News on the CLIC physics potential

- Motivation
- Top Physics
- Higgs Physics
- Future

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on behalf of the CLICdp Collaboration
Motivation: why CLIC?

Compact Linear Collider (CLIC):
- CERN √
  - √s: 380 GeV, 1.5 TeV, 3 TeV
  - Length: 11 km, 29 km, 50 km

International Linear Collider (ILC):
- Japan (Kitakami) √s: 250 (-500) GeV (+1 TeV)
  - Length: 17, 31 km (50 km)

Future Circular Collider (FCC-ee):
- CERN √
  - √s: 90-350 GeV
  - Circumference: 97.75 km

Circular Electron Positron Collider (CEPC):
- China √s: 90-240 GeV
  - Length: 100 km
Precise top quark mass

- **Strategy:** \(10 \text{ fb}^{-1} \) @ \(10 \sqrt{s}\) \(\rightarrow\) 50-75 MeV total (stat.+syst.) uncertainty
  - Expected 1S mass precision \(\approx 50\) MeV (NNNLO scale dominates)
    - Theoretical uncertainty \(\approx 10\) MeV, 1S \(\rightarrow \overline{MS}\) scheme [PRL 114, 142002 (2015)]
  - Significant improvement cf. HL-LHC estimates
- **t mass from cross-section outperforms “direct” kinematic measurement**
  - Compare to W mass from LEP2 (161-209 GeV)
Precise top quark mass

- **CLICdp work in progress**

- **CLIC flexibility:** Dedicated beam params reduce beamstrahlung

- **Strategy:** 10 fb\(^{-1}\) @ 10 \(\sqrt{s}\) → 50-75 MeV total (stat.+syst.) uncertainty
  - Expected 1S mass precision ≈50 MeV (NNNLO scale dominates)
    - Theoretical uncertainty ≈10 MeV, 1S → \(\overline{MS}\) scheme [PRL 114, 142002 (2015)]
    - Significant improvement cf. HL-LHC estimates
  - \(t\) mass from cross-section outperforms “direct” kinematic measurement
    - Compare to W mass from LEP2 (161-209 GeV)
\( t\bar{t} \) above threshold

- \( e^+e^- \to t\bar{t} \)
  - Near max. but away from threshold
  - 500 fb\(^{-1} \) \(\to\) 350k \( t\bar{t} \), test rare decays
  - Rich programme even in initial energy phase

- \( e^+e^- \to t\bar{t}H \) peaks \(\approx\) 800 GeV
  - Only CLIC (ILC \textit{just} in 500 GeV option)

- \( e^+e^- \to t\bar{t}\nu\bar{\nu} \) VBF
  - The higher the \( \sqrt{s} \) the better
Rare decays

- Focused on modes difficult for LHC
- Any evidence for top FCNC
  ▶ New physics
- Full detector simulation studies
  ▶ $t \rightarrow c + \text{missing energy}$
    ▪ Promising!
  ▶ $t \rightarrow c\gamma$
  ▶ $t \rightarrow cH \ (H \rightarrow b\bar{b})$
    ▪ $\text{Br}(t \rightarrow cH) \times \text{Br}(H \rightarrow b\bar{b}) < 10^{-4}$ (95% CL)

- CLIC copes with experimental challenges
  ▶ Separation of $b$ from
  ▶ Signature ~ SM processes
  ▶ Excellent vertex detector
  ▶ Control of multi-jet SM background
Boosted top reconstruction

- Jets in high-energy top decays not distinct
- Reconstruct “large” jet
  - Find substructure $\sim t \rightarrow Wb \rightarrow qqb$
- CLIC profits from LHC experience
  - e.g “Johns-Hopkins” top tagger

Typical event: $tt \rightarrow b\bar{q}q \bar{b}\ell\nu$

Transverse momentum (GeV)

- CLICdp work in progress
- $e^+e^- \rightarrow tt \rightarrow qqqqqq$
- $e^+e^- \rightarrow tt \rightarrow qqqqqq (|\cos\theta| \leq 0.5)$
- $e^+e^- \rightarrow qq (q=uds) \times 10$

CLICdp

$p_T$ [GeV]
Identified W and b-jet systems

Transverse momentum (GeV)

- Jets in **high-energy** top decays not distinct
- Reconstruct “large” jet
  - Find substructure $\sim t \rightarrow Wb \rightarrow qqb$
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**Typical event**

$t\bar{t} \rightarrow bq\bar{q} \bar{b}\ell\nu$

**CLICdp work in progress**
Asymmetries with radiative events

- 7 objects to be reconstructed:
  - 2 b-jets, 2 other jets
  - Charged lepton and neutrino
  - Photon(s) from ISR/Beamstrahlung

- \( \sqrt{s} \gg \) threshold, highly collimated jets
  - Use boosted reconstruction

- ISR used to measure differential in \( \sqrt{s}' \)

