Physics at the Compact Linear Collider (CLIC)

Ulrike Schnoor (CERN)

27.01.2020

Seminar Siegen
Outline

Current situation

CLIC accelerator

CLIC detector model

CLIC physics potential

Summary and Outlook
The Large Hadron Collider and the Higgs boson

**LHC: proton-proton collider**

- **CME** 7...8...13 TeV
- **Taking data** since 2010
- **4 experiments** ATLAS, ALICE, CMS, LHCb

- **Discovery of a Higgs boson (2012)** at CMS & ATLAS
- **Sparked investigation of the nature of electroweak symmetry breaking** ⇒ far from completed!

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Open questions and the physics landscape

Open Questions

- Dark Matter
- Dark Energy
- Origin of baryon asymmetry
- Origin of neutrino masses

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

Need for
- precision measurements
- sensitivity to elusive signatures
- extended energy/mass reach

New probe: the Higgs boson

- experimental results leave room for wide range of BSM EWSB scenarios
- still open aspects, including
  - Higgs couplings to lighter particles
  - Higgs self-coupling $\rightarrow$ shape of potential
  - possible other particles coupled to the Higgs

\[ V = -\mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2 \]
HL-LHC physics program

- Search for physics beyond the SM
- Continuation of top, Higgs, electroweak physics program of the LHC
Proposed electron-positron colliders at the energy frontier

**Linear $e^+e^-$ colliders**

- **Compact Linear Collider CLIC**
  - CERN
  - $\sqrt{s} = 380$ GeV, 1.5 TeV, 3 TeV
  - $\ell = 11$ km, 29 km, 50 km

- **International Linear Collider ILC**
  - Japan
  - $\sqrt{s} = 250$ GeV (500 GeV, 1 TeV)
  - $\ell = 17$ km (31 km, 50 km)

**Circular $e^+e^-$ colliders**

- **Future Circular Collider FCC-ee**
  - CERN
  - $\sqrt{s} = 90 – 350$ GeV
  - $\ell = 98$ km

- **Circular Electron Positron Collider**
  - China
  - $\sqrt{s} = 90 – 240$ GeV
  - $\ell = 100$ km
## Electron-positron vs. hadron collider

### Proton-proton collider

- Proton is compound object
  - Initial state unknown
  - Limited achievable precision
- High-energy circular colliders possible
- High rates of QCD backgrounds
  - Complex triggers
  - High levels of radiation

### Electron-positron collider

- $e^+, e^-$ are elementary
  - Initial state well-defined ($\sqrt{s}$, polarization)
  - High-precision measurements
- High energies ($\sqrt{s} > 350$ GeV) require linear colliders
- Clean experimental environment
  - Less/ no need for triggers
  - Lower radiation levels
Interesting physics processes in pp and ee collisions

Proton-proton collider

Electron-positron collider

Interesting events suppressed by $\gtrsim 8$ orders of magnitude

More “clean”, all events usable


Circular and linear colliders

Circular colliders

- Beam circulates for a long time
- Few accelerating cavities, many magnets
- High energy → need strong magnets
- Synchrotron radiation $\sim \frac{E^4}{m^4 r}$

Linear colliders

- Beam passes only once
- Few magnets, many accelerating cavities
- High energy → need high accelerating gradient
- High luminosity → high beam power (high bunch repetition)
Electron-positron colliders

Linear $e^+e^-$ colliders
- Can reach highest energies
- Luminosity rises with energy
- Beam polarization possible at all energies

Circular $e^+e^-$ colliders
- Energy limited by synchrotron radiation
- Large luminosity at lower energies
- Luminosity decreases with energy

Past colliders:
LEP2 (209 GeV) peak luminosity
$L = 10^{32} \text{cm}^{-2}\text{s}^{-1}$
CLIC accelerator
The Compact Linear Collider CLIC

Novel technology: radio-frequency devices with two-beam acceleration scheme

**Goal**  High gradient, efficient energy transfer (wall-plug to beam)

**Means**  High-frequency RF maximizes field in cavities for given energy

**Challenge**  Standard RF sources inefficient at high frequencies

→ **Idea**  Use standard low-frequency RF sources to accelerate a drive beam, which is then brought to high frequency

