Top-quark physics at CLIC

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on behalf of the CLICdp Collaboration
1 Introduction

2 Top-quark physics at CLIC
   - Top-quark mass measurement
   - Sensitivity to FCNC decays
   - Yukawa coupling measurement
   - Vector-boson fusion production
   - Electroweak couplings and global EFT analysis

3 Conclusions

For details see:

For more information on CLIC accelerator, detector and physics see:
- CLIC input to the European Strategy for Particle Physics Update 2018-2020
Introduction

Compact Linear Collider

Conceptual Design (CDR) presented in 2012

- high gradient, two-beam acceleration scheme
- staged implementation plan with energy from 380 GeV to 3 TeV
- footprint of 11 to 50 km
- $e^-$ polarisation

For details refer to:

P.N. Burrows, *The CLIC accelerator project: status and plans*, Accelerators for HEP parallel session, tomorrow
CLIC running scenario

Three construction stages (each 5 to 7 years of running) for an optimal exploitation of its physics potential

- $\sqrt{s} = 380$ GeV with $1 \text{ ab}^{-1}$ + $100 \text{ fb}^{-1}$ at $t\bar{t}$ threshold

focus on precision Standard Model physics, in particular Higgs boson and top-quark measurements
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  in particular **Higgs boson** and **top-quark** measurements

- $\sqrt{s} = 1.5\text{ TeV}$ with $2.5\text{ ab}^{-1}$

- $\sqrt{s} = 3\text{ TeV}$ with $5\text{ ab}^{-1}$
  focus on direct and indirect **BSM searches**, but also additional **Higgs boson** and **top-quark** studies
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- $\sqrt{s} = 3$ TeV with $5 \text{ ab}^{-1}$
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Other CLICdp contributions to EPS-HEP’2019:

- A.Robson, *The CLIC potential for new physics*, in *Searches for New Physics* parallel session, this afternoon,
- U.Schnoor, *The Higgs self-coupling at CLIC*, in *Higgs Physics*, yesterday,
- E.Leogrande, *The CLIC detector*, poster session
Top-quark processes

Close to 1.4 million top quarks and anti-quarks expected at the initial stage

Top pair-production at and above the threshold (380 GeV)
- top-quark mass
- rare decays
- electroweak couplings

380 GeV
Introduction

Top-quark processes

Top pair-production at and above the threshold (380 GeV)
- top-quark mass
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Additional processes open at high energies
- $t\bar{t}H \Rightarrow$ Yukawa coupling and CP properties
- $t\bar{t}v_e\bar{v}_e$ vector-boson fusion $\Rightarrow$ BSM constraints

Doubled at high energy: total of over 2.8 million (anti)top quarks
Threshold scan

Top pair production cross section around threshold:

- resonance-like structure corresponding to narrow $t\bar{t}$ bound state.

Very sensitive to top properties and model parameters:

- top quark mass $m_t$
- top quark width $\Gamma_t$
- strong coupling $\alpha_s$
- top Yukawa coupling $y_t$

Significant cross section smearing due to luminosity spectra and ISR

Smearing due to luminosity spectra reduced for dedicated running configuration (LowCharge)
Top-quark mass

**Threshold scan**

Precision top mass measurement possible already with $100 \text{ fb}^{-1}$

Baseline scan scenario: 10 cross section measurements, $10 \text{ fb}^{-1}$ each

About 20 MeV uncertainty on mass expected from mass and width fit (2D)
**Threshold scan**

Precision top mass measurement possible already with 100 fb\(^{-1}\)

Baseline scan scenario: 10 cross section measurements, 10 fb\(^{-1}\) each

\[ \begin{align*}
\text{CLICdp preliminary} \\
\text{Statistical uncertainty on } m_t [\text{MeV}] \\
\text{20 MeV}
\end{align*} \]

About 20 MeV uncertainty on mass expected from mass and width fit (2D)

However, \( \alpha_s \) and top-quark Yukawa coupling need to be constrained from independent measurements. Total systematic uncertainty \( \sim 50 \text{ MeV} \).
Direct measurement

From reconstruction of hadronic top-quark decays

Statistical precision $\sim 30$ MeV

Needs excellent control of JES
Large theoretical uncertainties
Top-quark mass

**Direct measurement**

From reconstruction of hadronic top-quark decays

![Graph showing the mass distribution of top quarks](image)

