Detectors at CLIC

Philipp Roloff (CERN)
on behalf of the CLIC physics and detector study

Joint Instrumentation Seminar, DESY Hamburg, 20/01/2012
Outline

• The CLIC accelerator
• Physics at CLIC
• Detector requirements
• The CLIC_ILD and CLIC_SiD detectors
  - Vertex detectors
  - Tracking
  - Calorimetry
• Background suppression and event reconstruction
The CLIC accelerator
e^+e^- collisions at high energies → linear accelerators

**International Linear Collider (ILC):**
- Based on superconducting RF cavities (like XFEL)
- Gradient: 32 MV/m
- Energy: 500 GeV, upgradable to 1 TeV
- Detector studies focussed mostly on up to 500 GeV, work for 1 TeV ongoing

**Compact Linear Collider (CLIC):**
- Based on 2-beam acceleration scheme
- Operated at room temperature
- Gradient: 100 MV/m
- Energy: 3 TeV, staged construction in steps starting from few hundred GeV possible
- Detector study focusses on 3 TeV, lower energies will be studies soon

Luminosities: \( \text{few } 10^{34} \text{ cm}^{-2}\text{s}^{-1} \)
2-beam acceleration scheme

Drive beam supplies RF power:
- 12 GHz bunch structure
- Low energy:
  2.4 GeV – 240 MeV
- High current: 100 A

Main beam for physics:
- High energy: 9 GeV – 1.5 TeV
- Current: 1.2 A
CLIC accelerator complex

326 klystrons
33 MW, 139 μs

drive beam accelerator
2.38 GeV, 1.0 GHz

1 km

delay loop

CR1

CR2

circumferences delay loop 73.0 m
CR1 146.1 m
CR2 438.3 m

drive beam accelerator
2.38 GeV, 1.0 GHz

1 km

delay loop

CR1

CR2

decelerator, 24 sectors of 876 m

326 klystrons
33 MW, 139 μs

BC2

245 m

e− main linac, 12 GHz, 100 MV/m, 21.02 km

BC2

245 m

e+ main linac

TA radius = 120 m

48.3 km

booster linac, 6.14 GeV

BC1

e− injector, 2.86 GeV

e−
PDR
398 m
e−
DR
493 m
e−

e+
PDR
398 m
e+
DR
493 m
e+

CR
combiner ring
TA
turnaround
DR
damping ring
PDR
predamping ring
BC
bunch compressor
BDS
beam delivery system
IP
interaction point
dump

20/01/2012 Philipp Roloff DESY Instrumentation Seminar
CLIC provides the potential for e+e- collisions up to $\sqrt{s} = 3$ TeV: Challenging machine environment → detailed detector studies are needed

CLIC physics and detector CDR:
• Physics potential
• Demonstrate that the physics can be measured at CLIC

Release of the CDR text (20.12.2011):
https://edms.cern.ch/document/1177771

Review in October 2011:
https://indico.cern.ch/conferenceTimeTable.py?confId=146521
**Selected CLIC parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>L (cm(^{-2})s(^{-1}))</td>
<td>(5.9 \cdot 10^{34})</td>
</tr>
<tr>
<td>Bunch separation</td>
<td>0.5 ns</td>
</tr>
<tr>
<td>#Bunches / train</td>
<td>312</td>
</tr>
<tr>
<td>Train duration</td>
<td>156 ns</td>
</tr>
<tr>
<td>Train rep. rate</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Crossing angle</td>
<td>20 mrad</td>
</tr>
<tr>
<td>Particles / bunch</td>
<td>(3.72 \cdot 10^{9})</td>
</tr>
<tr>
<td>(\sigma_x / \sigma_y) (nm)</td>
<td>(\approx 45 / 1)</td>
</tr>
<tr>
<td>(\sigma_z) ((\mu)m)</td>
<td>44</td>
</tr>
</tbody>
</table>

**Drive timing requirements for CLIC detector**

**Very small beam profile at the interaction point**

---

**CLIC:** trains at 50 Hz, 1 train = 312 bunches, 0.5 ns apart
Significant energy loss at the interaction point due to **Beamstrahlung**

![Graph showing Luminosity spectrum](image)

**Luminosity spectrum**

Full luminosity: \( L = 5.9 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \)

In the most energetic 1% (“peak luminosity”): \( L_{0.01} = 2.0 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \)

