Top-Quark Physics at High-Energy CLIC operation

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on behalf of the CLICdp collaboration

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Future $e^+e^-$ collider at the TeV scale

Novel accelerator technique based on radio-frequency devices and a two-beam acceleration scheme with gradient 100 MV/m

CDR published in 2012
First beams in 2035

<table>
<thead>
<tr>
<th>Energy staging</th>
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<tbody>
<tr>
<td>Stage</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>top scan</td>
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<tr>
<td>2</td>
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<tr>
<td>3</td>
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Cf. talk #884: The CLIC accelerator project status and plans (D. Schulte)
Cf. talk #526: Top physics at the first CLIC stage (F. Zarnecki)
The CLIC environment and detector concept

\textit{e^+e^- collider vs. hadron collider}

- Cleaner environment at lepton colliders allows higher precision measurements
- Beamstrahlung-induced backgrounds: $\gamma\gamma \rightarrow \text{hadrons}; e^+e^-$ pairs

- Designed for Particle Flow Analysis: Highly granular calorimetry
- Full detector simulation used for (most) top physics studies presented

Cf. talk #528: The CLIC detector (E. Sicking)
**Overview: Top physics at CLIC**

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

380 GeV close to production maximum
→ large event sample at Stage 1; boosted/radiative production at Stage 2&3

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

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

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

Cross section grows with collision energy
→ benefits from Stage 3

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Results from CLICdp-Draft-2018-003 (out soon)

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► Top electroweak couplings
► Top Yukawa coupling
► CP properties of $t \rightarrow H$ coupling
► BSM in $H/t$ sectors

Cf. talk #526: Top physics at the first CLIC stage (F. Zarnecki)
Boosted top tagging

- Substructure-based techniques developed at LHC → adapt to CLIC’s cleaner environment
- Boosted tops: more collimated jets \(\sim\) better mass reconstruction

Use linear collider jet algorithm VLC with large radius parameter

\[
\begin{align*}
\text{R}=0.4 & & \text{R}=1.0 \\
\text{CLICdp } \sqrt{s}=3 \text{ TeV} & & \text{CLICdp } \sqrt{s}=3 \text{ TeV} \\
|\cos(\theta_{\text{jet}})| \leq 0.80 & & |\cos(\theta_{\text{jet}})| \leq 0.80 \\
\text{VLC4 } \beta=1.0 \gamma=1.0 & & \text{VLC10 } \beta=1.0 \gamma=1.0
\end{align*}
\]

Preliminary
Boosted top tagging

- Substructure-based techniques developed at LHC $\rightarrow$ adapt to CLIC’s cleaner environment
- Boosted tops: more collimated jets $\sim$ better mass reconstruction

Top tagging algorithm

- Based on Johns Hopkins top tagger
- Iterative de-clustering
- Identify 3 or 4 hard subjets
- Mass cuts on the subjets ($m_W, m_t$)
- At linear colliders, background rates to $t\bar{t}$ low $\rightarrow$ operating point at high signal efficiency
- 23% better than with $m_t$ cut
- Jet substructure information in MVA
$t\bar{t} \rightarrow qqqq\ell\nu$ with lepton for charge tagging

**Event selection**

- One isolated lepton with $p_T > 10$ GeV
- Two step jet clustering:
  - $R=0.4$ inclusive jets $\rightarrow$ input to:
  - $N=2$ VLC with $R=1.4 \ (1.0)$ at 1.4 \ (3) TeV
- One top tagged jet from top tagger
- Veto isolated photons
- $\sqrt{s'_R} > 1.2 \ (2.6)$ TeV at 1.4 \ (3) TeV
- 2 BDTs for discrimination against
  - fully hadronic 4 and 6 quark backgrounds
  - 2 quark backgrounds with up to 2 leptons
- Combined BDT
Results for Boosted top pair production