Statistical precision $\sim 30$ MeV

Needs excellent control of JES

Large theoretical uncertainties

**Radiative events**

$e^+e^- \rightarrow t\bar{t} + \gamma_{ISR}$

From $t\bar{t}$ invariant mass distribution

![Graph showing the invariant mass distribution](image)

Statistical precision $\sim 100$ MeV

Total uncertainty of about 140 MeV
Predictions

FCNC top-quark decays are strongly suppressed in SM (CKM+GIM):

\[ BR(t \rightarrow c \gamma) \sim 5 \cdot 10^{-14} \]
\[ BR(t \rightarrow c h) \sim 3 \cdot 10^{-15} \]
\[ BR(t \rightarrow c Z) \sim 1 \cdot 10^{-14} \]
\[ BR(t \rightarrow c g) \sim 5 \cdot 10^{-12} \]
Top-quark FCNC decays

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Significant enhancement possible in many BSM scenarios

<table>
<thead>
<tr>
<th>Model</th>
<th>2HDM</th>
<th>MSSM</th>
<th>( \mathcal{R} ) SUSY</th>
<th>LH</th>
<th>Q singlet</th>
<th>RS</th>
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<td>( BR(t \to c \gamma) )</td>
<td>( 10^{-6} )</td>
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<td>( 10^{-5} )</td>
<td>( 10^{-7} )</td>
<td>( 8 \cdot 10^{-9} )</td>
<td>( 10^{-9} )</td>
</tr>
<tr>
<td>( BR(t \to c h) )</td>
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<td>( 10^{-4} )</td>
<td>( 10^{-6} )</td>
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Significant enhancement possible in many BSM scenarios

Maximum branching fractions possible:

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<td>(10^{-4})</td>
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Limits expected after HL-LHC running

\[ \text{BR}(t \to c\gamma) < 7.4 \cdot 10^{-5} \text{(CMS)} \]
\[ \text{BR}(t \to c h) < 2 \cdot 10^{-4} \text{(ATLAS)} \]
Top-quark FCNC decays

**Sensitivity @ 380 GeV**

Expected limits for 1 ab$^{-1}$ collected at 380 GeV CLIC

$$BR(t \to c\gamma) < 2.6 \cdot 10^{-5}$$

**Signature:**

- high energy isolated photon ($E_\gamma = 50 – 140$ GeV)
- high energy $c$-quark jet ($E_{c\,-\,jet} = 50 – 140$ GeV)
- one $b$-quark jet and a pair of light jets from spectator top
Top-quark FCNC decays

**Sensitivity @ 380 GeV**

Expected limits for 1 ab$^{-1}$ collected at 380 GeV CLIC

\[
\begin{align*}
\text{BR}(t \to c\gamma) &< 2.6 \cdot 10^{-5} \\
\text{BR}(t \to cH) \times \text{BR}(H \to bb) &< 8.8 \cdot 10^{-5}
\end{align*}
\]

**Signature:**
- final state compatible with SM $tt\bar{t}$ events
- three $b$-quark jets in the final state + $c$-quark jet
- invariant mass of two $b$-quark jets consistent with $h$ mass

Response distribution of the BDT for the $t \to cH$ selection
**Sensitivity @ 380 GeV**

Expected limits for 1 ab$^{-1}$ collected at 380 GeV CLIC

\[
\begin{align*}
BR(t \to c\gamma) &< 2.6 \cdot 10^{-5} \\
BR(t \to cH) \times BR(H \to b\bar{b}) &< 8.8 \cdot 10^{-5} \\
BR(t \to c\Xi) &< 1.0 - 3.4 \cdot 10^{-4}
\end{align*}
\]

**Signature:**

- $c$-quark jet
- large missing transverse momentum
- one $b$-quark jet and a pair or light jets from spectator top

95% C.L. limits on $BR(t \to c\Xi)$ as a function of DM particle mass

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A.F. Zarnecki (University of Warsaw)
**Yukawa coupling**

**Threshold scan**
Can be indirectly constrained from the threshold scan (9% contribution) ⇒ 0(10%) statistical uncertainty on $y_t$, dominated by systematic effects.