Most physics processes are studied well above the production threshold

\[ \sqrt{s'} = \sqrt{4 \cdot E_1 \cdot E_2} \]

\[ \sqrt{s'} = \sqrt{4 \cdot E_1 \cdot E_2} \]
Beam related backgrounds

- $e^+e^-$ pairs
- $\gamma\gamma \rightarrow$ hadrons
- Beam halo muons

Coherent $e^+e^-$ pairs:
7 · $10^8$ per BX, very forward

Incoherent $e^+e^-$ pairs:
3 · $10^5$ per BX, rather forward
→ Detector design issue
(high occupancies)

$\gamma\gamma \rightarrow$ hadrons
- “Only” 3.2 per BX
- Main background in calorimeters and trackers
→ Impact on physics

$\gamma/\gamma^*$

$\gamma/\gamma^*$

Particles [1/BX]

BX = bunch crossing

$\theta$ [rad]
Physics at CLIC
CLIC physics potential

Advantage of $e^+e^-$ collisions:
- Defined initial state
- Precision measurements possible due to clean conditions
- Well suited for weakly interacting states (e.g. sleptons, gauginos)
- Polarised (electron) beam

→ Complementary / enhanced discovery reach compared to the LHC

Examples highlighted in the CDR:
- Higgs physics (SM and non-SM)
- Top physics
- SUSY
- Higgs strong interactions
- $Z'$
- Contact interactions
- Extra dimensions
- ...

<table>
<thead>
<tr>
<th>SUSY Model 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Higgs</td>
</tr>
<tr>
<td>$\bar{\tau}, \bar{\mu}, \bar{\nu}$</td>
</tr>
<tr>
<td>charginos</td>
</tr>
<tr>
<td>squarks</td>
</tr>
<tr>
<td>SM</td>
</tr>
<tr>
<td>$\bar{\nu}<em>\tau, \bar{\nu}</em>\mu, \bar{\nu}_e$</td>
</tr>
<tr>
<td>neutralinos</td>
</tr>
</tbody>
</table>

√s (GeV) vs. cross section (fb)
SM Higgs production

s-channel: $\sim \frac{1}{s}$

At $\sqrt{s} = 3$ TeV: WW fusion $(e^+e^- \rightarrow H \nu_e \bar{\nu}_e)$ dominant

$M_h = 120$ GeV
Example Higgs observables

\[ \sigma(h \rightarrow \mu^+\mu^-) \rightarrow \pm 15\% \text{ (stat.)} \]

\[ \sigma(h \rightarrow b\bar{b}) \rightarrow \pm 0.22\% \text{ (stat.)} \]

<table>
<thead>
<tr>
<th>Coupling</th>
<th>Sensitivity to SM deviation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(H_{bb})</td>
<td>2</td>
</tr>
<tr>
<td>(H_{cc})</td>
<td>3</td>
</tr>
<tr>
<td>(H_{\mu\mu})</td>
<td>15</td>
</tr>
</tbody>
</table>
Resolving new physics models

Precision measurements at CLIC allow to discriminate between new physics models, e.g. following first observations at the LHC

Example: SUSY breaking models with nearly degenerate mass spectra
Detector requirements
Physics aims → detector needs

- **Momentum resolution**
  (e.g. Higgs recoil mass, $h \rightarrow \mu^+\mu^-$, leptons from BSM processes)
  $\frac{\sigma(p_T)}{p_T^2} \sim 2 \times 10^{-5} \text{GeV}^{-1}$

- **Jet energy resolution**
  (e.g. $W/Z/h$ separation)
  $\frac{\sigma(E)}{E} \sim 3.5 - 5\% \text{ for } E = 1000 - 50 \text{GeV}$

- **Impact parameter resolution**
  (b/c tagging, e.g. Higgs couplings)
  $\sigma(d_0) = \sqrt{a^2 + b^2 \cdot \text{GeV}}^2 / (p^2 \sin^3 \theta)$, $a \approx 5 \mu m, b \approx 15 \mu m$

- **Lepton identification, very forward electron tagging**

\[\sqrt{s} = 500 \text{ GeV}\]
Physics aims \( \rightarrow \) detector needs

- Momentum resolution
  (e.g. Higgs recoil mass, \( h \rightarrow \mu^+\mu^- \),
  leptons from BSM processes)

\[
\frac{\sigma (p_T)}{p_T^2} \sim 2 \times 10^{-5} \text{ GeV}^{-1}
\]

