\(e^+e^-\) collisions at the Compact Linear Collider

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Introduction

- The **Standard Model** of particle physics has been extremely successful (including prediction of the Higgs boson discovered at the Large Hadron Collider)

- However, it does not explain observations of:
  - Dark Matter
  - The baryon-antibaryon asymmetry
  - Light neutrino masses and mixing

- No guaranteed regime where **new physics** will emerge

→ Exploration of new territory motivates **ambitious future colliders**
Future of the Large Hadron Collider (LHC)

This talk: what could be the next step?

• Collect 20x more data within the next 20 years
Hadron and $e^+e^-$ colliders

**Hadron colliders (e.g. LHC):**

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

- High-energy circular colliders possible

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

**$e^+e^-$ colliders:**

- $e^+e^-$ are pointlike
  - Initial state well-defined ($\sqrt{s}$, polarisation)
  - High-precision measurements

- High energies ($\sqrt{s} \geq 380$ GeV) require linear colliders

- Clean experimental environment
  - Less / no need for triggers
  - Lower radiation levels
pp and $e^+e^-$ collisions

**pp collisions:**
Interesting events need to be found in huge number of collisions

**$e^+e^-$ collisions:**
More “clean”, all events usable
Circular vs. linear $e^+e^-$ colliders

Circular colliders:
- Can accelerate the beam in many turns
- Can use the beam many times
- For electrons synchrotron radiation can be large (e.g. 2.75 GeV/turn lost at LEP for $E = 105$ GeV) → maximal energy limited

Linear colliders:
- Almost no radiation in a linac
- Have to achieve energy in a single pass → high acceleration gradients needed
- Have to achieve luminosity in single pass → small beam size and high beam power needed
Studies of high-energy $e^+e^-$ colliders

Compact Linear Collider (CLIC): CERN
$\sqrt{s} = 380$ GeV, 1.5 TeV, 3 TeV
Length: 11 km, 29 km, 50 km

Future Circular Collider (FCC-ee): CERN
$\sqrt{s} = 90 - 365$ GeV
Circumference: 97.75 km

International Linear Collider (ILC):
Japan (Kitakami)
$\sqrt{s} = 250 - 500$ GeV
Length: 20 km, 31 km

Circular Electron Positron Collider (CEPC): China
$\sqrt{s} = 90 - 240$ GeV
Circumference: 100 km
Studies of high-energy pp colliders

Tunnels initially used for $e^+e^-$ collisions

High-Energy LHC (HE-LHC): CERN
$\sqrt{s} \approx 27$ TeV
Circumference: 27 km

Super proton proton Collider (SppC): China
$\sqrt{s} > 70$ GeV
Circumference: 100 km

Future Circular Collider (FCC-hh): CERN
$\sqrt{s} \approx 100$ TeV
Circumference: 97.75 km

02/04/2019 Philipp Roloff e$^+e^-$ collisions at CLIC
Compact Linear Collider (CLIC):
• Based on 2-beam acceleration scheme
• Operated at room temperature
• Gradient: 100 MV/m
• Energy: 380 GeV - 3 TeV
• Length: 50 km (for 3 TeV)
• $P(e^-) = \pm 80\%$
CLIC 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 layout at 3 TeV

Drive beam complex

- **588 klystrons, 20 MW, 148 μs**
- **Drive beam accelerator**
  - 2.4 GeV, 1.0 GHz
- **Decelerators**, 25 sectors
- **Delay loop**
- **CR1**
- **CR2**
- **CR2 Ø 140 m**
- **CR1 Ø 95 m**
- **Decelerators, each 878 m**
- **BC2**
- **TA**
- **e⁻ main linac**, 12 GHz, 72/100 MV/m
- **BDS** (Beam Delivery System)
- **IP** (Interaction Point)
- **2.5 km**
- **3.1 km**
- **e⁺ main linac**, 22 km
- **TA radius 300 m**
- **Main linac length 50.1 km**