**Direct measurement**
From the measurement of the $ttH$ production cross section

$$e^+e^- \rightarrow ttH \rightarrow bbbbqq\tau\nu_{\tau}$$
Yukawa coupling

**Threshold scan**
Can be indirectly constrained from the threshold scan (9% contribution) ⇒ 0(10%) statistical uncertainty on $y_t$, dominated by systematic effects

**Direct measurement**
From the measurement of the $ttH$ production cross section

Difficult measurement:
- very low statistics
- large backgrounds
- requires perfect detector performance (6-8 jets, 4 $b$-tags)

$$e^+e^- \rightarrow ttH \rightarrow bbbbqq\tau\nu_{\tau}$$
Yukawa coupling

Direct measurement

Fully-hadronic and semi-leptonic top-quark pair decays considered
Focus on dominant Higgs boson decay channel: $H \rightarrow b\bar{b}$

Semi-leptonic event selection

Hadronic event selection

Expected precision from combined measurement: $\frac{\Delta y_t}{y_t} = 2.7\%$
Yukawa coupling

Direct measurement

Fully-hadronic and semi-leptonic top-quark pair decays considered
Focus on dominant Higgs boson decay channel: \( H \to b\bar{b} \)

Semi-leptonic event selection

<table>
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<tr>
<th>Events in 1.5 ab(^{-1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t\bar{t}h-\ln4q-hbb )</td>
</tr>
<tr>
<td>( qqqq )</td>
</tr>
<tr>
<td>( qqqqvv )</td>
</tr>
<tr>
<td>( qqqqv )</td>
</tr>
<tr>
<td>( qqqqll )</td>
</tr>
</tbody>
</table>

Sensitivity to the CP mixing angle

\[
C_{tttH} = -ig_{ttH}(\cos\phi + isin\phi) \gamma
\]

\( \Delta\sin^2\phi \) vs. \( \sin^2\phi \)

Expected precision from combined measurement:

\[
\frac{\Delta y_t}{y_t} = 2.7\%
\]

\( \Rightarrow \) uncertainty of \(~0.07\) on \( \sin^2\phi \) describing CP violation in \( ttH \) coupling

A.F. Žarnecki (University of Warsaw)
Measurement of $e^+e^- \rightarrow t\bar{t}\nu_e\bar{\nu}_e$ production

At high-energy stages of CLIC contribution of vector-boson fusion to top-quark pair production becomes significant.

Background from $e^+e^- \rightarrow t\bar{t}$ can be reduced to negligible level using a cut on the total missing transverse energy, $E_T^{\text{miss}} > 20$ GeV
Vector-boson fusion

Measurement of $e^+e^- \rightarrow t\bar{t}\nu_e\bar{\nu_e}$ production

At high-energy stages of CLIC contribution of vector-boson fusion to top-quark pair production becomes significant.

Reconstructed $t\bar{t}$ invariant mass distribution is sensitive to possible new physics contributions. **Shown as an example is the EFT operator $Q_{\phi t}$**
Electroweak couplings

Top-quark pair production

Pair production provides direct access to top electroweak couplings

Possible higher order corrections

⇒ sensitive to “new physics” contribution
Electroweak couplings

Top-quark pair production

Pair production provides direct access to top electroweak couplings

Possible higher order corrections⇒ sensitive to “new physics” contribution

New physics effects can be constrained through measurement of:

- total cross-section
- forward-backward asymmetry
- helicity angle distribution in top decays
Electroweak couplings

**Top-quark pair production**

Pair production provides direct access to top electroweak couplings

Possible higher order corrections $\Rightarrow$ sensitive to “new physics” contribution

New physics effects can be constrained through measurement of:

- total cross-section
- forward-backward asymmetry
- helicity angle distribution in top decays

Additional constraints obtained by:

- using electron beam polarisation
- measurements at different $\sqrt{s}$ (also using radiative events!)
Electroweak couplings

Top-quark pair production

Forward-backward asymmetry is extracted from the reconstructed polar-angle distributions for semi-leptonic events.

Radiative events at 1.4 TeV

380 GeV
Top-quark pair production

Forward-backward asymmetry is extracted from the reconstructed polar-angle distributions for **semi-leptonic events**.

