The Compact Linear Collider: CLIC

DESY Colloquium, 19 November 2019
Aidan Robson, University of Glasgow
CLIC

- Project overview
- Physics reach
- Detector concept & technologies
- Project realisation
- Comparison with other options
- Outlook

Compact Linear Collider: \(e^+e^-\) collisions up to 3TeV
http://clic.cern/
Collaborations

http://clic.cern/

CLIC accelerator collaboration
~60 institutes from 28 countries

CLIC accelerator studies:
• CLIC accelerator design and development
• (Construction and operation of CLIC Test Facility, CTF3)

CLIC detector and physics (CLICdp)
30 institutes from 18 countries

Focus of CLIC-specific studies on:
• Physics prospects & simulation studies
• Detector optimization + R&D for CLIC
The Compact Linear Collider

- A high-luminosity, multi-TeV electron–positron collider
- Planned for construction at CERN in three energy stages:
  - 380GeV, focusing on precision Higgs boson and top-quark physics
  - 1.5 and 3TeV, expanding Higgs and top studies including Higgs self-coupling, and opening higher direct and indirect sensitivity to Beyond Standard Model (BSM)
  - Nominal physics programme lasts for 25–30 years; approvable in stages
  - Benefit of linear machine: length/energy staging plan can be updated in response to developing physics landscape
CLIC History

- 3-volume CDR 2012

- 4 Yellow Reports 2018

- Key accelerator technologies have been demonstrated
- CLIC is now a mature project – ready for construction starting ~2026, with first collisions ~2035
CLIC at 380GeV

- Two-beam acceleration scheme

Power extraction and transfer

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CLIC at 380GeV

- Delay loops create drive-beam structure
CLIC at 380GeV

- Two-beam acceleration scheme

Power extraction and transfer
CLIC at 3TeV
Accelerator challenges

Four challenges:

High-current drive beam bunched at 12 GHz
Power transfer + main-beam acceleration
~100 MV/m gradient in main-beam cavities
Alignment & stability

Drive beam quality:
Produced high-current drive beam bunched at 12 GHz

Examples of measurements from CLIC Test Facility, CTF3, at CERN.

CTF3 now the ‘CERN Linear Electron Accelerator for Research’ facility, CLEAR
Accelerator challenges

Demonstrated 2-beam acceleration

Four challenges:

High-current drive beam bunched at 12 GHz

Power transfer + main-beam acceleration

~100 MV/m gradient in main-beam cavities

Alignment & stability

31 MeV = 145 MV/m
Accelerator challenges

X-band performance: achieved 100 MV/m gradient in main-beam RF cavities

Four challenges:

High-current drive beam bunched at 12 GHz
Power transfer + main-beam acceleration
~100 MV/m gradient in main-beam cavities
Alignment & stability
Accelerator challenges

Nano-beams

The CLIC strategy:

- Align components (10 μm over 200 m)
- Control/damp vibrations (from ground to accelerator)
- Measure beams well – allow to steer beam and optimize positions
- Algorithms for measurements, beam and component optimization, feedbacks
- Tests in small accelerators of equipment and algorithms (FACET at Stanford, ATF2 at KEK, CTF3, Light-sources)

Four challenges:

High-current drive beam bunched at 12 GHz
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Four challenges:

High-current drive beam bunched at 12 GHz
Power transfer + main-beam acceleration
~100 MV/m gradient in main-beam cavities

Alignment & stability

2008

CLIC emittance at damping rings

Horizontal emittance [nm]

Vetical emittance [pm]
Physics landscape

- What is:
  - dark matter?
  - dark energy?
  - origin of neutrino masses?
  - origin of matter/antimatter asymmetry?

- Why are we not seeing new physics around the TeV scale?
  - is the mass scale beyond the LHC reach?
  - is the mass scale within the LHC’s reach, but final states are elusive?

