ( 7.5 \lambda )</td>
</tr>
</tbody>
</table>
Introduction to Particle Flow Reconstruction

Typical jet contents:

- 60% charged particles: \( \sigma(p_T)/p_T^2 \sim 2 \times 10^{-5} \text{ GeV}^{-1} \)
- 30% photons: \( \sigma(E)/E < 20\% / \sqrt{E} \)
- 10% neutral hadrons: \( \sigma(E)/E > 50\% / \sqrt{E} \)

Ideally, fully reconstruct the shower for each particle and match tracks to showers.

At higher jet energies, confusion (mis-matching of energy depositions and particles) deteriorates the resolution.

At even higher energies, leakages becomes a factor in the jet energy resolution.

PFA possible without high granularity
At CLIC: High granularity essential for background reduction
Detector Readout

Triggerless readout of the whole bunch train
Starting time of Physics event inside the train is identified offline

<table>
<thead>
<tr>
<th>Subdetector</th>
<th>Reco Window</th>
<th>Hit Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECAL</td>
<td>10 ns</td>
<td>~ 1 ns</td>
</tr>
<tr>
<td>HCAL Endcap</td>
<td>10 ns</td>
<td>~ 1 ns</td>
</tr>
<tr>
<td>HCAL Barrel</td>
<td>100 ns</td>
<td>~ 1 ns</td>
</tr>
<tr>
<td>Silicon Detectors</td>
<td>10 ns</td>
<td>10 ns / \sqrt{12}</td>
</tr>
<tr>
<td>TPC (CLIC_ILD)</td>
<td>Entire train</td>
<td>n/a</td>
</tr>
</tbody>
</table>

19 TeV $\rightarrow$ 1.2 TeV remaining in reconstruction window

Passed to track finding and PFA reconstruction

156 ns

necessary for development of shower in tungsten
PFA Calorimetry at CLIC

1.2 TeV "extra energy" in reco window

100 GeV "extra energy" after timing cuts

Combination of time and $p_T$ cuts

3 sets of cuts defined: loose, default, tight
Jet Finding at CLIC

Durham-style jet finders used in exclusive mode sensitive to background.

Analyses in CDR used $k_T$ algorithm as implemented in FastJet.

"Beam Jets" pick up most of the forward boosted background.
Flavor Tagging at CLIC

Efficient tagging of b- and c-jets is a crucial component of the Higgs program at a linear collider. Using (basically) the ZVTOP algorithm as implemented by the LCFI collaboration.

Background somewhat deteriorates the tagging efficiency.
Reconstruction Summary

Intense beams at CLIC pose a challenge for the reconstruction:

- 19 TeV additionally deposited in the calorimeters

Three ways to reduce impact:

1. Reconstruction time slice:
   Identify interesting event offline and remove out-of-time hits

2. Reconstructed particle time:
   Compute the time of the particle from the (energy-weighted) average of the calorimeter hits. Remove low-$p_T$, late arriving particles

3. Jet reconstruction:
   Beam jets pick up a lot of the forward-boosted background
Physics Studies at CLIC

Studies have been done with detailed detector simulation
Background taken into account

- (Standard Model) Higgs Studies
- Studies of Physics Beyond the Standard Model
Higgs Physics at CLIC
Higgs Physics at CLIC

Higgs Recoil method: First sensitivity to invisible decays

Top Yukawa coupling

Higgs width

Higgs BR: second generation fermions c quarks, muons

Higgs self-coupling: < 20%
Higgs Recoil Method

Reconstruct the Z in the di-muon channel

Well-known value for $E_{CM}$ allows to plot the recoil against the Z

No information about the Higgs decay enters this plot → sensitivity to invisible decays