Main beam complex

- **Booster linac**
  - 2.86 to 9 GeV
- **BC1**
- **BC2**
- **e⁻ injector**
  - 2.86 GeV
  - 359 m
- **e⁺ injector**
  - 2.86 GeV
  - 389 m

**Legend**
- **CR**: combiner ring
- **TA**: turnaround
- **DR**: damping ring
- **PDR**: predamping ring
- **BC**: bunch compressor
- **BDS**: beam delivery system
- **IP**: interaction point
- **Danger**
- **e⁺e⁻ collisions at CLIC**
The CLIC Test Facility (CTF3)

CTF3 successfully demonstrated:
- Drive beam generation
- RF power extraction
- Two-beam acceleration up to a gradient of 145 MeV/m

- CTF3 completed its mission in 2016
- A new facility since 2017 (based on the CTF3 probe beam):
  CERN Linear Electron Accelerator for Research (CLEAR)
2-beam acceleration module in CTF3

drive beam

main beam

e^{+}e^{-} collisions at CLIC
CLIC accelerating structures

- 12 GHz (X-band)
- Break down rate (BDR): $p \leq 3 \cdot 10^{-7}$ m$^{-1}$ pulse$^{-1}$
- R&D programme established gradient $O(100$MV/m$)$
- Shorter pulses have less breakdowns
CLIC technology applications

Collaboration with many facilities: photon sources, medical applications → lots of experience being built up

Example: SwissFEL
• 104 C-band structures (5.7 GHz, 2 m long)
• Beam up to 6 GeV at 100 Hz
• Similar µm-level tolerances
• Length similar to 800 CLIC structures
CLIC would be implemented in several energy stages

**Current baseline scenario:**

<table>
<thead>
<tr>
<th>Stage</th>
<th>$\sqrt{s}$ [TeV]</th>
<th>$\mathcal{L}_{\text{int}}$ [ab$^{-1}$]</th>
<th>$P(e^-) = -80%$</th>
<th>$P(e^-) = +80%$</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>

- The strategy can be adapted to possible discoveries at the (HL-)LHC or the initial CLIC stage(s)
- 1 year = $1.2 \times 10^7$ seconds (based on CERN experience)
CLIC at 380 GeV

Compact Linear Collider (CLIC)

- **380 GeV** - 11.4 km (CLIC380)
- Drive/main beam injector
- LHC - existing infrastructure

e$^+$$^-$ collisions at CLIC
CLIC at 3 TeV

Compact Linear Collider (CLIC)
- 380 GeV - 11.4 km (CLIC380)
- 1.5 TeV - 29.0 km (CLIC1500)
- 3.0 TeV - 50.1 km (CLIC3000)

e^+e^- collisions at CLIC
Cost and power

380 GeV: \(5890^{+1470}_{-1270}\) MCHF

Upgrade to 1.5 TeV: add \(\approx5100\) MCHF
Upgrade to 3 TeV: add another \(\approx7300\) MCHF

380 GeV: large improvement compared to CDR (2012)

1.5 and 3 TeV: power not yet optimised → will be done next

<table>
<thead>
<tr>
<th></th>
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<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>380</td>
<td>168</td>
<td>25</td>
<td>9</td>
</tr>
<tr>
<td>1500</td>
<td>364</td>
<td>38</td>
<td>13</td>
</tr>
<tr>
<td>3000</td>
<td>589</td>
<td>46</td>
<td>17</td>
</tr>
</tbody>
</table>
Comparison to other $e^+e^-$ collider options

Linear colliders:
• Can reach the highest energies
• Luminosity rises with energy
• Beam polarisation at all energies
• Potential to benefit from novel accelerator techniques

Circular colliders:
• Large luminosity at lower energies
• Luminosity decreases with energy