Address both possibilities:
- precision measurements
- sensitivity to elusive signatures
- extended energy/mass reach

- Higgs is a new probe
  - what we’ve experimentally proven so far could hold in a wide range of BSM EWSB scenarios
  - need to probe all aspects:
    - Higgs couplings to lighter particles
    - higher-order terms of the Higgs potential (self-couplings)
    - possible existence of other particles coupled to the Higgs
Physics landscape

For significant improvement on projected HL-LHC sensitivities, future facilities need Higgs couplings precisions at the sub-percent level.

document content:

example scenarios in which \( M \sim 1\text{TeV} \) for new particles

<table>
<thead>
<tr>
<th>Model</th>
<th>( \kappa_V )</th>
<th>( \kappa_b )</th>
<th>( \kappa_{\gamma} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Singlet Mixing</td>
<td>( \sim 6% )</td>
<td>( \sim 6% )</td>
<td>( \sim 6% )</td>
</tr>
<tr>
<td>2HDM</td>
<td>( \sim 1% )</td>
<td>( \sim 10% )</td>
<td>( \sim 1% )</td>
</tr>
<tr>
<td>Decoupling MSSM</td>
<td>( \sim -0.0013% )</td>
<td>( \sim 1.6% )</td>
<td>( \sim -0.4% )</td>
</tr>
<tr>
<td>Composite</td>
<td>( \sim -3% )</td>
<td>( \sim -(3 - 9)% )</td>
<td>( \sim -9% )</td>
</tr>
<tr>
<td>Top Partner</td>
<td>( \sim -2% )</td>
<td>( \sim -2% )</td>
<td>( \sim +1% )</td>
</tr>
</tbody>
</table>

What we want from a next-generation collider:

- Guaranteed physics:
  study of Higgs and top quark properties, and exploration of EWSB phenomena, with the best possible precision and sensitivity

- Exploration potential:
  exploit both direct (large \( Q^2 \)) and indirect (precision) probes
CLIC Staging

3 pillars of the CLIC physics programme:
- Higgs physics
- Top-quark physics
- Beyond Standard Model physics

Staging scenario designed around this

- Physics programme extends over 25–30 years
- Ramp-up and up-time assumptions consistent with other future projects arXiv:1810.13022, Bordry et al.
- Electron polarisation:
  - enhances Higgs production at high-energy stages
  - provides additional observables sensitive to NP
  - helps to characterise new particles in case of discovery

Baseline polarisation scenario adopted:

Emphasis on getting to multi-TeV collisions quickly

| Stage | $\sqrt{s}$ [TeV] | $\mathcal{L}_{\text{int}}$ [ab$^{-1}$] | $P(e^-) = -80\%$ | $P(e^-) = +80\%$
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.38 (and 0.35)</td>
<td>1.0</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>2</td>
<td>1.5</td>
<td>2.5</td>
<td>2.0</td>
<td>0.5</td>
</tr>
<tr>
<td>3</td>
<td>3.0</td>
<td>5.0</td>
<td>4.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>
CLIC Physics at the initial stage

- Initial stage \( \sqrt{s}=380\text{GeV} \)
- **Precision Higgs physics:**
  - ZH process allows H reconstruction Z recoil \( \rightarrow \) model-indep. extraction of \( g_{HZZ} \) coupling – need to start at energy where ZH is abundant
  
  \[
  \sigma_{ZH} \propto g_{HZZ}^2 \\
  \frac{\sigma_{ZH} \cdot \text{Br}(H \rightarrow bb)}{\sigma_{vvH} \cdot \text{Br}(H \rightarrow bb)} \propto \frac{g_{HZZ}^2}{g_{HWW}^2} \\
  \]

- At 380GeV we can use ZH(Z->qq) as well as ZH(Z->ll) – more separated from backgrounds – compensates for lower cross-section
- Higgs studies are all full GEANT-based simulation studies including beam backgrounds
- Imaging calorimetry allows e.g. \( H \rightarrow bb/cc/gg \) separation

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Higgs coupling sensitivity

- Combine all 3 stages for best measurements
  -> global fit including correlations
- Precision ≤ 1% for most couplings
- c/b/W/Z couplings significantly more precise than HL-LHC already after 380GeV stage
- BR(H→inv.) < 0.69% at 90% CL (for 350 GeV CLIC)
- $\Gamma_H$ is extracted with 4.7 – 2.5% precision