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**Two-beam acceleration**

Scheme: Dense, low energy drive beam RF power extracted to accelerate less particles per bunch to higher energy per particle
Two-beam acceleration scheme

**Drive beam**  high current (100 A); lower energy (2.4 GeV)
12 GHz frequency after combiner rings/delay loops

**Power Extraction**  and Transfer Structures (PETS): decelerate the beam → extract its energy → guide it via waveguides to the main beam accelerating structures

**Main beam**  High energy up to 1.5 TeV; lower current 1.2 A

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**CLIC technology**

- RF cavities:
- Operated at room temperature
- Gradient 100 MV/m
Layout of the CLIC accelerator complex

- **Drive Beam**
  - 540 klystrons
  - 20 MW, 142 µs
  - 2.4 GeV, 1.0 GHz

- **Delay Loop**
  - CR1: 293 m
  - CR2: 439 m

- **Decelerator**
  - 25 sectors of 878 m

- **Main Beam**
  - Booster Linac: 2.86 to 9 GeV

- **Linacs**
  - **e- main linac**: 12 GHz, 100 MV/m, 21 km
  - **e+ main linac**: 50 km

- **Injectors**
  - **e- injector**: 2.86 GeV
  - **e+ injector**: 2.86 GeV

- **Other Elements**
  - CR: combiner ring
  - TA: turnaround
  - DR: damping ring
  - PDR: predamping ring
  - BC: bunch compressor
  - BDS: beam delivery system
  - IP: interaction point
  - Dump

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Real-life test facilities

**CTF3, the CLIC Test Facility**

Successful demonstration of
- Drive beam generation
- RF power extraction
- Gradient up to 145 MV/m

**The two-beam module**

Test module without beam for tests of
- thermo-mechanical effects
- engineering
- alignment and support
- vacuum, etc.

**X-band test facility**

Test and development of high-gradient accelerating structures

**C-band facilities**

using CLIC technology (SwissFEL)
CLIC staged implementation and map

<table>
<thead>
<tr>
<th>Stage</th>
<th>$\sqrt{s}$ [GeV]</th>
<th>$L_{\text{int}}$ [fb$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>380</td>
<td>1000</td>
</tr>
<tr>
<td>top scan</td>
<td>350</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>1500</td>
<td>2500</td>
</tr>
<tr>
<td>3</td>
<td>3000</td>
<td>5000</td>
</tr>
</tbody>
</table>

$\Rightarrow$ stages can be adapted to possible discoveries at the LHC

Even further in the future: Upgrade with Plasma Wakefield technology possible
Beam properties and experimental conditions
Linear colliders operate in **bunch trains**

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

- **Low duty cycle → power pulsing** of detectors possible

### CLIC bunch structure and experimental conditions

<table>
<thead>
<tr>
<th>Energy stage(s)</th>
<th>380 GeV</th>
<th>1.5 and 3 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Train repetition rate</td>
<td>50 Hz</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Bunches / train</td>
<td>356</td>
<td>312</td>
</tr>
<tr>
<td>Train duration</td>
<td>178 ns</td>
<td>156 ns</td>
</tr>
<tr>
<td>Bunch separation</td>
<td>0.5 ns</td>
<td>0.5 ns</td>
</tr>
<tr>
<td>Duty cycle</td>
<td>0.00089 %</td>
<td>0.00078 %</td>
</tr>
</tbody>
</table>
Beam-beam interaction

High luminosities achieved by using extremely small beam sizes

- At 3 TeV: bunch size $\sigma_x = 40$ nm, $\sigma_y = 1$ nm, $\sigma_z = 44$ $\mu$m
- Flat beams: high luminosity while minimizing electromagnetic fields
- Electromagnetic interaction of $e^+$ and $e^-$ beams
  $\sim$ synchrotron radiation: beamstrahlung
- Collective (beam) effect; real photons

Beamstrahlung:

- modifies energy spectrum of the colliding $e^+e^-$ pairs
- produces $e^{\pm}\gamma$ and $\gamma\gamma$ collisions
- drives detector requirements to a large extend
Beam-induced backgrounds

Coherent and incoherent $e^+e^-$ pairs

19k particles per bunch train (3 TeV)
High occupancies $\rightarrow$ impact on detector granularity and design