**380 GeV**

- \( \sqrt{s} = 380 \text{ GeV}, D^2_{<1} \)
- **CLICdp**
  - WHIZARD
  - Reco. corrected
  - \( P(e^+) = -80\% \)
  - \( P(e^+) = +80\% \)

**Boosted top decays at 1.4 TeV**

- \( \sqrt{s} = 1.4 \text{ TeV}, P(e^+) = -80\% \)
- **CLICdp**
  - Fit
  - Corrected pseudo-data
  - Total MC reco.
  - Background only
  - \( \mathcal{L}_{\text{int}} = 750 \text{ fb}^{-1} \)

- \( \sqrt{s'} \geq 1.2 \text{ TeV} \)
**Top-quark pair production**

Forward-backward asymmetry is extracted from the reconstructed polar-angle distributions for semi-leptonic events.

---

**380 GeV**

\[ \sqrt{s} = 380 \text{ GeV}, D^2 < 1 \]

<table>
<thead>
<tr>
<th>Events / 0.1</th>
</tr>
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<tbody>
<tr>
<td>2500</td>
</tr>
<tr>
<td>2000</td>
</tr>
<tr>
<td>1500</td>
</tr>
<tr>
<td>1000</td>
</tr>
<tr>
<td>500</td>
</tr>
<tr>
<td>0</td>
</tr>
</tbody>
</table>

\[ \cos(\theta^*) \]

- **WHIZARD**
- **Reco. corrected**
- **P(e) = -80%**
- **P(e) = +80%**

**CLICdp**

\[ L_{\text{int}} = 250 \text{ fb}^{-1} \]

---

**Boosted top decays at 3 TeV**

\[ \sqrt{s} = 3 \text{ TeV}, P(e^\prime) = -80\% \]

\[ L_{\text{int}} = 1.5 \text{ ab}^{-1} \]

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>1000</td>
</tr>
<tr>
<td>800</td>
</tr>
<tr>
<td>600</td>
</tr>
<tr>
<td>400</td>
</tr>
<tr>
<td>200</td>
</tr>
<tr>
<td>0</td>
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\[ \cos(\theta^*) \]

- **WHIZARD**
- **Corrected pseudo-data**
- **Fit**
- **Total MC reco.**
- **Background only**

\[ \sqrt{s^*} \geq 2.6 \text{ TeV} \]
Global EFT analysis

EFT framework

BSM effects induced by heavy new physics (above the direct reach of CLIC) are universally described by Effective Field Theory (EFT) operators.

The top-quark pair production process sensitive to seven $d = 6$ operators (out of nine) corresponding to direct BSM coupling to top-quark (“top-philic” operators).

\[
\begin{align*}
Q_{\varphi t} &= (\varphi^\dagger i_\mu \varphi)(\bar{t}_\gamma^\mu t) \\
Q_{tB} &= (\bar{q}_\sigma^{\mu\nu} t)\bar{\varphi}B_{\mu\nu} \\
Q_{tW} &= (\bar{q}_\sigma^{\mu\nu} t)\tau^I\bar{\varphi}W_{\mu\nu}^I
\end{align*}
\]

\[
\begin{align*}
Q_{\varphi q} &= Q_{\varphi q}^{(1)} - Q_{\varphi q}^{(3)} = (\varphi^\dagger i_\mu \varphi)(\bar{q}_\gamma^\mu q) - (\varphi^\dagger i_\mu \varphi)(\bar{q}\tau^I_\gamma^\mu q) \\
Q_{lt,B} &= (\bar{t}_\gamma^\mu t)(\bar{e}_\gamma^\mu e + \frac{1}{2}\bar{l}_\gamma^\mu l) \overset{\text{EOM}}{=} \frac{1}{2} Q_{\varphi t} + \frac{1}{g} \bar{t}_\gamma^\mu t D^v B_{\mu\nu} + \ldots \\
Q_{lq,B} &= (\bar{q}_\gamma^\mu q)(\bar{e}_\gamma^\mu e + \frac{1}{2}\bar{l}_\gamma^\mu l) \overset{\text{EOM}}{=} \frac{1}{2} Q_{\varphi q}^{(1)} + \frac{1}{g} \bar{q}_\gamma^\mu q D^v B_{\mu\nu} + \ldots \\
Q_{lq,W} &= (\bar{q}_\tau^I_\gamma^\mu q)(\bar{l}_\gamma^\mu l) \overset{\text{EOM}}{=} -Q_{\varphi q}^{(3)} - \frac{2}{g} \bar{q}_\tau^I_\gamma^\mu q D^v W_{\mu\nu}^I + \ldots
\end{align*}
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Global EFT analysis

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BSM effects induced by heavy new physics (above the direct reach of CLIC) are universally described by Effective Field Theory (EFT) operators.