→ Guaranteed physics case at initial stage
→ Each energy stage contributes significantly

updated to new luminosity scenario arXiv:1812.01644

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**CLIC Physics at the initial stage**

- **Initial stage** $\sqrt{s}=380\text{GeV}$
- **Precision top-quark physics:**

  - Intending threshold scan near $\sqrt{s}=350$ GeV (10 points, ~1 year) as well as main initial-stage baseline $\sqrt{s}=380\text{GeV}$
  - sensitive to top mass, width and couplings
  - observe 1S ‘bound state’, $\Delta m_t \sim 50$ MeV

- **Top pair-production cross-section, both polarisations ~1%**
- **Top forward-backward asymmetries ~3–4%**

  - Statistically optimal observables for top EWK couplings
  - all input to global fits

  -> Guaranteed physics case at initial stage

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Top-quark physics at CLIC: JHEP11 (2019) 003

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Higgs self-coupling

- Higgs self-coupling requires high energy

- Direct access to two processes that behave differently with non-SM values of self-coupling:

<table>
<thead>
<tr>
<th></th>
<th>1.4TeV</th>
<th>3TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>σ(HHνeν)</td>
<td>&gt;3σ EVIDENCE, $\frac{Δσ}{σ} = 28%$</td>
<td>&gt;5σ OBSERVATION, $\frac{Δσ}{σ} = 7.3%$</td>
</tr>
<tr>
<td>σ(ZHH)</td>
<td>&gt;5σ OBSERVATION</td>
<td></td>
</tr>
<tr>
<td>$g_{HHH}/g_{HHH}^{SM}$</td>
<td>1.4TeV: −34%, +36% rate-only analysis</td>
<td>1.4 + 3TeV: −7%, +11% differential analysis</td>
</tr>
</tbody>
</table>

Template fit at 3TeV using two variables: $M(HH)$ differential distribution and BDT score

Gives unrivalled sensitivity to Higgs self-coupling:

$$Δg_{HHH}/g_{HHH} = +11\% \quad \text{−7\%}$$

arXiv:1901.05897

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High energy stages, 1.5 and 3 TeV

**Precision Higgs physics:**
- Increases VBF single-Higgs production
- Adds ttH and HH production
- Allows precise measurement of $g_{HHH}$

**Precision top-quark physics:**
- Cross-sections, asymmetries and optimal observables at all energies (necessary to disentangle effects), including boosted regime, study of ttH
- Can probe CP-odd component of ttH coupling to $0.02 < \Delta \sin^2 \phi < 0.08$ for full range of $\sin^2 \phi$

**Precision two-fermion and multi-boson measurements**
- Increases VBF single-Higgs production
- Adds ttH and HH production
- Allows precise measurement of $g_{HHH}$
- Cross-sections, asymmetries and optimal observables at all energies (necessary to disentangle effects), including boosted regime, study of ttH
- Can probe CP-odd component of ttH coupling to $0.02 < \Delta \sin^2 \phi < 0.08$ for full range of $\sin^2 \phi$

BSM physics reach via precision measurements:

At low energy ($\sqrt{s}=m_Z$)

Imagine measuring

$$ \frac{d\sigma}{\sigma_{SM}} \bigg|_{\sqrt{s}=m_Z} \sim 10^{-4} \quad \Rightarrow \quad \delta g_{Z\ell} \sim 10^{-4} $$

\[ \left( \frac{3000}{91.2} \right)^2 \sim 1000 \]

Effect grows as $s$

At high energy ($\sqrt{s}=3\text{TeV}$)

$$ \frac{d\sigma}{\sigma_{SM}} \bigg|_{\sqrt{s}=3\text{TeV}} \sim 10\% \quad \Rightarrow \quad \delta g_{Z\ell} \sim 10^{-4} $$

...equivalent to

$\delta g_{Z\ell}$ strongly benefit from high energies

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Global sensitivity to BSM effects