- Jet energy resolution
  (e.g. W/Z/h separation)

\[
\frac{\sigma (E)}{E} \sim 3.5 - 5\% \text{ for } E = 1000 - 50 \text{ GeV}
\]

- Impact parameter resolution
  (b/c tagging, e.g. Higgs couplings)

\[
\sigma (d_0) = \sqrt{a^2 + b^2 \cdot GeV^2 / (p^2 \sin^3 \theta)} , \ a \approx 5 \mu m , \ b \approx 15 \mu m
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- Lepton identification, very forward electron tagging
Physics aims → detector needs

• Momentum resolution
  (e.g. Higgs recoil mass, $h \rightarrow \mu^+\mu^-$, leptons from BSM processes)
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  \frac{\sigma(p_T)}{p_T^2} \sim 2 \times 10^{-5} \text{ GeV}^{-1}
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• Jet energy resolution
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  \[
  \sigma(d_0) = \sqrt{a^2 + b^2 \cdot GeV^2/p^2 \sin^3 \theta}, \ a \approx 5 \mu m, \ b \approx 15 \mu m
  \]

• Lepton identification, very forward electron tagging
3.2 $\gamma\gamma \rightarrow \text{hadr.} \ \text{Interactions per bunch crossing:}$

- 19 TeV in the calorimeters per 156 ns bunch train
- 5000 tracks with a total momentum of 7.3 TeV

**Triggerless readout of full bunch train:**
- Time-stamping in tracking detectors and calorimeters
- Multi-hit storage / readout
- Filtering algorithms at reconstruction level (→ later)
The CLIC_ILD and CLIC_SiD detectors
Detector overview

1.) Low-mass vertex detector with 20 x 20 μm² pixels

2.) Main trackers: TPC+silicon (CLIC_ILD), all-silicon (CLIC_SiD)

3.) Fine grained (PFA) calorimetry, 1+7.5 λ

Strong solenoids (4-5 T)

Instrumented return yoke for muon ID

Complex forward region with final beam focusing (not discussed in this talk)

≈ 7 m
CLIC detector concepts

Based on validated ILC designs, adapted and optimised to the CLIC conditions:

- Denser HCAL in the barrel (Tungsten, 7.5 $\lambda$)
- Redesign of the vertex and forward detectors (backgrounds)
Vertex detectors
Vertex detector

Requirements:
• 20 x 20 $\mu$m$^2$ pixel size
• Material: 0.2% $X_0$ per layer:
  - Very thin materials / sensors
  - Low-power design, power pulsing, low-mass cooling
• Time stamping precision: 5 - 10 ns (to reject backgrounds)
• Radiation level: $\approx 10^{10}$ $n_{eq}$ /cm$^2$ /yr ($10^{-4}$ of LHC)

CLIC_ILD:
Vertex & forward tracking
**Vertex detector layouts**

**CLIC_ILD:** 3 double layers, $1.84 \cdot 10^9$ pixels

**CLIC_SiD:** 5 single layers, $2.76 \cdot 10^9$ pixels
Occupancies in the CLIC_ILD vertex region

**Barrel cylinder layers**

- Direct hits from incoherent $e^+e^-$ pairs dominate
- Barrel: up to 1.9% train occupancy / pixel
- Forward: up to 2.9% train occupancy / pixel
  (including safety factors for simulation uncertainty and clustering)
Vertex detector: $P \approx 500 \text{ W} \rightarrow$ need low mass cooling solutions

**Forced (dry) air flow:**
- Baseline for barrel region
- No extra material
- Up to 240 liter/s flow, $\approx 40 \text{ km/h flow velocity}$

**Options in forward disks:**
- Evaporative CO$_2$ cooling (high pressure $\rightarrow$ thick tubes)
- Water cooling (sub-atmospheric pressure)

**Micro-channel cooling:**
- Ongoing R&D (e.g. NA62 upgrade)
- Integrate cooling channels in Silicon
- May be suitable for regions where sufficient air flow can not be established
1.) **Hybrid technologies:**
   - Thinned high-resistivity fully depleted sensors
   - Fast, low-power highly integrated readout chip
   - Low mass interconnects

**Pros:**
- Factorisation of sensor + readout R&D
  → Readout chips profit fully from advancing industry standards

**Cons:**
- Interconnect difficult / expensive → needs R&D
  - Harder to reduce material

• Thinned high-resistivity fully depleted sensors:
  - 50 µm active thickness
  - ALICE pixel upgrade → meets CLIC goals