Absolute measurement of gauge coupling, limited only by beamstrahlung

$$\frac{\Delta \sigma}{\sigma} \approx 4\% \quad \frac{\Delta g_{HZZ}}{g_{HZZ}} \approx 2\%$$

only statistical uncertainty quoted
Higgs BR measurements at 3 TeV

GEANT4-based detector simulation studies
Realistic simulation of pile-up background
achievable measurement uncertainty on
h → bb: 0.22%  h → mu mu: 15%
h → cc: 3.2%

tri-linear self-coupling: ∼20% (in progress)
Physics Beyond the Standard Model

First stage defined by physics
350 GeV / 500 GeV
(Higgs, top)

Later stages guided by future observations

Staging scenario A:
Stage 1: 500 GeV
Stage 2: 1400 GeV
Stage 3: 3000 GeV
Gaugino Pair Production

$e^+e^- \rightarrow \tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0W^+W^-$
$e^+e^- \rightarrow \tilde{\chi}_2^0\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0hh$
$e^+e^- \rightarrow \tilde{\chi}_2^0\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0Zh$

Signature: 4 Jets + missing Energy
Separation of heavy bosons based on reconstructed invariant mass

\[
\begin{align*}
\sigma(\tilde{\chi}_1^+\tilde{\chi}_1^-) &= 10.6 \text{ fb} \pm 0.25 \text{ fb} \\
m(\tilde{\chi}_1^\pm) &= 643.2 \text{ GeV} \pm 7 \text{ GeV} \\
\sigma(\tilde{\chi}_2^0\tilde{\chi}_2^0) &= 3.3 \text{ fb} \pm 0.11 \text{ fb} \\
m(\tilde{\chi}_2^0) &= 643.1 \text{ GeV} \pm 10 \text{ GeV}
\end{align*}
\]

only statistical uncertainty quoted

Detailed Detector Simulation including background
3 TeV CLIC
Heavy Higgs Bosons

Test of flavor tagging in boosted jets and reconstruction of high-energy jets

\[ e^+e^- \rightarrow H^0 A^0 \rightarrow b\bar{b}b\bar{b} \]

\[ e^+e^- \rightarrow H^+ H^- \rightarrow t\bar{b}b\bar{t} \]

\[ m(H^+/H^-) = 906.3 \text{ GeV} \pm 2.4 \text{ GeV} \]
\[ m(A^0/H^0) = 902.4 \text{ GeV} \pm 2.8 \text{ GeV} \]

Sensitivity nearly up to \( 1/2 \sqrt{s} \)

1.1 fb
0.5 fb

only statistical uncertainty quoted
Physics Summary

The CLIC environment at 3 TeV presents a unique opportunity for physics at the TeraScale

Detailed simulation studies show that the impact of the background can be controlled

Excellent detector performance allows precision measurements of heavy objects even at 3 TeV
Hardware R&D

Hadronic Calorimeters
  Scintillator Plates in W absorber structure
  Glass RPC in W absorber structure

Vertex Detector Engineering
Vertex Detector Pixels
Analog HCAL

HCAL tests in 2010+2011
10 mm thick **Tungsten absorber** plates
scintillator active layers, 3×3 cm² cells

longitudinal shower profile, pions  
visible Energy, protons

CERN SPS 2011

Validation of GEANT 4 models in tungsten stack

Good agreement found
Digital HCAL

~ 500,000 channels
World record for hadronic calorimetry

54 glass RPC chambers, 1m² each
PAD size 1×1 cm²
Digital readout (1 threshold)
100 ns time-slicing
Fully integrated electronics
Main DHCAL stack (39) + tail catcher (15)

CERN test setup includes fast readout RPC (T3B)

W-DHCAL π⁻ at 210 GeV (SPS)
Inner Tracking Detectors

R&D

**Material budget goal**: 0.2% $X_0$ per layer

**Time stamping**: 10 ns

**Excellent flavor tagging**: small pixels $\sim$25x25 μm², small inner radius (2.7 cm)

Radiation level $< 10^{11} \text{ n}_{\text{eq}} \text{ cm}^{-2}\text{year}^{-1} \leq 10^4$ lower than LHC
Low-mass Cooling