The top-quark pair production process sensitive to seven $d = 6$ operators (out of nine) corresponding to direct BSM coupling to top-quark ("top-philic" operators).

Measurements at one energy stage are insufficient to simultaneously constrain all couplings in the seven-dimensional EFT parameter space.

Only by combining data collected at different energies (and polarisations) all Wilson coefficients can be constrained simultaneously!

Sensitivity to the four-fermion operators significantly improves with energy
Global EFT analysis

Constraints on BSM effects
Summary of the global EFT analysis of measurements involving top quark
Results based on statistically optimal observables

High energy CLIC can reach “new physics” scales in the 100 TeV range
**Global EFT analysis**

**Discovery reach**

5σ discovery range for top compositeness from global EFT analysis

![Graph showing the discovery reach for top compositeness](image)

- top-quark compositeness can be discovered at CLIC up to \( \sim 10 \) TeV
- more than 20 TeV can be reached in favourable configurations
Conclusions

CLIC
An attractive and cost-effective option for next large facility at CERN

The initial stage of CLIC: optimal for Higgs and top-quark measurements
- precise determination of top-quark mass
- searches for rare top-quark decays
- constraints on electroweak couplings

Subsequent CLIC stages:
- higher energies, luminosities and cross sections (for many processes)
- direct measurement of the top-quark Yukawa coupling
- precision measurements complementary to those at low energy
- indirect BSM searches extending to \(0(100)\) TeV scales

For details see:
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Thank you!
Formal European Strategy submissions

- The Compact Linear e\(^+\)e\(^-\) Collider (CLIC): Accelerator and Detector, arXiv:1812.07987
- The Compact Linear e\(^+\)e\(^-\) Collider (CLIC): Physics Potential, arXiv:1812.07986

Yellow Reports


Journal publications

- Top-quark physics at the CLIC electron-positron linear collider arXiv:1807.02441
- Higgs physics at the CLIC electron-positron linear collider arXiv:1608.07538

Public CLICdp notes

- Updated CLIC luminosity staging baseline and Higgs coupling prospects arXiv:1812.01644
- CLICdet: The post-CDR CLIC detector model CLICdp-Note-2017-001
Compact Linear Collider (CLIC)

- **380 GeV** - 11.4 km (CLIC380)
- **1.5 TeV** - 29.0 km (CLIC1500)
- **3.0 TeV** - 50.1 km (CLIC3000)
Expected CLIC luminosity

Comparison to other project

- Stage 1 luminosity “per IP” similar to FCC-ee with half the construction cost and half the power consumption
- The only $e^+e^-$ project that can go into the TeV domain
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, 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

Compact Linear Collider

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A.F. Żarnecki (University of Warsaw)

Top-quark physics at CLIC
CLIC detector concept

CLICdet

Based on detailed simulation studies, detector R&D and beam tests.

Optimised for Particle Flow reconstruction

Full exploitation of physics potential from 380 GeV to 3 TeV

For details refer to arXiv:1812.07337
Detector performance

**Top-quark event reconstruction**

High efficiency of $t\bar{t}$ event reconstruction thanks to the clean environment.

- **380 GeV**
- Full reconstruction of the decay products at the first energy stage.
- High energy and mass resolution from Particle Flow reconstruction.
- Based on high calorimeter granularity and precise tracking.

Flavour tagging with **LcFiPLUS**: essential for proper event reconstruction and non-resonant background suppression.
Top-quark event reconstruction
High efficiency of $t\bar{t}$ event reconstruction thanks to the clean environment

3 TeV

Full reconstruction of the decay products at the first energy stage.

At high energy stages, dedicated algorithms developed for tagging boosted top-quark decays.

Reconstructing 'fat' jets and looking at their substructure

Flavour tagging with LCFIPlus: essential for proper event reconstruction and non-resonant background suppression.