• Fast low-power readout chips:
  - **Timepix3** (2012) in 130 nm IBM CMOS:
    - 55 x 55 µm² pixels
    - 1.5 ns time resolution → exceeds CLIC goals
    - $P \approx 10$ µW / pixel
  - **CLICPix** (prototypes ≈2014) in 65 nm, 20 x 20 µm² pixels
2.) **Integrated technologies:**

- Sensor and readout combined in one chip
- Charge collection in epitaxial layer

**Pros:**
- Allows for very low material solutions
- Synergy with R&D for ILC detectors

**Cons:**
- Harder to achieve good time resolution and sufficient S/N

- Several active R&D programs (targeted to ILC requirements)
- Attempts to reach faster signal collection and ns time-stamping capability (compatible with CLIC requirements):
  - MIMOSA CMOS with high-resistivity epitaxial layers
  - Chronopixel CMOS
  - INMAPS
  - High voltage CMOS

3.) **New technologies:**

- Silicon-On-Insulator (SOI)
- Full 3D-integrated pixel sensors
Tracking
Tracking in CLIC_ILD

TPC + silicon tracking in 4T field

Performance goal on momentum resolution achieved
Occasionalcies in the TPC

The readout time of the TPC is much longer than a CLIC bunch train

→ The TPC integrates the background of a full train at CLIC

Plots are for Gas Electron Multiplier (GEM) + Pad readout, voxels of 25 ns

→ A TPC at CLIC may need a larger inner radius or very small pads

Similar study with micromegas + pixel readout is starting
Tracking in CLIC_SiD

All silicon tracker in 5T field:
• Vertex detector and tracker viewed as one system
• Combined seeding and tracking

Two readout (KPiX) chips bump bonded to the sensor

Performance goal on momentum resolution achieved

\[ \sigma(\Delta p_T / p_{\text{true}}) \text{ [GeV]} \]

- Single $\mu^-$
- $\theta = 90^\circ$
- $\theta = 30^\circ$
- $\theta = 10^\circ$
Calorimetry
Calorimetry and PFA

Detector design driven by jet energy resolution and background rejection
→ Fine-grained calorimetry + particle flow analysis (PFA)

What is PFA?
Typical jet composition:
• 60% charged particles
• 30% photons
• 10% neutral hadrons

Always use the best available measurement:
• charged particles
  → tracking detectors: 😊😊
• photons → ECAL: 😊
• neutrals → HCAL: 😞

Hardware and software!
Calorimetry: technology

**ECAL:**
- Silicon pads or scintillator
- Tungsten absorber
- Cell sizes: $25 \text{ mm}^2$ (CLIC_ILD) $11 \text{ mm}^2$ (CLIC_SiD)
- 30 layers in depth
- $23 \chi_0$ and $1 \lambda$

**HCAL:**
- Several options for sensors
- Tungsten (barrel), steel (forward)
- Cell sizes: $9 \text{ cm}^2$ (analog) $1 \text{ cm}^2$ (digital)
- 60 - 75 layers in depth
- $7.5 \lambda$
Tungsten HCAL prototype

Main purpose: Validation of Geant4 simulation for hadronic showers in tungsten

Data taken 2010/11 at CERN-PS/SPS, mixed beams 1-300 GeV

Scintillator tiles 3x3 cm²
Read out by SiPM
Analog HCAL testbeam

10 GeV pion

Time structure of the showers:

More details:
Talk by Frank Simon on 24/06/2011

Mean time of first hit [ns]

T3B tile index

200 ns time window
- T3B data
- QGSP_BERT_HP
- QGSP_BERT

100 GeV pion
Time development in hadronic showers

In steel 90% of the energy is recorded within 6 ns (corrected for time-of-flight).
In tungsten only 82% of the energy is deposited within 25 ns:
(much larger component of the energy in nuclear fragments)

→ Energy resolution degrades if not the majority of calorimeter hits is read

→ Need to integrate over ≈100 ns in the reconstruction, keeping the background level low
Background suppression and event reconstruction
Background suppression

Triggerless readout of full bunch train:

1.) Identify \( t_0 \) of physics event in offline event filter
   - Define reconstruction window around \( t_0 \)
   - All hits and tracks in this window are passed to the reconstruction
     → Physics objects with precise \( p_T \) and cluster time information

2.) Apply cluster-based timing cuts
   - Cuts depend on particle-type, \( p_T \) and detector region
   → Protects physics objects at high \( p_T \)
### Time windows and hit resolutions