• Temperature < 30°C
• Except barrel layer 2 (40°C)
• Conduction not taken into account

Mass Flow: 20.1 g/s
Average velocity:
@ inlet: 11.0 m/s
@ z=0: 5.2 m/s
@ outlet: 6.3 m/s

ANSYS finite element simulation of air-flow cooling:
Spiral disk geometry allows for air flow into barrel
Sufficient heat removal
Power Delivery

**DC/DC converters outside pixel-sensor area**

**Flexible Kapton cables** with Al conductor for power delivery

**Power pulsing @ 50 Hz,** reducing avg. power

**Local energy storage** and voltage regulation with Si capacitors (~10 μF/chip) and LDO regulators
CLICPix demonstrator

Hybrid approach pursued: (<= other options possible)
• Thin (~50 μm) silicon sensors (Micron, CNM, VTT)
• Thinned High density ASIC in very-deep-sub-micron:
• TimePix3, Smallpix <= R&D steps
• CLICpix
• Low-mass interconnect
• Micro-bump-bonding (Cu-pillar option, Advacam)
• Through-Silicon-Vias (R&D with CEA-Leti)
• Chip-stitching

CLICpix
64×64 pixel demonstrator
• 65 nm technology
• 25×25 μm² pixels
• 4-bit TOA and TOT information
• 10 nsec time-slicing
• Power 2 W/cm² (continuous)
With sequential power pulsing 50 mW/cm²
• CLIC CDR (#1), A Multi-TeV Linear Collider based on CLIC Technology, CERN-2012-003, https://edms.cern.ch/document/1234244/
• CLIC CDR (#2), Physics and Detectors at CLIC, CERN-2012-003, arXiv:1202.5940
• CLIC CDR (#3), The CLIC Programme: towards a staged e+e- Linear Collider exploring the Terascale, CERN-2012-005, http://arxiv.org/abs/1209.2543
Organisation of CLIC Detector and Physics study

Pre-collaboration structure, based on a “Memorandum on Cooperation”
http://lcd.web.cern.ch/LCD/Home/MoC.html
Faster implementation possible, (e.g. for lower-energy Higgs factory): klystron-based initial stage

Lucie Linssen, CLIC workshop, 28 January 2013
Further exploration of the physics potential

- Complete picture of Higgs prospects at ~350 GeV, ~1.4 TeV, ~3 TeV
- Discovery reach for BSM physics
- Sensitivity to BSM through high-precision measurements

Detector Optimisation studies

- Optimisation studies linked to physics (e.g. aspect ratio, forward region coverage);
- Interplay between occupancies and reconstruction;
- Interplay between technology R&D and simulation models.

Technology demonstrators

- Many common developments with ILC
- Complemented with CLIC requirements

Drives the CLIC staging strategy

cf. LHC results

Lucie Linssen, CLIC workshop, 28 January 2013
R&D objectives: 2013-2016

R&D => technology demonstrators

Implementation examples demonstrating the required functionality

**Vertex detector**
Demonstration module, meeting requirements of high precision, 10 ns time stamp and ultra-low mass

**Main tracker**
Demonstration modules, including manageable occupancies in the event reconstruction

**Calorimeters**
Demonstration modules, technological prototypes + addressing control of cost

**Electronics**
Demonstrators, in particular in view of power pulsing

**Magnet systems**
Demonstrators of conductor technology, safety systems and moveable service lines

**Engineering and detector integration**
Engineering design and detector integration harmonized with hardware R&D demonstrators

Challenging and interesting detector technologies
Considered feasible in a 5-year R&D program

Lucie Linssen, CLIC workshop, 28 January 2013
Summary of CLIC detector & physics CDR studies

- Feasibility of precision physics measurements demonstrated
- Staged implementation of CLIC => large potential for SM and BSM physics

Good progress with understanding detectors at CLIC

- Based on ILD and SiD concepts
- Detector requirements now well understood
- => challenging, but feasible through realistic R&D