Includes CLIC measurements of:
- Higgs
- Top
- WW
- $e^+e^-\rightarrow f\bar{f}$

Strongly benefits from high-energy running

Universal EFT fit

$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2} O_i$

Scale of new decoupled physics

Dimension-6 operators

Standard Model

Effects grow with energy from $e^+e^-\rightarrow HH$

Smaller value corresponds to higher scale $\Lambda$ probed

Higgs
Top
WW
$e^+e^-\rightarrow f\bar{f}$


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New physics searches

- Issues not addressed by SM include:
  - origin of the weak scale interactions
  - dark matter
  - origin of matter/antimatter asymmetry

- CLIC can probe TeV-scale electroweak particles, or particles that interact with the SM with electroweak-sized couplings, well above the HL-LHC reach

- Direct searches:
  - For standard final states, SM background cross-sections typically comparable with signal
  - Clean $e^+e^-$ environment helps to isolate non-standard signatures

- Indirect searches: can interpret precision measurements in particular model scenarios

$\Rightarrow$ explore landscape for broad classes of theories
Composite Higgs or top would appear through SM-EFT operators – translate EFT limits into characteristic coupling strength $g_*$ of composite sector and mass $m_*$

CLIC can **discover** compositeness up to $\sim 10\text{TeV}$ compositeness scale ($\sim 30 - \sim 50\text{TeV}$ in favourable conditions) – above what HL-LHC can **exclude**

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**Higgs and top compositeness**

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arXiv:1812.02093 The CLIC Potential for New Physics
**Higgs + heavy singlet**

**Direct search** for real scalar singlet $\phi$:

\[
h = h_0 \cos \gamma + S \sin \gamma
\]
\[
\phi = S \cos \gamma - h_0 \sin \gamma
\]

$\gamma$ is mixing angle of SM-like Higgs ($m_h=125\text{GeV}$), and singlet-like state $\phi$.

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arXiv:1807.04743 – Buttazzo, Redigolo, Sala, Tesi
arXiv:1812.02093 The CLIC Potential for New Physics
**Higgs + heavy singlet**

Direct search for real scalar singlet \( \phi \):

- \( \sin^2 \gamma < 0.9\% \) 95\% CL (380GeV)
- \( \sin^2 \gamma < 0.24\% \) 95\% CL (380GeV+1.5TeV+3TeV)

Complementary:

Indirect search using Higgs couplings

- \( h = h_0 \cos \gamma + S \sin \gamma \)
- \( \phi = S \cos \gamma - h_0 \sin \gamma \)

\( \gamma \) is mixing angle of SM-like Higgs (\( m_h=125\text{GeV} \)), and singlet-like state \( \phi \)

arXiv:1608.07538

arXiv:1812.02093 The CLIC Potential for New Physics

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**Dark matter**

**Higgsino:**

WIMP dark matter candidate, connected to weak scale naturalness, and gauge coupling unification

When other superpartners decoupled:

\[ \chi^\pm \text{ slightly heavier than } \chi^0 \]

\[ \chi^\pm \rightarrow \pi^\pm \chi^0 \text{ leaving ‘disappearing track’ in detector} \]

reach Higgsino mass of 1.1 TeV, required for DM relic mass density – even with some level of background

- \( \geq 1 \text{ stub} \)
- \( 2 \text{ stub} \)
- \( \geq 1 \text{ stub}+\gamma(50) \)
- \( \geq 1 \text{ stub}+\gamma(100) \)
- \( \geq 1 \text{ stub}+\gamma(200) \)
- \( 2 \text{ stub}+\gamma(50) \)
- \( 2 \text{ stub}+\gamma(100) \)
- \( 2 \text{ stub}+\gamma(200) \)

**Electroweak precision tests:**

[arXiv:1810.10993 - Di Luzio, Gröber, Panico]

**Precision measurements of**

\[ \frac{d\sigma}{d(\cos \theta)} \text{ in } e^+e^- \rightarrow ff \]

sensitive to new states

\[ \rightarrow \text{ exclude mass ranges} \]