$\gamma\gamma \rightarrow$ hadrons

17k particles per bunch train (3 TeV)
Main background in calorimeters and trackers $\rightarrow$ impact on detector granularity, design and physics measurements

- Bunch trains with 312 bunches every 0.5 ns
- $\gamma\gamma \rightarrow$ hadrons suppressed with timing cuts
CLIC detector
Detector requirements

+ **Momentum resolution:**
  Higgs recoil mass, \( H \rightarrow \mu\mu \),
  leptons from BSM processes

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

+ **Energy resolution for light quarks:**
W/Z/H separation

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

+ **Impact parameter resolution:**
b/c tagging, e.g. Higgs couplings

\[
\sigma(d_0) = \sqrt{a^2 + b^2 \text{GeV}^2 / (p^2 \sin^3 \theta)},
\]

\( a \approx 5\mu\text{m}, \ b \approx 15\mu\text{m} \)

+ **Lepton identification, very forward e/\gamma tagging**
+ **Requirements from beam-induced backgrounds**
Overview of the detector

Designed for Particle Flow Analysis and optimized for CLIC environment

- 4 T B-field
- Vertex detector (3 double layers)
- Large Silicon tracker R=1.5m
- Highly granular calorimeters:
  - Si-W-ECAL 40 layers (22 $X_0$)
  - Scint-Fe-HCAL 60 layers (7.5 $\lambda_I$)

Precise timing for background suppression
Particle Flow Calorimetry

Particle Flow principle

Average jet composition

► 60 % charged particles
► 30 % photons
► 10 % neutral hadrons

Always use the best information

► charged particles → tracker
► photons → ECAL
► neutral hadrons → HCAL

Traditional approach: jet energy measured in ECAL and HCAL

Particle Flow: Need very good spatial resolution to avoid confusion ⇒ highly granular calorimeters

⇒ Hardware + Software
Timing resolution to suppress backgrounds

$\gamma\gamma \rightarrow \text{hadrons}$ background: uniformly distributed in bunch train (unlike signal)

- can be efficiently suppressed with pT-dependent timing cuts on reconstructed
  particles (= particle flow objects)

$t\bar{t}$ event at 3 TeV with background from $\gamma\gamma \rightarrow \text{hadrons}$ from bunch train

1.2 TeV background
in the reconstruction window $\geq 10$ ns
around physics event
Timing resolution to suppress backgrounds

$\gamma \gamma \rightarrow$ hadrons background: uniformly distributed in bunch train (unlike signal) $\Rightarrow$ can be efficiently suppressed with pT-dependent timing cuts on reconstructed particles (= particle flow objects)

$t \bar{t}$ event at 3 TeV with background from $\gamma \gamma \rightarrow$ hadrons from bunch train

1.2 TeV background in the reconstruction window $\geq 10$ ns around physics event

100 GeV background after timing cuts
Detector performance in full simulation

Full detector simulation

- Simulation based on Geant4
- Reconstruction chain including tracking, particle flow, identification, flavor tagging

Tracking performance: Momentum resolution

\[ \sigma(p_T/p_{T,\text{true}}) \ [\text{GeV}^{-1}] \]

\[ \Delta E = \sqrt{s^2E + c^2E^2} \]

(stochastic term \( s \), constant term \( c \))
DELPHES fast simulation for CLICdet

- Performance parameters based on full simulation of CLICdet documented in arXiv:1812.07337
- Workflow: tracking and identification efficiencies, momentum and calorimeter resolutions, jet clustering, flavor tagging, isolation, particle flow
- Linear collider jet algorithm VLC implemented in DELPHES
- Separate cards for the 3 energy stages to mimic effect of beam-induced background on jet energy resolution

Validation compared to full simulation, for the three stages

- Good agreement found for invariant masses, energy and angular observables of jets and leptons

HZ (Z → q̅q) at 350 GeV

Hνν(H → μμ) at 1.4 TeV

WW → ℓνq̅q̅ at 3 TeV

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CLIC physics
Ingredients specific to linear collider Monte Carlo generation

- Beam polarization
- Hard processes for $e^+e^-$, $e^\pm\gamma$, $\gamma\gamma$
- Simulation of ISR
- Capabilities to include beamstrahlung from parametrization (e.g. CIRCE2) or beam-beam event files