Development program for the next CLIC phases

- Anticipating energy frontier machine choice ~2017
- Anticipating start of construction by ~2023

Welcome to join !

lcd.web.cern.ch/lcd/
http://lcd.web.cern.ch/LCD/Home/MoC.html
Backup
Power Pulsing Measurements

Test setup with active loads emulating analog pixel F/E:

- Equivalent thickness cable + LDO + cap.: 0.145% X0 / layer in vtx region
- Power pulsing at 50 Hz
- Load current of 2 A (half ladder) during 15 μs
- Monitor load voltages and currents
- Observed ripple ΔV < 20 mV, acceptable for CLICPix
- Agreement between measurement and simulation
Based on 200 days/year at 50% efficiency (accelerator + data taking combined)

Target figures: >600 fb\(^{-1}\) at first stage, 1.5 ab\(^{-1}\) at second stage, 2 ab\(^{-1}\) at third stage

Fig. 5.2: Integrated luminosity in the scenarios optimised for luminosity in the first energy stage (left) and optimised for entry costs (right). Years are counted from the start of beam commissioning. These figures include luminosity ramp-up of four years (5%, 25%, 50%, 75%) in the first stage and two years (25%, 50%) in subsequent stages.
Z' Sensitivity Study
CLIC_ILD $\leftrightarrow$ and CLIC_SiD $\leftrightarrow$ tracker

TPC + silicon tracker in 4 Tesla field

all-silicon tracker in 5 Tesla field

Time Projection Chamber (TPC) with MPGD readout

Lucie Linssen, CLIC workshop, 28 January 2013
ECAL

Si or Scint. (active) + Tungsten (absorber)
cell sizes 13 mm$^2$ or 25 mm$^2$
30 layers in depth

HCAL

Several technology options: scint. or gas
Tungsten (barrel), steel (endcap)
cell sizes 9 cm$^2$ (analog) or 1 cm$^2$ (digital)
60-75 layers in depth
Total depth $7.5 \Lambda_i$

High precision on jets
↓
ECAL + HCAL have to fit inside coil
↓
CLIC needs Tungsten absorber in HCAL
↓
Requires beam tests to validate Geant4

Simulated jet energy resolution

(No jet clustering, without background overlay)
# Higgs Summary

Higgs studies for $m_H = 120$ GeV

<table>
<thead>
<tr>
<th>$\sqrt{s}$ (GeV)</th>
<th>Process</th>
<th>Decay mode</th>
<th>Measured quantity</th>
<th>Unit</th>
<th>Generated value</th>
<th>Stat. error</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>350</td>
<td>$ZH \to \mu^+ \mu^- X$</td>
<td>$\sigma$</td>
<td>fb</td>
<td>4.9</td>
<td>4.9%</td>
<td></td>
<td>Model independent, using $Z$-recoil</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mass</td>
<td>GeV</td>
<td>120</td>
<td>0.131</td>
<td></td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>SM Higgs production</td>
<td>$ZH \to q\bar{q}q\bar{q}$</td>
<td>$\sigma \times \text{BR}$</td>
<td>fb</td>
<td>34.4</td>
<td>1.6%</td>
<td>$ZH \to q\bar{q}q\bar{q}$ mass reconstruction</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mass</td>
<td>GeV</td>
<td>120</td>
<td>0.100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>$ZH, H\nu\bar{\nu}$</td>
<td>$\sigma \times \text{BR}$</td>
<td>fb</td>
<td>80.7</td>
<td>1.0%</td>
<td></td>
<td>Inclusive sample</td>
</tr>
<tr>
<td></td>
<td>$\to \nu\bar{\nu}q\bar{q}$</td>
<td>Mass</td>
<td>GeV</td>
<td>120</td>
<td>0.100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1400</td>
<td>$H \to \tau^+\tau^-$</td>
<td>$\sigma \times \text{BR}$</td>
<td>fb</td>
<td>19.8</td>
<td>&lt;3.7%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3000</td>
<td>$WW$ fusion</td>
<td>$H \to b\bar{b}$</td>
<td>$\sigma \times \text{BR}$</td>
<td>fb</td>
<td>285</td>
<td>0.22%</td>
<td>Higgs tri-linear coupling</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$H \to c\bar{c}$</td>
<td>fb</td>
<td>13</td>
<td>3.2%</td>
<td></td>
<td>$g_{HWW}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$H \to \mu^+\mu^-$</td>
<td>fb</td>
<td>0.12</td>
<td>15.7%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1400</td>
<td>$WW$ fusion</td>
<td>Higgs</td>
<td>$\sigma \times \text{BR}$</td>
<td>fb</td>
<td>285</td>
<td>0.22%</td>
<td>Higgs tri-linear coupling</td>
</tr>
<tr>
<td>3000</td>
<td></td>
<td>$g_{HWW}$</td>
<td>fb</td>
<td>0.12</td>
<td>15.7%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| $g_{HHH}$ | $\approx 20\%$ | $g_{HHH}$ | $\approx 20\%$ |
SUSY Summary