NB: Peak luminosity at LEP2 (209 GeV) was $\approx 10^{32} \text{ cm}^{-2}\text{s}^{-1}$
## CLIC experimental conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>380 GeV</th>
<th>1.5 TeV</th>
<th>3 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity L (10^{34} cm^{-2} sec^{-1})</td>
<td>1.5</td>
<td>3.7</td>
<td>5.9</td>
</tr>
<tr>
<td>L above 99% of √s (10^{34} cm^{-2} sec^{-1})</td>
<td>0.9</td>
<td>1.4</td>
<td>2.0</td>
</tr>
<tr>
<td>Repetition frequency (Hz)</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Bunch separation (ns)</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Number of bunches per train</td>
<td>352</td>
<td>312</td>
<td>312</td>
</tr>
<tr>
<td>Beam size at IP σ_x/σ_y (nm)</td>
<td>149/2.9</td>
<td>~60/1.5</td>
<td>~40/1</td>
</tr>
<tr>
<td>Beam size at IP σ_z (μm)</td>
<td>70</td>
<td>44</td>
<td>44</td>
</tr>
</tbody>
</table>

- Drives timing requirements for CLIC detector
- Very small beam

**CLIC:** trains at 50 Hz, 1 train = 312 bunches, 0.5 ns apart

- 156 ns
- 20 ms
Beam-induced backgrounds

- $e^+e^-$ pairs
- $\gamma\gamma \rightarrow$ hadrons

**$e^+e^-$ pairs:**
High occupancies
→ **Detector design issue**
(small cell sizes)

**$\gamma\gamma \rightarrow$ hadrons**
Main background
in calorimeters and trackers
→ **Impact on physics**
(needs suppression in the data)
Principle of a particle physics detector

- Particles interact with detector material
  - Charged: Ionisation, excitation of detector atoms ...
  - Neutral: Photo effect, Compton effect, pair production ....

- Particles differ in the way they interact with material
  - Identify particle types
CLIC detector concept

- Ultra low-mass vertex detector with \( \approx 25 \times 25 \mu m^2 \) pixels
- Main trackers: silicon-based (large pixels / short strips)
- Fine grained (PFA) calorimetry, \( 1+7.5 \lambda \)
- Strong solenoid magnet (4 T)
- Complex forward region with compact calorimeters
- Instrumented return yoke for muon ID

CLICdp-Note-2017-001
CLIC silicon vertex/tracker R&D

Sensor + readout technology

<table>
<thead>
<tr>
<th>Sensor + readout technology</th>
<th>Currently considered for</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bump-bonded Hybrid planar sensors</td>
<td>Vertex</td>
</tr>
<tr>
<td>Capacitively coupled HV-CMOS sensors</td>
<td>Vertex</td>
</tr>
<tr>
<td>Monolithic HV-CMOS sensors</td>
<td>Tracker</td>
</tr>
<tr>
<td>Monolithic HR-CMOS sensor</td>
<td>Tracker</td>
</tr>
<tr>
<td>Monolithic SOI sensors</td>
<td>Vertex, Tracker</td>
</tr>
</tbody>
</table>

Simulation/Characterisation

- Challenging requirements lead to extensive detector R&D program
- ~10 institutes active in vertex/tracker R&D
- Collaboration with ATLAS, ALICE, LHCb, Mu3e, AIDA-2020

Detector integration

D. Dannheim, VCI2019
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!
Beam-induced background from $\gamma\gamma \rightarrow$ hadrons can be efficiently suppressed by applying $p_T$-dependent timing cuts on individual reconstructed particles (= particle flow objects).
Transverse momentum resolution of \(2 \times 10^{-5} \text{ GeV}^{-1}\) achieved for high-energy tracks in the central part of the detector.

Physics projections are based on realistic full detector simulations and include the impact of beam-beam effects.
How to look for new physics?