E.g. for \( n=3 \text{ Dirac fermion, } m=2 \text{ TeV} \)

saturates DM relic mass density:

can be excluded by CLIC

**Other states 95% Exclusion Reach**

SU(3) x SU(2) x U(1) representation; different \( n \)-tuple multiplicities

**arXiv:1812.02093 The CLIC Potential for New Physics**
We observe a matter-dominated universe

For baryogenesis to account for this, need to add something to the SM

EW phase transition required to be first order

Explored for CLIC in the Higgs+singlet model: resonant di-Higgs searches

Sensitive to the interesting region

regions compatible w/ unitarity, perturbativity, and absolute stability of the EW vacuum

well-constrained by CLIC Higgs self-coupling (black) and CLIC resonant di-Higgs searches at 1.5 TeV and 3 TeV
Interpretations and full programme

Precision Higgs couplings and self-coupling
Precision electroweak and top-quark analysis
Sensitivity to BSM effects in the SMEFT
Higgs and top compositeness
Baryogenesis
Direct discoveries of new particles
Extra Higgs boson searches
Dark matter searches
Lepton and flavour violation
Neutrino properties
Hidden sector searches
Exotic Higgs boson decays

Many more studies in CERN Yellow Report:
The CLIC Potential for New Physics (250 pages)


Precise timing required for beam background rejection

1ns in calorimetry, 5ns in vertexing/tracking

High precision:
- jet energy resolution
- momentum resolution
- impact parameter resolution

$$\sigma(E)/(E) \sim 3.5\% \text{ for } E>100\text{GeV}$$
$$\sigma(p_T)/p_T^2 \sim 2 \times 10^{-5} \text{ GeV}^{-1}$$
$$\sigma_{d0} \sim 5 \times 15/(\rho[\text{GeV}] \sin^{3/2} \theta) \mu m$$

High bunch charge density $\Rightarrow$ beam-related backgrounds

small effect at $\sqrt{s}=380\text{GeV}$
large effect at high energies

Collider environment

CLIC
Beam structure at 3TeV

Not to scale!

20 ms

156 ns

Located at DESY, November 2019

CALICE / FCAL

CLICdp vertexing/tracking programme
CLICdet

Ultra low-mass vertex detector with 25µm pixels

Main tracker, silicon-based (large pixels and/or strips)

Forward region with LumiCal and BeamCal

Fine-grained calorimetry used for Particle Flow Analysis

End coils for field-shaping

Solenoid magnet $B=4T$

Return yoke (iron) with detectors for muon ID

Tracker spatial resolution: 7µm
Material: 1–2% $X_0$/layer

Vertex detector spatial resolution: 3µm
Material: 0.2% $X_0$/layer

-> forced air cooling

Triggerless readout

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CLICdet Performance

Full characterization of the detector model in arXiv:1812.07337

Displaced single $\mu$, $\theta < 100$ deg, $0 < y < 600$ mm, 80$< \phi < 100$ deg

Tracking efficiency

CLICdp

VLC7 Jets, with 3TeV BG
- $50$ GeV
- $100$ GeV
- $250$ GeV
- $750$ GeV
- $1500$ GeV

Achieve jet energy resolution target in presence of beam backgrounds

Software tools developed/maintained by the CERN group and widely used
Stringent requirements for CLIC vertex & tracker detectors inspired broad and integrated technology R&D programme

Benefit from rapid progress in Si industry and synergies with HL-LHC

**Highlights:**

- Full efficiency obtained from hybrid assemblies of 50μm thin sensors that satisfy CLIC time-stamping requirements
- Sensor design with enhanced charge-sharing is underway to reach required spatial resolution with thin sensors
- Good progress towards reducing detector mass with active-edge sensors and through-Si interconnects
- Promising results from fully integrated technologies; CLIC-specific fully integrated designs underway (CLICTD, CLIPS)
- Developed advanced simulation/analysis tools for detector performance optimisation
- Feasibility of power-pulsing demonstrated; power consumption specification met
- Feasibility of air cooling demonstrated in simulation & full vertex detector mockup
Realisation as a project
Power and energy

- Power estimate redone bottom-up for 380GeV CLIC

  Much reduced compared with CDR, from optimised drive-beam complex, more efficient klystrons and injectors, and better estimates of nominal conditions

- Total power 168MW
  (Klystron-based option: 164 MW)