Results of detailed simulation study for a given SUSY model (model III)
CLIC operated at 1.4 TeV, 1.5 ab⁻¹
Results from earlier stage(s) not taken into account
## Susy models I & II

<table>
<thead>
<tr>
<th>√s (TeV)</th>
<th>Process</th>
<th>Decay mode</th>
<th>SUSY model</th>
<th>Measured quantity</th>
<th>Unit</th>
<th>Generator value</th>
<th>Stat. error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$\tilde{\mu}_R \tilde{\mu}_R \rightarrow \mu^+ \mu^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$</td>
<td>I &amp; II</td>
<td>$\sigma$</td>
<td>fb</td>
<td>0.72</td>
<td>2.8%</td>
</tr>
<tr>
<td>3.0</td>
<td>Sleptons production</td>
<td>$\tilde{e}_R^+ \tilde{e}_R^- \rightarrow e^- e^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$</td>
<td>II</td>
<td>$\tilde{\ell}$ mass</td>
<td>GeV</td>
<td>1010.8</td>
<td>0.6%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\tilde{\chi}_1^0$ mass</td>
<td>GeV</td>
<td>340.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.0</td>
<td></td>
<td>$\tilde{\nu}_e \tilde{\nu}_e \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 e^+ e^- W^+ W^-$</td>
<td></td>
<td>$\sigma$</td>
<td>fb</td>
<td>3.07</td>
<td>7.2%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\tilde{\chi}_1^\pm$ mass</td>
<td>GeV</td>
<td>1097.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\tilde{\chi}_1^\mp$ mass</td>
<td>GeV</td>
<td>643.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.0</td>
<td>Chargino production</td>
<td>$\tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 W^+ W^-$</td>
<td>II</td>
<td>$\tilde{\chi}_1^+$ mass</td>
<td>GeV</td>
<td>643.2</td>
<td>1.1%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\tilde{\chi}_1^-$ mass</td>
<td>GeV</td>
<td>10.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Neutralino production</td>
<td>$\tilde{\chi}_2^0 \tilde{\chi}_2^0 \rightarrow h/Z^0 h/Z^0 \tilde{\chi}_1^0 \tilde{\chi}_1^0$</td>
<td></td>
<td>$\chi_2^0$ mass</td>
<td>GeV</td>
<td>643.1</td>
<td>1.5%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\tilde{\chi}_2^0$ mass</td>
<td>GeV</td>
<td>3.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.0</td>
<td>Production of right-handed squarks</td>
<td>$\bar{q}_R \bar{q}_R \rightarrow q q \tilde{\chi}_1^0 \tilde{\chi}_1^0$</td>
<td>I</td>
<td>Mass</td>
<td>GeV</td>
<td>1123.7</td>
<td>0.52%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\sigma$</td>
<td>fb</td>
<td>1.47</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.0</td>
<td>Heavy Higgs production</td>
<td>$H^0 A^0 \rightarrow b\bar{b}b\bar{b}$</td>
<td>I</td>
<td>Mass</td>
<td>GeV</td>
<td>902.4</td>
<td>0.3%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Width</td>
<td>GeV</td>
<td>906.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$H^+ H^- \rightarrow \tilde{t}\tilde{b} \tilde{b} \tilde{t}$</td>
<td></td>
<td>Mass</td>
<td>GeV</td>
<td>906.3</td>
<td>0.3%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Width</td>
<td>GeV</td>
<td>902.4</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
PFA Performance w/o background