Main generator: Whizard+Pythia

Correlations between beams are important
- Impact on cross section measurements and lab-frame observables
- Simulation with beam-beam interactions tool GuineaPig

[1309.0372]
Jet reconstruction at CLIC

<table>
<thead>
<tr>
<th>hadron collider</th>
<th>lepton collider</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avoid contamination from:</td>
<td>pile-up</td>
</tr>
<tr>
<td>Boost w.r.t. detector frame:</td>
<td>yes</td>
</tr>
</tbody>
</table>

- Lepton colliders: \([E, \theta]\); hadron colliders: \([p_T, y]\)
- \(\gamma\gamma \rightarrow \) hadrons is forward peaked, reduce forward size for background robustness

**VLC algorithm**

Valencia Linear Collider algorithm:
- Sequential recombination algorithm
- Modified distance measures

Long. invariant \(\tilde{\text{generalized }} k_T\) [1404.4294]
CLIC physics in three stages

Stage 1
- Higgs physics: single Higgs production in HZ and VBF
- Top physics: $t\bar{t}$ production and threshold scan
  $\Rightarrow$ precision far beyond that of the HL-LHC

Stage 2
- $ttH$ production

Stage 2,3
- Searches for new particles
- Precision EW measurements providing indirect sensitivity to new physics at higher scales
- Higgs self-coupling
- BSM Searches

25-30 years physics program

Electron polarisation scenario:

<table>
<thead>
<tr>
<th>Stage</th>
<th>$\sqrt{s}$ [TeV]</th>
<th>$L_{\text{int}}$ [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>
**Top physics**

**$t\bar{t}$ production**

Stage 1: 380 GeV close to production maximum
→ large event samples

**$t\bar{t}H$ production**

Maximum $\sigma$ near 800 GeV
LC lumi higher at higher energy
→ CLIC Stage 2 close to maximum $ttH$ rate

**VBF $t\bar{t}H$**

Benefits from highest energies

- Top mass
- Top electroweak couplings
- Rare top decays
- Top Yukawa coupling
- CP properties of $t \to H$ coupling
- BSM in $H/t$ sectors
Goal: Highest precision top mass measurement

Dedicated runs of CLIC in several steps around 350 GeV (tt threshold), total 100 fb$^{-1}$

Expected measurement precision on 1S mass: $\approx 50$ MeV

- Theoretical uncertainties: parametric uncertainties from $\alpha_s$, perturbative QCD uncertainty (dominant)
- Experimental uncertainties: beam energy and luminosity spectrum, remaining background predictions
- Statistical uncertainty: 20 MeV

CLIC beam parameters optimised for lower beamstrahlung
Stage 1: two production mechanisms → reduces uncertainties and guarantees model-independence

**Higgsstrahlung** $e^+ e^- \rightarrow ZH$
- dominant up to $\approx 450$ GeV

**WW fusion** $e^+ e^- \rightarrow H \nu_e \bar{\nu}_e$
- dominant above $\approx 450$ GeV

**Double Higgs production**
- ZHH: second stage
- VBF: benefits from highest energies
Higgsstrahlung

\[ Z \rightarrow ee, \mu\mu \]

- Identify HZ events from the Z recoil mass

\[ M^2 = s - 2E_{q\bar{q}}\sqrt{s} + M_{q\bar{q}}^2 \]

\[ \Rightarrow \] model-independent measurement of the \( g_{HZZ} \) coupling

\[ Z \rightarrow q\bar{q} \]

Measurement of \( g_{HZZ} \) → substantial improvement in precision possible

\[ H \rightarrow \text{invisible} \]

Find invisible Higgs decays in a model-independent way

\[ \text{BR}(H \rightarrow \text{inv.}) < 0.97\% \text{ at } 90\% \text{ C.L. for CLIC at 350 GeV} \]
Higgs properties: combined fits

- Global fits to $\sigma \times$ BR measurements in HZ and VBF production in various channels $\rightarrow$ model-independent and model-dependent

**Model-independent fit**

Only possible at lepton colliders

- 11 free parameters including the total width
- no assumptions on additional Higgs decays

Model-dependent global fit

Model-dependent:

- 10 free parameters
- Total width is sum of partial widths $\Rightarrow$ No decays to non-SM particles
- Comparison to LHC results