- Fold with running model for energy consumption
  CERN currently consuming ~1.2TWh per year
- Machine recosted bottom-up in 2017–18
- 380GeV CLIC: 5.9 BCHF
- From 380 GeV to 1.5 TeV, add 5.1 BCHF (drive-beam RF upgrade and lengthening of main linac)
- From 1.5 TeV to 3 TeV, add 7.3 BCHF (second drive-beam complex and lengthening of main linac)

<table>
<thead>
<tr>
<th>Cost (MCHF)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Main Beam Production</strong></td>
</tr>
<tr>
<td>Injectors</td>
</tr>
<tr>
<td>Damping Rings</td>
</tr>
<tr>
<td>Beam Transport</td>
</tr>
<tr>
<td><strong>Drive Beam Production</strong></td>
</tr>
<tr>
<td>Injectors</td>
</tr>
<tr>
<td>Frequency Multiplication</td>
</tr>
<tr>
<td>Beam Transport</td>
</tr>
<tr>
<td><strong>Main Linac Modules</strong></td>
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<tr>
<td>Main Linac Modules</td>
</tr>
<tr>
<td>Post decelerators</td>
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<tr>
<td><strong>Main Linac RF</strong></td>
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<tr>
<td>Main Linac Xband RF</td>
</tr>
<tr>
<td><strong>Beam Delivery and Post Collision Lines</strong></td>
</tr>
<tr>
<td>Beam Delivery Systems</td>
</tr>
<tr>
<td>Final focus, Exp. Area</td>
</tr>
<tr>
<td>Post-collision lines/dumps</td>
</tr>
<tr>
<td><strong>Civil Engineering</strong></td>
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<tr>
<td>Civil Engineering</td>
</tr>
<tr>
<td><strong>Infrastructure and Services</strong></td>
</tr>
<tr>
<td>Electrical distribution</td>
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<tr>
<td>Survey and Alignment</td>
</tr>
<tr>
<td>Cooling and ventilation</td>
</tr>
<tr>
<td>Transport / installation</td>
</tr>
<tr>
<td><strong>Machine Control, Protection and Safety systems</strong></td>
</tr>
<tr>
<td>Machine Control Infrastructure</td>
</tr>
<tr>
<td>Machine Protection</td>
</tr>
<tr>
<td>Access Safety &amp; Control System</td>
</tr>
<tr>
<td><strong>Total (rounded)</strong></td>
</tr>
</tbody>
</table>

5890$^{+1470}_{-1270}$ MCHF;
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, pre-series and system optimisation studies, 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

2020
Update of the European Strategy for Particle Physics

2026
Ready for construction

2035
First collisions
Towards industrialisation

Investigating paths to industrialisation

Baseline manufacturing technique: bonding and brazing

Alternatives: brazing as for SwissFEL machining halves

Target is structures that are low-cost & easy-to-manufacture
CLIC technology applications

SwissFEL: C-band linac
- 104 x 2m-long C-band structures (beam → 6 GeV @ 100 Hz)
- Similar μm-level tolerances
- Length ~ 800 CLIC structures
- Being commissioned

CLIC technology for different applications
- EU co-funded FEL design study
- SPARC at INFN-LNF
- …many other small systems…

INFN Frascati advanced acceleration facility
EuPRAXIA@SPARC_LAB

Eindhoven University led
SMART*LIGHT Compton Source

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Strategy considerations

Efforts to synthesize prospects from different proposed colliders summarized in European Strategy for Particle Physics Briefing Book
Possible scenarios