Used in the reconstruction software for CDR simulations:

<table>
<thead>
<tr>
<th>Subdetector</th>
<th>Reconstruction 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 Endcaps</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>$10/\sqrt{12}$ ns</td>
</tr>
<tr>
<td>TPC</td>
<td>entire bunch train</td>
<td>n/a</td>
</tr>
</tbody>
</table>

- CLIC hardware requirements
- Achievable in the calorimeters with a sampling every $\approx 25$ ns
Impact of the timing cuts

\[ e^+ e^- \rightarrow H^+ H^- \rightarrow t\bar{b}b\bar{t} \ (8 \text{ jet final state}) \]

1.2 TeV background in the reconstruction window

100 GeV background after (tight) timing cuts
Jet reconstruction at CLIC I

$e^+e^- \rightarrow \tilde{q}_R \tilde{q}_R \rightarrow q\bar{q} \tilde{\chi}_1^0 \tilde{\chi}_1^0$

Two jets + missing energy

- Using Durham $k_T$ à la LEP
  \rightarrow Timing cuts are effective, but not sufficient
Jet reconstruction at CLIC II

\[ e^+ e^- \rightarrow \tilde{q}_R \tilde{q}_R \rightarrow q\bar{q} \tilde{\chi}_1^0 \tilde{\chi}_1^0 \]

Two jets + missing energy

- Using Durham \( k_T \) à la LEP
  \( \rightarrow \) Timing cuts are effective, but not sufficient

- “hadron collider” \( k_T \), \( R = 0.7 \)
  \( \rightarrow \) Background significantly reduced further
  \( \rightarrow \) Need timing cut + jet finding for background reduction
Test of the di-jet mass reconstruction

Chargino and neutralino pair production:

\[ e^+ e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 W^+ W^- \]
\[ e^+ e^- \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0 \rightarrow hh \tilde{\chi}_1^0 \tilde{\chi}_1^0 \quad 82\% \]
\[ e^+ e^- \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0 \rightarrow Zh \tilde{\chi}_1^0 \tilde{\chi}_1^0 \quad 17\% \]

Reconstruct \( W^\pm/Z/h \) in hadronic decays → four jets and missing energy
Test of the lepton reconstruction

- Slepton production very clean at CLIC
- SUSY “model II”: slepton masses $\approx 1$ TeV
- Investigated channels include:
  
  $e^+e^- \rightarrow \tilde{\mu}_R^+\tilde{\mu}_R^- \rightarrow \mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0$
  
  $e^+e^- \rightarrow \tilde{\epsilon}_R^+\tilde{\epsilon}_R^- \rightarrow e^+e^-\tilde{\chi}_1^0\tilde{\chi}_1^0$
  
  $e^+e^- \rightarrow \tilde{\nu}_e\tilde{\nu}_e \rightarrow e^+e^-W^+W^-\tilde{\chi}_1^0\tilde{\chi}_1^0$

- Leptons and missing energy
- Masses from endpoints of energy spectra

$M(\tilde{\mu}_R) = 1014.29 \pm 5.57$ GeV

$M(\tilde{\epsilon}_R) = 341.75 \pm 6.38$ GeV

$M(\tilde{\chi}_1^0) = 314.38 \pm 5.54$ GeV
More detector benchmarks

- Full physics simulation and reconstruction with pileup from beam background ($\gamma \gamma \rightarrow \text{hadr.}$)

- Seven channels chosen to cover various crucial aspects of detector performance (jet measurements, missing energy, isolated leptons, flavour tagging, ...)
Summary and outlook

- Main message of the CLIC physics and detector CDR: Physics at a 3 TeV CLIC $e^+e^-$ collider can be measured with high precision, despite challenging background conditions

- Backgrounds studied in detail:
  - Require high granularity in space and time
  - Define detector requirements and guide future R&D

- Next project phase (5 years):
  - CLIC detector R&D (within the international LC R&D program)
  - Further physics studies (LHC input) + detector optimisation

- Signatories to support the physics case and R&D towards a future linear collider based on CLIC technology are currently collected here:

  https://indico.cern.ch/conferenceDisplay.py?confId=136364
Backup slides
Examples for hybrid approach

Thinned high-resistivity fully depleted sensors:
• 50 μm active width
• Example: ALICE pixel upgrade → meets CLIC goals