- Significantly better than HL-LHC or not possible at hadron colliders
- Similar to HL-LHC
Higgs self-coupling at CLIC

- Self-coupling determines shape of the Higgs potential
- Implications for vacuum metastability, hierarchy problem, electroweak phase transition, baryogenesis

Higgs self-coupling at linear colliders

- No HH production channel accessible below 500 GeV in $e^+e^-$
- Sizable ZHH production starts at $\sqrt{s} \gtrsim 500$ GeV
- HH$\nu_e\bar{\nu}_e$ production grows with energy
- Influence of beam polarisation: $P(e^-) = -80\% (+80\%): HH\nu_e\bar{\nu}_e$ rate modified by factor 1.8 (0.2)

modification of the vertex defined as $\kappa_{HHH} := \frac{g_{HHH}}{g_{HHH}^{SM}}$
Analysis strategy

Full simulation study with **Whizard+Pythia** and CLIC_ILD detector model

1901.05897

**Higgs self-coupling at CLIC**

- Measure $W$-boson fusion di-Higgs production $HH\nu_e\bar{\nu}_e$ at 3 TeV
- Extract $g_{HHH}$ from cross section and kinematics
- Take into account the smaller contributions from $ZHH$ and $HH\nu_e\bar{\nu}_e$ at 1.4 TeV

Cross-section dependence on $g_{HHH}$: →

⇒ Measurements of cross sections can be used to extract $g_{HHH} / g_{SM}$

⇒ Ambiguity in $HH\nu_e\bar{\nu}_e$

@CLIC: resolved by using 2 production modes and differential information
Sensitive differential distributions

Differential distributions help to distinguish different values of $\kappa_{HHH}$ [1309.7038]
Shape differences in lower invariant mass $M_{HH}$ region for
  ▶ different values of $\kappa_{HHH}$
  ▶ in particular, distinguish $\kappa_{HHH} < 1$ from $\kappa_{HHH} > 1$ even if similar cross section ($\rightarrow$ resolve ambiguity)

3TeV $HH\nu_e\overline{\nu}_e$ analysis makes use of differential information

Signal selection: 4 b-tagged jets, missing $E_T$, Boosted Decision Tree
Signal region:
Signal = 766 events
Background = 4527 events
Measure $g_{HHH}$ in di-Higgs events

From total rate of observed HH events

Measure the cross section, extract the self-coupling:
$\Delta \sigma \sim \Delta g_{HHH}/g_{HHH}^{SM}$

$\Rightarrow -10\%, +11\%$

From differential information in HH$\nu_e \overline{\nu}_e$ events

- Use two observables sensitive to $g_{HHH}$: BDT score and $M_{HH}$
- Perform template fit for different $g_{HHH}$

$\Rightarrow -7\%, +11\%$ precision on $g_{HHH}$
Global fit including Higgs self-coupling

- Model broad range of possible new physics effects in Effective Field Theory (EFT)
- HH production measurements can be influenced by more BSM effects other than modified Higgs self-coupling
- Other BSM effects can be constrained in other measurements

\[ \Rightarrow \] estimate total effect: global SM-EFT fit

\[ \Rightarrow \] at CLIC: global and individual constraints on Higgs self-coupling very similar due to the comprehensive, high-precision Higgs programme at all three energy stages

Results from: The CLIC Potential for New Physics

[1812.02093, Sec. 2.2]
Comparison to other proposed projects

- CLIC is earliest project where $\Delta \kappa_{\text{HHH}} < 10\%$ can be reached
- Direct access and two sizable production modes at CLIC
- **Global** and exclusive constraints very similar (see previous slide)

(from [1910.11775] ($\kappa_3 = \kappa_{\text{HHH}}$))
Unique capability of CLIC: measuring the Higgs self-coupling to -7%, +11% uncertainty

Direct accessibility of HH production at 1.4 and 3 TeV

Challenging measurements: small cross section, forward b-quarks

Benefits from excellent heavy flavor tagging, jet energy resolution of CLIC detector