- Extract $\sigma_{t\bar{t}}^{\text{fid}}$ and $A_{FB}$

<table>
<thead>
<tr>
<th>$\sqrt{s}$</th>
<th>380 GeV</th>
<th>1.4 TeV</th>
<th>3 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P(e^-)$</td>
<td>-80%</td>
<td>+80%</td>
<td>-80%</td>
</tr>
<tr>
<td>$\Delta \sigma_{t\bar{t}}^{\text{fid}} / \sigma_{t\bar{t}}^{\text{fid}}$</td>
<td>0.68%</td>
<td>0.96%</td>
<td>1.8%</td>
</tr>
<tr>
<td>$\Delta A_{FB} / A_{FB}$</td>
<td>5.3%</td>
<td>4.1%</td>
<td>2.5%</td>
</tr>
</tbody>
</table>

- Polar angle comparison between parton level and efficiency- and background-corrected reconstruction level
Radiative events: $\sqrt{s'}$ below nominal $\sqrt{s} = 1.4$ TeV ($\sigma_{tt}$, luminosity spectrum, ISR)

$t\bar{t} \rightarrow qqqq\ell\nu$ with lepton used for charge determination

Extract $\cos \theta^*$ in $\sqrt{s'}$ intervals: 400-900 GeV, 900-1200 GeV, $\geq$ 1200 GeV

**Selection strategy:**

- Selection of isolated lepton and 2 large-$R$ jets
- Associate jets to $t \rightarrow$ hadronic or $b$ from $t \rightarrow$ leptonic according to top decay angle
- Kinematic fit to reconstruct $\sqrt{s'} \sim$ resolution of $\approx$ 75 GeV
- 2 BDTs based on kinematics and jet substructure (N-subjettiness): trained for $\sqrt{s'} \leq 1200$ GeV and $\sqrt{s'} > 1200$ GeV separately
Top pair production in radiative events at 1.4 TeV

- Radiative events: $\sqrt{s'}$ below nominal $\sqrt{s} = 1.4$ TeV ($\sigma_{tt}$, luminosity spectrum, ISR)
- $t\bar{t} \rightarrow qqqq\ell\nu$ with lepton used for charge determination
- Extract $\cos(\theta^*)$ in $\sqrt{s'}$ intervals: 400-900 GeV, 900-1200 GeV, $\geq 1200$ GeV
Associated $ttH$ production at 1.4 TeV

Final states studied:
- $H \rightarrow b\bar{b}$
- $t\bar{t}$ fully-hadronic and semi-leptonic

Event selection
- Isolated lepton finder $\rightarrow$ no lepton: fully-hadronic, else: semi-leptonic
- Jet clustering; assignment to $W$, top, Higgs based on minimum $\chi^2 = \frac{(m_{ij} - m_W)^2}{\sigma_W^2} + \frac{(m_{ijk} - m_t)^2}{\sigma_t^2} + \frac{(m_{lm} - m_H)^2}{\sigma_H^2}$
- BDTs trained for the 2 channels including reconstructed $m_H$, event shapes, jet kinematics, flavor tagging info

Cross section and Yukawa coupling with 1.5 ab$^{-1}$
- Semi-leptonic channel: $\Delta \sigma/\sigma = 11.1\%$
- Fully-hadronic channel: $\Delta \sigma/\sigma = 9.6\%$
- Combined precision: 7.3\%$
- Yukawa coupling: $\frac{\Delta g_{ttH}}{g_{ttH}} = 3.8\%$
- Will be improved by adding beam polarisation
σ_{t\bar{t}} measurement sensitive to CP mixing in the ttH coupling

Mixing angle $\phi$ parametrized as

$$ig_{ttH}(\cos \phi + i \sin \phi \gamma_5)$$

Dependence of cross section on $\sin^2 \phi$ allows to extract expected sensitivity:

$\Delta \sin^2 \phi \approx 0.1$ for $0 < \sin^2 \phi < 1$ (almost independent)

Can be further improved making use of polarized beams and differential distributions
Vector Boson Fusion production at 3 TeV