Fast low-power readout chips:
• Timepix3 (2012) in 130 nm IBM CMOS:
  - 55 x 55 μm² pixels
  - 1.5 ns time resolution → exceeds CLIC goals
  - $P \approx 350 \text{ mW}/\text{cm}^2$ → meets CLIC goals
    (with power pulsing)
• CLICPix (prototypes ≈2014) in 65 nm:
  - 20 x 20 μm² pixels

Low-mass interconnects between sensor+readout:
• Cost driver → needs further R&D
• Technologies: Through-Silicon Vias (TSV),
  3D interconnects, edgeless sensors,
  stitching of CMOS arrays
Examples for integrated approach

- Several active R&D programs (targeted to ILC requirements)

- Attempts to reach faster signal collection and ns time-stamping capability (compatible with CLIC requirements):
  - **MIMOSA CMOS** chip family (currently 350 nm): developing high-resistivity epitaxial layers, smaller feature sizes
  - **Chronopixel CMOS** sensors with fully depleted epitaxial layer
  - **INMAPS** technology: deep p-well barrier protects n-well charge collector, improves charge collection, allows for high-resistivity epitaxial layer and full featured CMOS MAPS technology
  - **High voltage CMOS**: CMOS signal processing electronics embedded in reverse-biased deep n-well that acts as signal collecting electrode
  - **Silicon-On-Insulator (SOI)**: ≈200 nm SiO₂ isolation layer separates charge collection and readout functionality
  - **Full 3D-integrated pixel sensors**: Thinned high-resistivity sensitive tier coupled to additional tiers with advanced analog+digital functionality
HCAL resolution

\[ \frac{\sigma}{E} [\%] \]

\[ \cos \theta \leq 0.7 \]

\[ Z \rightarrow uds, \text{jet energy:} \]
- \(45.5 \text{ GeV}\)
- \(100 \text{ GeV}\)
- \(250 \text{ GeV}\)
- \(500 \text{ GeV}\)
- \(1 \text{ TeV}\)
- \(1.5 \text{ TeV}\)

Number of \( \lambda_i \)'s in CLIC HCAL

\[ \text{Number of } \lambda_i \text{'s in CLIC HCAL} \]
# PFO based timing cuts

<table>
<thead>
<tr>
<th>Region</th>
<th>$p_t$ range</th>
<th>Time cut</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Photons</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>central</td>
<td>$0.75 \text{ GeV} \leq p_t &lt; 4.0 \text{ GeV}$</td>
<td>$t &lt; 2.0 \text{ nsec}$</td>
</tr>
<tr>
<td>(cos $\theta \leq 0.975$)</td>
<td>$0 \text{ GeV} \leq p_t &lt; 0.75 \text{ GeV}$</td>
<td>$t &lt; 1.0 \text{ nsec}$</td>
</tr>
<tr>
<td>forward</td>
<td>$0.75 \text{ GeV} \leq p_t &lt; 4.0 \text{ GeV}$</td>
<td>$t &lt; 2.0 \text{ nsec}$</td>
</tr>
<tr>
<td>(cos $\theta &gt; 0.975$)</td>
<td>$0 \text{ GeV} \leq p_t &lt; 0.75 \text{ GeV}$</td>
<td>$t &lt; 1.0 \text{ nsec}$</td>
</tr>
<tr>
<td><strong>Neutral hadrons</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>central</td>
<td>$0.75 \text{ GeV} \leq p_t &lt; 8.0 \text{ GeV}$</td>
<td>$t &lt; 2.5 \text{ nsec}$</td>
</tr>
<tr>
<td>(cos $\theta \leq 0.975$)</td>
<td>$0 \text{ GeV} \leq p_t &lt; 0.75 \text{ GeV}$</td>
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</tr>
<tr>
<td><strong>Charged PFOs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>all</td>
<td>$0.75 \text{ GeV} \leq p_t &lt; 4.0 \text{ GeV}$</td>
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</tr>
<tr>
<td></td>
<td>$0 \text{ GeV} \leq p_t &lt; 0.75 \text{ GeV}$</td>
<td>$t &lt; 1.5 \text{ nsec}$</td>
</tr>
</tbody>
</table>

- Track-only minimum $p_t$: 0.5 GeV
- Track-only maximum time at ECAL: 10 nsec
Influence of pileup

![Graphs showing the influence of pileup.](image)
Figure 19: Separation of $W$ and $Z$ from the chargino decay without overlay (left) and with 60 BX of background (right) for CLIC_SiD.