<table>
<thead>
<tr>
<th>CLIC double Higgs and Higgs self-coupling programme:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4 TeV</td>
</tr>
<tr>
<td>$\sigma(\text{HH} \nu_e \bar{\nu}_e)$</td>
</tr>
<tr>
<td>$\Delta \sigma \over \sigma = 28 %$</td>
</tr>
<tr>
<td>$\sigma(\text{ZHH})$</td>
</tr>
<tr>
<td>$\Delta \kappa_{\text{HHH}}$</td>
</tr>
<tr>
<td>-34 %, +36 %</td>
</tr>
</tbody>
</table>

- Global EFT fit
- BSM interpretation (e.g. Baryogenesis)

⇒ Together with the high-precision in the couplings of the Higgs to SM particles at CLIC, this measurement will test the nature of the electroweak symmetry breaking mechanism
Interpretation: Baryogenesis

- Shape of the Higgs potential connected to the phase transition of the early universe from the unbroken to the broken electroweak symmetry
- Baryogenesis with a Higgs + singlet model: CLIC sensitive to the interesting regions

--- CLIC 1.5 TeV $\epsilon_{b\text{-}tag} = 90\%$
--- constraint from $\Delta \kappa_{HHH} = 20\%$ at 95% C.L.
--- CLIC 3 TeV di-Higgs searches $\epsilon_{b\text{-}tag} = 90\%$
— CLIC 3 TeV di-Higgs searches $\epsilon_{b\text{-}tag} = 70\%$
○ regions compatible with unitarity, perturbativity, and absolute stability of the EW vacuum
● regions also compatible with baryogenesis

Gray areas: indirect reach from other measurements at Stage 1 (dark), Stage 2 (middle), Stage 3 (light)
based on di-Higgs production at CLIC
Indirect BSM reach via precision measurements

CLIC high-energy stages at 1.5 and 3 TeV:
- increases VBF Higgs production
- adds ttH and HH production
- precision top-quark physics
- precision measurements of two-fermion and multi-boson processes

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

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

Effect grows as $s$
\[ \left( \frac{3000}{91.2} \right)^2 \sim 1000 \]
...equivalent to
\[ \frac{d\sigma}{\sigma_{SM}} \bigg|_{\sqrt{s}=3\text{TeV}} \sim 10\% \quad \Rightarrow \quad \delta g_{Z\ell} \sim 10^{-4} \]

same precision!

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

\[ \Rightarrow \text{strongly benefit from high energies} \]
Global sensitivity to BSM effects in EFT

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

Scale of new decoupled physics

Includes CLIC measurements of

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

Strongly benefits from high-energy running

Universal EFT fit

- HL-LHC (3/ab, S1) + LEP/SLD
- HL-LHC (3/ab, S2) + LEP/SLD
- CLIC Stage 1
- HL-LHC preliminary
- CLIC Stage 1+2
- CLIC Stage 1+2+3

Smaller value corresponds to higher scale \( \Lambda \) probed

Electroweak gauge boson scattering

- Make use of fully hadronic final states (JER allows to separate W,Z)
- Example studies done in $e^+e^- \rightarrow W^+W^-\nu\bar{\nu}$ and $e^+e^- \rightarrow ZZ\nu\bar{\nu}$

Limits on anomalous quartic gauge couplings via $\chi^2$ fit to sensitive observables: $M_{VV}$, $\cos \theta^*_{VV}$, $\cos \theta^*_{Jets}$

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CLIC 3 TeV

HL-LHC: Similar sensitivity as CLIC 3 TeV
Long-lived particles at CLIC

- Long-lived particles signatures: displaced or disappearing tracks
- Challenging at the LHC due to pile-up, triggers
- 2 studies at CLIC:
  - Hidden valley Higgs decay: displaced vertices
  - Degenerate Higgsino Dark Matter: disappearing tracks

Hidden valley particles in
\[ H \rightarrow \pi^0\pi^0 \rightarrow b\bar{b}b\bar{b} \]

\[ m_n = 50 \text{ GeV} \]

CLIC 3 TeV

⇒ Require 5 hits for the tracking algorithm

95 % C.L. limits on \( \sigma \times \text{BR} \)