(no jet clustering, without background overlay)
Detector Costing (no labor)

Table 5.4: Value estimate of the CLIC detectors.

<table>
<thead>
<tr>
<th></th>
<th>CLIC_ILD (MCHF)</th>
<th>CLIC_SiD (MCHF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertex</td>
<td>13</td>
<td>15</td>
</tr>
<tr>
<td>Tracker</td>
<td>51</td>
<td>17</td>
</tr>
<tr>
<td>Electromagnetic calorimeter</td>
<td>197</td>
<td>89</td>
</tr>
<tr>
<td>Hadronic calorimeter</td>
<td>144</td>
<td>86</td>
</tr>
<tr>
<td>Muon system</td>
<td>28</td>
<td>22</td>
</tr>
<tr>
<td>Coil and yoke</td>
<td>117</td>
<td>123</td>
</tr>
<tr>
<td>Other</td>
<td>11</td>
<td>12</td>
</tr>
<tr>
<td>Total (rounded)</td>
<td>560</td>
<td>360</td>
</tr>
</tbody>
</table>

Fig. 5.9: Cost structure of the CLIC detectors.
## Vertex Region Layout

<table>
<thead>
<tr>
<th></th>
<th>CLIC_ILD</th>
<th>CLIC_SiD</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Central beam pipe</strong></td>
<td>$R_i = 29.4,\text{mm}$ \hspace{3cm} $d = 0.6,\text{mm}$</td>
<td>$R_i = 24.5,\text{mm}$ \hspace{3cm} $d = 0.5,\text{mm}$</td>
</tr>
<tr>
<td><strong>Barrel region</strong></td>
<td>3 double layers $</td>
<td>z</td>
</tr>
<tr>
<td><strong>Forward region</strong></td>
<td>3 double layers $z = 160, 207, 255,\text{mm}$</td>
<td>7 single layers $z = 120, 160, 200, 240, 280, 500, 830,\text{mm}$</td>
</tr>
<tr>
<td><strong>Sensors</strong></td>
<td>$20,\mu\text{m} \times 20,\mu\text{m}$, $\sigma_{x_p} \approx 3,\mu\text{m}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$X/X_0 = 0.18%$ per double layer</td>
<td>$X/X_0 = 0.11%$ per single layer</td>
</tr>
<tr>
<td><strong>Surface area</strong></td>
<td>$0.736,\text{m}^2$</td>
<td>$1.103,\text{m}^2$</td>
</tr>
<tr>
<td><strong>Number of channels</strong></td>
<td>$1.84 \times 10^9$</td>
<td>$2.76 \times 10^9$</td>
</tr>
</tbody>
</table>
The Silicon Envelope in numbers
(current scheme)