1.) Direct searches:
   Looking for *new particles* and unknown effects

2.) Learning from SM processes:
   - Precision study of production and decay properties of *known SM particles*
   - Focus on the Higgs boson and top quark which have not been studied in $e^+e^-$ collisions so far

→ Both approaches benefit from the highest possible energies!
Higgs and top-quark physics:

- Single Higgs production
- Double Higgs production
  - Top-quark mass
- EFT analysis
Single Higgs production

**Higgsstrahlung:** $e^+e^- \rightarrow ZH$
- $\sigma \sim 1/s$, dominant up to $\approx 450$ GeV

**WW fusion:** $e^+e^- \rightarrow H\nu\bar{\nu}_e$
- $\sigma \sim \log(s)$, dominant above $450$ GeV
- Large statistics at high energy

**$t\bar{t}H$ production:** $e^+e^- \rightarrow t\bar{t}H$
- Accessible $\geq 500$ GeV, maximum $\approx 800$ GeV
- Direct extraction of the top-Yukawa coupling
Higgsstrahlung: $e^+e^- \rightarrow ZH$

Using $Z \rightarrow e^+e^-, \mu^+\mu^-$:
- HZ events can be identified from the Z recoil mass alone
- Higgs width and couplings without assumptions (requires lepton collider)

- Best precision at 240/250 GeV (tracking resolution, beam energy spectra)

$$m_{recoil}^2 = (\sqrt{s} - E_Z)^2 - |\vec{p}_Z|^2$$

Known at lepton collider

Using $Z \rightarrow q\bar{q}$:
- Almost model-independent measurement of $g_{HZZ}$ possible using hadronic Z decays
- Substantial improvement in precision possible

- Better precision at 350 GeV found than at 250 GeV or 420 GeV

CLIC coupling sensitivity

Precision on Higgs coupling strength to other SM particles

- Already the first CLIC stage significantly better than HL-LHC for several couplings: $\kappa_W$, $\kappa_Z$, $\kappa_b$ and $\kappa_c$

- The full CLIC program enhances the precision further

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Double Higgs production

$e^+e^- \rightarrow ZHH$:
- Cross section maximum $\approx 600$ GeV

$e^+e^- \rightarrow HH\nu\bar{\nu}$:
- Benefits from high-energy operation

**Projected precision:**
- $\Delta(\lambda) = \pm 50\%$ at HL-LHC
- $\Delta(\lambda) = -7\% +11\%$ at CLIC for 1.4 and 3 TeV combined

<table>
<thead>
<tr>
<th>Model</th>
<th>$\Delta g_{hhh}/g_{hhh}^{SM}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixed-in Singlet</td>
<td>$-18%$</td>
</tr>
<tr>
<td>Composite Higgs</td>
<td>tens of $%$</td>
</tr>
<tr>
<td>Minimal Supersymmetry</td>
<td>$-2%^{a}\quad -15%^{b}$</td>
</tr>
<tr>
<td>NMSSM</td>
<td>$-25%$</td>
</tr>
</tbody>
</table>

*Phys. Rev. D 88, 055024 (2013)*

arXiv:1901.05897
Top-quark pair production

\[ \sigma(e^+e^- \rightarrow t\bar{t} + X) \text{ [fb]} \]

- \( e^+e^- \rightarrow t\bar{t}: \)
  - Production threshold at \( \sqrt{s} \approx 2m_{\text{top}} \)
  - 380 GeV is near the maximum
    \( \rightarrow \) large event samples (for rare decays etc.)

- \( e^+e^- \rightarrow t\bar{t}H: \)
  - Maximum near 800 GeV

- \( e^+e^- \rightarrow t\bar{t}v_e \bar{v}_e \) (Vector Boson Fusion):
  - Benefits from highest energies
  - Potential high-energy probe of the top Yukawa coupling
Threshold scan

- Measurement at different centre-of-mass energies in the \( \bar{t}t \) production threshold region (data also useful for Higgs physics)

- Expected precision on 1S mass: \( \approx 50 \) MeV (currently dominated by theory NNNLO scale uncertainty)

- Theoretical uncertainty in the order of 10 MeV when transforming the measured 1S mass to the \( \overline{\text{MS}} \) mass scheme
  

- Other methods: ISR photons, direct reconstruction (less precise)