CLICdp-Note-2018-001
Degenerate Higgsino Dark Matter

- Small mass difference between chargino and neutralino; mixing: pure Higgsino
- Process: chargino pair production where the $\chi_1^\pm$ decay to a neutralino and a pion:
  $$e^+e^- \rightarrow \tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0\pi^+\tilde{\chi}_1^0\pi^-$$
- Stub tracks from charged Higgsino with mass 1.05 TeV and lifetime 6.9 mm
- Whizard+Pythia, CLICdet at 3 TeV, with ISR and Beamspectrum included

stub track search:
- $\geq 4$ hits in the tracking system
- disappearing within the tracking system
- no associated calorimeter entry
- prompt, isolated, minimum $p_T$
- $dE/dx$ requirement

[1812.02093]
Result: reach 1.05 TeV = mass compatible with thermal DM density
Summary and Outlook
Summary

- CLIC: Compact Linear Collider = future electron-positron collider at the Terascale
- Accelerator scheme demonstrated in various test facilities
- CLICdet detector model adapted to CLIC high-energy beam environment
- Baseline energy stages optimised for physics cases
- CLIC physics: High-precision top, Higgs, and electroweak physics
  → e.g. Top threshold scan, Higgs self-coupling in HH production
Outlook

- December 2018 - May 2020: European Strategy Update process
- CLIC timeline:

**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, Drive Beam Facility and other system verifications, 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

**2019 - 2020 Decisions**
- Update of the European Strategy for Particle Physics; decision towards a next CERN project at the energy frontier (e.g. CLIC, FCC)

**2025 Construction Start**
- Ready for construction; start of excavations

**2035 First Beams**
- Getting ready for data taking by the time the LHC programme reaches completion
Thanks and further reading

Yellow reports:
Additional Material
Luminosity and beam-beam interaction

Luminosity

\[ \mathcal{L} \sim \frac{N^2}{\sigma_x \sigma_y} \]

Electromagnetic fields

\[ B \sim \frac{\gamma N}{\sigma_z(\sigma_x + \sigma_y)} \]

⇒ prefer flat beams \( \sigma_y \ll \sigma_x \)

Bunch particles are strongly influenced by the fields: they are deflected and radiate Beamstrahlung
HH cross-section measurements at 1.4 and 3 TeV

- HH$\nu_e\bar{\nu}_e$ production at 1.4 and 3 TeV studied in full simulation
- ZHH production at 1.4 TeV: assumptions based on full-simulation ZH study
- Minimal programme of CLIC for HH cross-section measurements:

<table>
<thead>
<tr>
<th></th>
<th>1.4 TeV ($\mathcal{L} = 2.5 \text{ ab}^{-1}$)</th>
<th>3 TeV ($\mathcal{L} = 5 \text{ ab}^{-1}$)</th>
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</table>
| $\sigma(\text{HH}\nu_e\bar{\nu}_e)$ | $3.6 \sigma$  
$\frac{\Delta\sigma}{\sigma} = 28\%$  
**EVIDENCE** | $> 5 \sigma$ for $\mathcal{L} \gtrsim 700 \text{ fb}^{-1}$  
$\frac{\Delta\sigma}{\sigma} = 7.3\%$  
**OBSERVATION** |
| $\sigma(\text{ZHH})$ | $5.9 \sigma$  
**OBSERVATION** | not studied yet  
(less sensitive to self-coupling) |

- **direct acces**
- **two production modes**

- Next: extracting $g_{HHH}$ from these measurements

Current CLIC baseline has the second energy stage at 1.5 TeV instead of 1.4 TeV which is still used for the full-simulation samples studied here.
Higgs self-coupling and Higgs-gauge coupling HHWW

Several diagrams contribute to $HH\bar{\nu}_e\bar{\nu}_e$, incl. HHWW vertex → modification parametrized as

$$\kappa_{HHWW} = \frac{g_{HHWW}}{g_{HHWW}^{SM}}$$

Modifications of invariant di-Higgs mass:

$\rightarrow$ distinguish $g_{HHH}$ from $g_{HHWW}$

2D limits

Simultaneous fit of $g_{HHH}$ and $g_{HHWW}$ based on $M_{HH}$ in bins of the BDT score plus the $\sigma(ZHH)$ measurement at 1.4 TeV:
References

- **Electron-positron vs. hadron collider**
  
  http://www.quantumdiaries.org/wp-content/uploads/2015/05/feynmanDiagram_DrellYan_wRad.png

- **Beam-induced backgrounds:** \( \gamma\gamma \rightarrow \) hadrons diagram
  
  http://cronodon.com/images/QCD_19.jpg