Possible scenarios of future colliders

- **ILC**: 250 GeV
  - Japan
  - 9 years
  - 31 km tunnel
  - 2 ab⁻¹
- **FCC**: 1 TeV
  - Cern
  - 11 years
  - 40 km tunnel
  - 4-5.4 ab⁻¹
- **SppC**: Similar to FCC-hh
  - China
  - 100 km tunnel
  - 16/2.6/5.6 ab⁻¹
- **FCC-ee**: 350-365 GeV
  - 100 km tunnel
  - 11 years
  - 1.7 ab⁻¹
- **FCC hh**: 150 TeV
  - 100 km tunnel
  - 15 years
  - 30-30 ab⁻¹
- **HL-LHC**: 13 TeV
  - 8 years
  - 100 km tunnel
  - 3-4 ab⁻¹
- **HE-LHC**: 27 TeV
  - 8 years
  - 100 km tunnel
  - 10 ab⁻¹
- **LHeC**: 1.2 TeV
  - 2 years
  - 6 years
  - 0.25-1 ab⁻¹
- **FCC eh**: 3.5 TeV
  - 11 km tunnel
  - 5 years
  - 2 ab⁻¹
- **CLIC**: 380 GeV
  - 1 ab⁻¹
  - 11 km tunnel
  - 2.5 ab⁻¹
- **1 TeV**:
  - 100 km tunnel
  - 4-5.4 ab⁻¹

From U. Bassler via S. Bethke

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EFT fit results projected onto Higgs couplings – improvement with respect to HL-LHC

<table>
<thead>
<tr>
<th>HE-LHC</th>
<th>ILC500</th>
<th>CLIC250</th>
<th>CLIC380</th>
<th>CLIC1500</th>
<th>CLIC3000</th>
<th>CEPC</th>
<th>FCCee365</th>
<th>FCCee/eh/hh</th>
</tr>
</thead>
<tbody>
<tr>
<td>( g_{HZZ}^{\text{eff}} )</td>
<td>1.7</td>
<td>1.2</td>
<td>7.7</td>
<td>( \geq 10 )</td>
<td>5.5</td>
<td>( \geq 10 )</td>
<td>( \geq 10 )</td>
<td>6.9</td>
</tr>
<tr>
<td>( g_{HWW}^{\text{eff}} )</td>
<td>1.8</td>
<td>1.3</td>
<td>6.7</td>
<td>( \geq 10 )</td>
<td>4.9</td>
<td>( \geq 10 )</td>
<td>( \geq 10 )</td>
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<td>( g_{H\gamma\gamma}^{\text{eff}} )</td>
<td>1.7</td>
<td>1.3</td>
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<td>( g_{H\gamma\gamma}^{\text{eff}} )</td>
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<td>1.1</td>
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<td>1.4</td>
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<td>( g_{Hcc}^{\text{eff}} )</td>
<td>*</td>
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<td>( \geq 10 )</td>
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<td>( \delta g_1^{\gamma} \times 10^2 )</td>
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<td>1.4</td>
<td>6.7</td>
<td>( \geq 10 )</td>
<td>( \geq 10 )</td>
<td>( \geq 10 )</td>
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<tr>
<td>( \delta \kappa_1 \times 10^2 )</td>
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<td>( \lambda_1 \times 10^2 )</td>
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</table>

SMEFT ND (*) not measured at HL-LHC

From J. de Blas

ILC500, CLIC1500, FCCee365 perform broadly similarly for Higgs couplings

→ look beyond, to top and BSM programmes
EFT fit results

Highlighted where CLIC1500 more sensitive than FCCee – benefit of high energy

From J. de Blas
Interpretations and full programme

Wider programme; compare CLIC and FCChh:

Composite Higgs, $2\sigma$

$g_*$ vs $m_*$ [TeV]

DESY, November 2019
Interpretations and full programme

Wider programme; compare CLIC and FCChh:

![Graph showing Y-Universal Z', 2σ vs M [TeV]]

HL-LHC
CLIC
FCChh
ILC

European Strategy Update
Interpretations and full programme

From J. Alcaraz, EWSB Dynamics and Resonances
https://indico.cern.ch/event/808335/contributions/3365188/attachments/1843613/3023844/Alcaraz_BSM1.pdf
Interpretations and full programme

FCC-hh has (unsurprisingly) the best mass reach for new resonances, in general:
– For new Z’ bosons via direct production with couplings ~weak coupling size
– For W’, gravitons, strongly-coupled resonances, vector-like quarks, ...