- Precision at the HL-LHC limited to several hundred MeV

arXiv:1807.02441
Global Effective Field Theory fit

precision reach of the Universal EFT fit

\[ \mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i \]

**CLIC input to fit:**
Higgs couplings, top quark observables, WW production, two-fermion production

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New physics potential
Compositeness at CLIC

\[ m_*: \text{compositeness scale} \]
\[ g_*: \text{coupling strength of the composite sector} \]

Discovery of Higgs compositeness scale up to 10 TeV (40 TeV for \( g_* \approx 8 \))
Discovery of top compositeness scale up to 8 TeV (20 TeV for small \( g_* \))

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Direct new physics searches

- Direct observation of new particles coupling to $\gamma^*/Z/W$ → precision measurement of new particle masses and couplings

- The sensitivity often extends up to the kinematic limit (e.g. $M \leq \sqrt{s} / 2$ for pair production)

- Very rare processes accessible due to low backgrounds (no QCD) → CLIC especially suitable for electroweak states

- Polarised electron beam and threshold scans might be useful to constrain the underlying theory

---

**Cross-section [fb]**

- **Higgs**
- $\bar{\tau}, \bar{\mu}, \bar{e}$
- Charginos
- Squark families
- $S M \bar{t}\bar{t}$
- $\bar{\tau}_R, \bar{\mu}_R, \bar{e}_R$
- Neutralinos
Direct observation of sparticles

Example: Phenomenological MSSM with 11 parameters

- Global fit to current experimental data (LHC results, low-energy and flavour experiments, CDM measurements)
- In this model, many gaugions and sleptons are accessible at CLIC, stop and sbottom are possible
  → Direct discoveries are (still) a main motivation for high-energy CLIC operation

arXiv:1710.11091
Higgs plus heavy singlet

Heavy singlet mixing with Higgs boson:
\[ h = h_0 \cos \gamma + S \sin \gamma \]
\[ \phi = S \cos \gamma - h_0 \sin \gamma \]

Direct production:
\[ e^+e^- \rightarrow \nu\bar{\nu}\phi, \phi \rightarrow hh \]

Indirect sensitivity from Higgs couplings

→ Both approaches are complementary

CERN-2018-009-M

02/04/2019 Philipp Roloff e^+e^- collisions at CLIC
**Dark Matter searches...**

... using stub tracks:

\[
e^+e^- \rightarrow \chi^+\chi^- (+\gamma)
\]

**Small mass difference:** \( \chi^\pm \rightarrow \chi^0\pi^\pm \)

**Long-lifetime:** \( \chi^\pm \) leaves a short, disappearing ("stub") track in the detector

- CLIC might discover the thermal Higgsino at 1.1 TeV

**Electroweak n-plet states with hypercharge Y: (1,n,Y)**

\[
(1,2,1/2)_{DF}
\]

CERN-2018-009-M
Summary and conclusions
• Technology-driven schedule from start of construction

• After go-ahead, at least 5 years are needed before construction can start
  → first beams could be available by 2035
CLIC collaborations

CLIC accelerator collaboration
≈60 institutes from 28 countries

CLIC detector & physics (CLICdp) Collaboration: 30 institutes from 18 countries

http://clic-study.web.cern.ch

- CLIC accelerator design and development (construction and operation of CTF3)

http://clicdp.web.cern.ch

- Physics prospects and simulation studies
- Detector optimisation and R&D for CLIC
Summary and conclusions

• An e^+e^- collider is widely considered to be the next large international project high-energy particle physics

• CLIC is the only mature option for a multi-TeV e^+e^- collider

• Very active R&D projects for accelerator and physics/detector

• Energy-staging → optimal for physics:

| 380 GeV: | Optimised for precision SM Higgs and top physics |
| 1.5 TeV, 3 TeV: | Best sensitivity for new physics searches, rare Higgs processes and decays |

• 380 GeV CLIC could be ready for physics in 2035 – at “affordable” cost