<table>
<thead>
<tr>
<th>Component</th>
<th>Layer #</th>
<th># modules</th>
<th># sensors/module</th>
<th># channels</th>
<th>Total surface m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIT1</td>
<td>1st layer</td>
<td>33</td>
<td>3</td>
<td>66,000</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>2nd layer</td>
<td>99</td>
<td>1</td>
<td>198,000</td>
<td>0.9</td>
</tr>
<tr>
<td>SIT2</td>
<td>1st layer</td>
<td>90</td>
<td>3</td>
<td>180,000</td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td>2nd layer</td>
<td>270</td>
<td>1</td>
<td>540,000</td>
<td>2.7</td>
</tr>
<tr>
<td>SET</td>
<td>1st layer</td>
<td>1260</td>
<td>5</td>
<td>2,520,000</td>
<td>55.2</td>
</tr>
<tr>
<td></td>
<td>2nd layer</td>
<td>1260</td>
<td>5</td>
<td>2,520,000</td>
<td>55.2</td>
</tr>
<tr>
<td>ETD_F</td>
<td>X or U or V</td>
<td>82/quad</td>
<td>2 or 3 or possibly 4</td>
<td>2,000,000</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>idem</td>
<td>idem</td>
<td>idem</td>
<td>idem</td>
<td>30</td>
</tr>
</tbody>
</table>

Total number of channels:
10^6 (SIT) + 5x10^6 (SET) + 4x10^6 (2 ETD) = 10 x10^6 channels

Total area:
7 (SIT)+110 (SET) +2x30(ETDs) = 180 m²

Total number of modules:
500 (SIT) + 2500 (SET) + 2000 (ETDs)= 5000 modules with unique size sensors

=>Achieved: a unified and simple design for all components (except FTD)
### Key Parameters of the CLIC machine

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>500 GeV</th>
<th>3 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centre-of-mass energy</td>
<td>$\sqrt{s}$</td>
<td>TeV</td>
<td>0.5</td>
<td>3.0</td>
</tr>
<tr>
<td>Repetition frequency</td>
<td>$f_{rep}$</td>
<td>Hz</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Number of bunches per train</td>
<td>$n_b$</td>
<td></td>
<td>354</td>
<td>312</td>
</tr>
<tr>
<td>Bunch separation</td>
<td>$\Delta t$</td>
<td>ns</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Accelerating gradient</td>
<td>$G$</td>
<td>MV/m</td>
<td>80</td>
<td>100</td>
</tr>
<tr>
<td>Total luminosity</td>
<td>$\mathcal{L}_{\text{total}}$</td>
<td>$10^{34} \text{cm}^{-2} \text{s}^{-1}$</td>
<td>2.3</td>
<td>5.9</td>
</tr>
<tr>
<td>Luminosity above 99% of $\sqrt{s}$</td>
<td>$\mathcal{L}_{0.01}$</td>
<td>$10^{34} \text{cm}^{-2} \text{s}^{-1}$</td>
<td>1.4</td>
<td>2.0</td>
</tr>
<tr>
<td>Number of photons per electron/positron</td>
<td>$n_\gamma$</td>
<td></td>
<td>1.3</td>
<td>2.1</td>
</tr>
<tr>
<td>Average energy loss due to beamstrahlung</td>
<td>$\Delta E/E$</td>
<td></td>
<td>0.07</td>
<td>0.28</td>
</tr>
<tr>
<td>Number of coherent pairs per bunch crossing</td>
<td>$N_{\text{coh}}$</td>
<td></td>
<td>$2 \times 10^{-2}$</td>
<td>$6.8 \times 10^8$</td>
</tr>
<tr>
<td>Energy of coherent pairs per bunch crossing</td>
<td>$E_{\text{coh}}$</td>
<td>TeV</td>
<td>15</td>
<td>$2.1 \times 10^8$</td>
</tr>
<tr>
<td>Number of incoherent pairs per bunch crossing</td>
<td>$n_{\text{incoh}}$</td>
<td>$10^6$</td>
<td>0.08</td>
<td>0.3</td>
</tr>
<tr>
<td>Energy of incoherent pairs per bunch crossing</td>
<td>$E_{\text{incoh}}$</td>
<td>$10^6 \text{ GeV}$</td>
<td>0.36</td>
<td>23</td>
</tr>
<tr>
<td>Hadronic events per bunch crossing</td>
<td>$n_{\text{had}}$</td>
<td></td>
<td>0.3</td>
<td>3.2</td>
</tr>
</tbody>
</table>
Background Properties