CLIC highly competitive for new physics via contact interactions:
– For new Z’ bosons with couplings > 1 (above the weak coupling size)
– For 2fermion - 2boson contact interactions (e+e-→ZH channel)
– New physics scales from deviations in Higgs couplings

From J. Alcaraz, EWSB Dynamics and Resonances
https://indico.cern.ch/event/808335/contributions/3365188/attachments/1843613/3023844/Alcaraz_BSM1.pdf
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<td>ILC</td>
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<td>0.25</td>
<td>2</td>
<td>11</td>
<td>129 (upgr. 150-200)</td>
<td>4.8-5.3 GILCU + upgrade</td>
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<td></td>
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<td>0.5</td>
<td>4</td>
<td>10</td>
<td>163 (204)</td>
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<td></td>
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<td>168</td>
<td>5.9 GCHF</td>
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<td>8</td>
<td>(370)</td>
<td>+5.1 GCHF</td>
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<td>1.5</td>
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<td>7</td>
<td>(590)</td>
<td>+7.3 GCHF</td>
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<td>5</td>
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<td>149</td>
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<td>0.091+0.16</td>
<td>150+10</td>
<td>4+1</td>
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<td>3</td>
<td>282</td>
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<tr>
<td></td>
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<td>0.365 (+0.35)</td>
<td>1.5 (+0.2)</td>
<td>4 (+1)</td>
<td>340</td>
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<td>60 / 7000</td>
<td>1</td>
<td>12</td>
<td>(+100)</td>
<td>1.75 GCHF</td>
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<td>pp</td>
<td>100</td>
<td>30</td>
<td>25</td>
<td>580 (550)</td>
<td>17 GCHF (+7 GCHF)</td>
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<td>pp</td>
<td>27</td>
<td>20</td>
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<td>7.2 GCHF</td>
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</table>

Strategy-making needs to inject cost, timelines, judgement on magnet readiness...

from D. Schulte, ESPP Open Symposium, Granada
Responding to issues arising during European Strategy discussions:

Z-pole running:
CLIC’s staging scenario prioritizes high-energy running but it would be possible to have a dedicated run at the Z pole reaching luminosity of $0.36 \times 10^{-34} \text{cm}^{-2}\text{s}^{-1}$ (like “Giga-Z”)

Interaction points:
CLIC’s baseline is a single interaction point / single experiment. However, it would be possible to operate two detectors in push-pull mode, and at the initial energy stage it would be possible to have two beam-delivery systems and two interaction points

Luminosity:
It would be possible to run at 100Hz instead of 50Hz, and double the integrated luminosity collected
“My scenario”

- In my view the European Strategy should not assume an Asian collider (but of course adapt in case one is realised)
- We should invest in CLIC now so that it could be ready to go ahead in 2026
- Build CLIC380 starting in 2026
- See how wakefield acceleration techniques and high-field magnets develop (even muon colliders...?)
- After CLIC380, re-evaluate physics and R&D landscape and decide whether to continue to CLIC1500 (or CLIC1000 or whatever re-optimisation) or move to e.g. a hadron machine

– CLIC provides the most flexible starting point
Four CERN Yellow Reports:
The CLIC 2018 Summary Report
The CLIC Potential for New Physics
The CLIC Project Implementation Plan
Detector Technologies for CLIC

Two formal ESU submissions
Many supporting notes and papers

Available at:
http://clic.cern/european-strategy
CLIC perspective

- CLIC is now a mature project, ready to start construction in ~2026, with first collisions ~2035
- The main accelerator technologies have been demonstrated
- The coupling of lepton collider precision and multi-TeV energies gives a physics case that is broad and profound, from precision Higgs and top measurements, and their interpretation in new physics scenarios, to direct BSM searches
- The starting energy of 380GeV is optimised and provides a guaranteed physics programme
- The timescale is attractive
- The detector concept and detector technologies R&D are advanced
- A linear machine provides flexibility to adapt the staging scenario to a developing physics landscape, and polarisation gives extra physics sensitivity
- The cost is compatible with LHC-like resources, and the accelerator staging brings cost staging and accompanying implications on affordability
- A linear tunnel provides a natural infrastructure for the future beyond CLIC
- **CLIC is the best option for the next collider at CERN, and decisions are being taken now**

http://clic.cern/european-strategy