- $WW \rightarrow t\bar{t}$ process probes coupling of longitudinal $W$ bosons to top quark $\sim$ electroweak symmetry breaking
- Sensitive to BSM scenarios, parametrized with top-philic EFT operators

**Analysis strategy:** WHIZARD parton level

- Background suppressed by cuts on missing energy
- Limits on EFT couplings from $t\bar{t}$ invariant mass and scattering angle distributions

$Q_{\varphi t}$: top-philic $d = 6$ EFT operator
(left: $C_{\varphi t} = -0.83 \text{ TeV}^{-2}$)
Top-philic EFT interpretation

- Use statistically optimal observables to set limits on top-philic EFT operators in a global fit
- Analysis of top pair production in $e^+ e^- \rightarrow t\bar{t} \rightarrow bW^+ \bar{b}W^- \rightarrow bW^+ \bar{b}W^-$ final state including total rate information

Energy dependence of EFT operators effects on cross section

Cf. talk #525 BSM Searches at CLIC (R. Franceschini)

[G. Durieux 2017]
Top-philic EFT interpretation

- Use statistically optimal observables to set limits on top-philic EFT operators in a global fit
- Analysis of top pair production in $e^+e^- \to t\bar{t} \to bW^+\bar{b}W^-$ final state including total rate information

Based on $\sqrt{s} = 380$ GeV, 1.4 TeV, 3 TeV using $\mathcal{L} = 500$ fb$^{-1}$, 1.5 ab$^{-1}$, 3 ab$^{-1}$ incl. equal share of $P(e^-) = \pm 80\%$

bars: limits from global fit
ticks: single operator limits
Summary and conclusions

Top physics at CLIC $\sim$ high precision measurements

- Top mass (threshold scan around 350 GeV)
- Top pair cross section and FB asymmetry
- **Higher energy stages crucial** for BSM sensitivity in top physics
  - Direct access to top Yukawa coupling and its structure (e.g. CP admixture) in ttH
  - Access VBF production of $t\bar{t}$
  - Significantly enhanced sensitivity to some EFT operators

- CLIC is the only proposed $e^+e^-$ collider option aiming for 1.5 TeV and 3 TeV
Additional material
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
Results and systematic uncertainties for top-pair production in radiative events

<table>
<thead>
<tr>
<th>CLICdp Preliminary</th>
<th>$\sqrt{s'} \in [400, 900)$ TeV</th>
<th>$\sqrt{s'} \in [900, 1200)$ TeV</th>
<th>$\sqrt{s'} \geq 1200$ GeV</th>
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<tr>
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<td>-80% +80%</td>
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<td>-80% +80%</td>
</tr>
<tr>
<td>$\sigma_{t\bar{t}}$ [fb]</td>
<td>16.56 8.63 11.01 5.87 18.41 9.84</td>
<td></td>
<td></td>
</tr>
<tr>
<td>stat. unc. [fb]</td>
<td>1.31 0.83 0.38 0.29 0.37 0.28</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$A_{FB}$</td>
<td>0.458 0.514 0.546 0.588 0.562 0.621</td>
<td></td>
<td></td>
</tr>
<tr>
<td>stat. unc.</td>
<td>0.081 0.105 0.034 0.045 0.018 0.024</td>
<td></td>
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Integrated luminosity 750 fb$^{-1}$ per polarisation state

**Systematic uncertainties for radiative $t\bar{t}$ events**

- Background normalization: $\Delta \sigma_{t\bar{t}}/\sigma_{t\bar{t}} = 1 - 3\%$
- Background shape in $\cos \theta^*$: $\Delta \sigma_{t\bar{t}}/\sigma_{t\bar{t}} = 0.2 - 0.8\%$
- Bias of reconstructed $A_{FB}$ vs. truth $A_{FB}$: $\Delta A_{FB}/A_{FB} = 2 - 6\%$

⇒ Statistical uncertainty dominant
The CLIC detector concept

Designed for Particle Flow Analysis and optimized for CLIC environment

- 4 T B-field
- Vertex detector (3 double layers)
- Large Silicon tracker R=1.5 m
- 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

Cf. talk #528: The CLIC detector (E.Sicking)
Top-philic EFT operators

Effective field theory top-philic basis introduced in
“Top-Quark Physics at the CLIC Electron-Positron Linear Collider”

\[
\begin{align*}
Q_{\varphi t} &= (\varphi^\dagger i\vec{D}_\mu \varphi)(\bar{t}\gamma^\mu t) \\
Q_{t\varphi} &= (\varphi^\dagger \varphi)(\bar{q} t \tilde{\varphi}) \\
Q_{tB} &= (\bar{q}\sigma^{\mu\nu} t)\tilde{\varphi}B_{\mu\nu} \\
Q^{(1)}_{\varphi q} &= (\varphi^\dagger i\vec{D}_\mu \varphi)(\bar{q}\gamma^\mu q) \\
Q^{(3)}_{\varphi q} &= (\varphi^\dagger i\vec{D}_\mu \varphi)(\bar{q} \tau^I \gamma^\mu q) \\
Q_{tW} &= (\bar{q}\sigma^{\mu\nu} t)\tilde{\varphi}W^I_{\mu\nu} \\
Q_{lt,B} &= (\bar{t}\gamma^\mu t)(\bar{e}\gamma_\mu e + \frac{1}{2}\bar{l}\gamma_\mu l)^{EOM} = \frac{1}{2}Q_{\varphi t} + \frac{1}{g}\bar{t}\gamma^\mu t D^\nu B_{\mu\nu} + \ldots \\
Q_{lq,B} &= (\bar{q}\gamma^\mu q)(\bar{e}\gamma_\mu e + \frac{1}{2}\bar{l}\gamma_\mu l)^{EOM} = \frac{1}{2}Q_{\varphi q} + \frac{1}{g}\bar{q}\gamma^\mu q D^\nu B_{\mu\nu} + \ldots \\
Q_{lq,W} &= (\bar{q}\tau^I \gamma^\mu q)(\bar{l}\tau^I \gamma_\mu l)^{EOM} = -Q^{(3)}_{\varphi q} - \frac{2}{g}\bar{q}\tau^I \gamma^\mu q D^\nu W^I_{\mu\nu} + \ldots \\
\end{align*}
\]

Conventions correspond to Warsaw basis\(^i\) except \(Q_{lt,B}, Q_{lq,B}\) and \(Q_{lq,W}\) which are linear combinations of Warsaw basis four-fermion operators

Forward-backward asymmetry and differential cross section

- $\theta^*$: Polar angle between incoming electron and produced top quark in the $t\bar{t}$ rest system

- Differential cross section:
  
  \[ \frac{d\sigma}{d(\cos(\theta^*))} = \sigma_1 (1 + \cos(\theta^*))^2 + \sigma_2 (1 - \cos(\theta^*))^2 + \sigma_3 (1 - \cos^2(\theta^*)) \]

- Forward and backward cross sections:

  \[ \sigma_F = \int_0^{\pi/2} \frac{d\sigma}{d(\cos(\theta^*))} d\theta^* \quad \text{and} \quad \sigma_B = \int_{\pi/2}^{\pi} \frac{d\sigma}{d(\cos(\theta^*))} d\theta^* \]

- Forward-backward asymmetry:

  \[ A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} \]
\[ \tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min \{ \Delta R_{1,k}, \Delta R_{2,k}, \ldots, \Delta R_{N,k} \}, \] (1)

- \( k \): constituent particles of the jet with \( p_{T,k} \)
- \( \Delta R_{J,k} = \sqrt{\Delta \eta^2 + \Delta \phi^2} \): distance between each candidate subjet \( J \) and constituent particle \( k \)
- \( d_0 = R_0 \cdot \sum_k p_{T,k} \)
- \( R_0 \): jet radius used in the large-\( R \) jet clustering
- \( \tau_N \) quantifies to what degree a jet can be regarded as composed of \( N \) subjets