- Asymmetries, cross-sections input to form factor studies

\[
\frac{s}{s'} = s \times \left( \begin{array}{c}
0 \\
0.2 \\
0.4 \\
0.6 \\
0.8 \\
1 \\
1.2 \\
1.4 \\
\end{array} \right)
\]

\[
\sqrt{s} = 1.4 \text{ TeV}
\]

\[
\sqrt{s} = 3 \text{ TeV}
\]

CLICdp work in progress
Top Form Factors

\[ \Gamma_{\mu}^{\mu X}(k^2) = -ie \left\{ \gamma_{\mu} \left( F_{1V}^X(k^2) + \gamma_5 F_{1A}^X(k^2) \right) + \frac{\sigma_{\mu\nu} k^\nu}{2m_t} \left( i F_{2V}^X(k^2) + \gamma_5 F_{2A}^X(k^2) \right) \right\} \]

- **HL-LHC**, $\sqrt{s} = 14$ TeV, $L = 3000$ fb⁻¹
- **ILC initial**, $\sqrt{s} = 500$ GeV, $L = 500$ fb⁻¹
  - EPJ C75 (2015) 512
- **CLIC initial**, $\sqrt{s} = 380$ GeV, $L = 500$ fb⁻¹
  - PRELIMINARY
- **CLIC**, $\sqrt{s} = 380$ GeV, $L = 500$ fb⁻¹ ($\sigma_{\text{th. uncert.}} \sim 3\%$)
  - PRELIMINARY

**CP Conserving FF**

- **HL-LHC**, $\sqrt{s} = 14$ TeV, $L = 3000$ fb⁻¹
- **ILC initial**, $\sqrt{s} = 500$ GeV, $L = 500$ fb⁻¹
- **ILC nominal**, $\sqrt{s} = 500$ GeV, $L = 4000$ fb⁻¹
- **CLIC initial**, $\sqrt{s} = 380$ GeV, $L = 500$ fb⁻¹
- **CLIC**, $\sqrt{s} = 3$ TeV, $L = 3000$ fb⁻¹

**CP Violating FF**

[CERN YR 2016-004, arxiv:1710.06737]


[Phys. Rev. D 71, 054013 (2005)]

[EPJC 75, 512 (2015)]

[ience基金会]

[21-Mar-2018]

Moriond QCD 2018 / Nigel Watson
Top Form Factors

\[ \Gamma_{1\mu}^X(k^2) = -ie \left\{ \gamma_\mu \left( F_{1V}^X(k^2) + \gamma_5 F_{1A}^X(k^2) \right) + \frac{\sigma_{\mu\nu} k^\nu}{2m_t} \left( \gamma_2 F_{2V}^X(k^2) + \gamma_5 F_{2A}^X(k^2) \right) \right\} \]

Disentangled by beam polarisation +: \( \sigma(\text{tt}) \); F-B asymmetry; lepton helicity angle

Sensitivity to contact interactions rises with energy – good for CLIC
Higgs physics at CLIC

Dominant processes:

Higgsstrahlung
\( \sigma \sim 1/s \)
Higgs id. from Z recoil

WW(ZZ) - fusion
\( \sigma \sim \log(s) \)
Large yield at high E

For unpolarised beams.
H\nu increases \( \times 1.8 \) for -80% e\(^{-}\) polarisation
(baseline plan)

\[ \text{[EPJ C (2017) 77:475]} \]

\[ \begin{array}{cccc}
L_{\text{int}} & 350 \text{ GeV} & 1.4 \text{ TeV} & 3 \text{ TeV} \\
\# ZH \text{ events} & 500 \text{ fb}^{-1} & 1.5 \text{ ab}^{-1} & 2 \text{ ab}^{-1} \\
\# H\nu_{e}\bar{\nu}_{e} \text{ events} & 68 000 & 20 000 & 11 000 \\
\# H\nu_{e}^{+}\nu_{e}^{-} \text{ events} & 17 000 & 370 000 & 830 000 \\
\end{array} \]
e^+e^- \rightarrow ZH @ \sim 350 \text{ GeV}

- Select via recoil mass of Z
  - model-independent measurement
    - \Delta \sigma_{HZ} \sim g_{ZHH}

\begin{align*}
Z \rightarrow \mu\mu & \quad \text{BR}\sim3.5\% \quad \text{very clean} \\
Z \rightarrow ee & \quad \text{BR}\sim3.5\% \quad \text{very clean} \\
Z \rightarrow qq & \quad \text{BR}\sim70\% \quad \text{almost model independent}
\end{align*}

- \text{HZ} \rightarrow Hq\bar{q} \quad \text{access to invisible Higgs decay}
  - Estimated sensitivity, BR(H \rightarrow \text{invisible}) < 1\% @ 90\% CL
  - Better precision at 350 GeV than 250/420 GeV
  - Trade-off between detector resolution and physics background

\[ \Delta(\sigma_{HZ}) = \pm 3.8\% \]
\[ \Delta(g_{HZZ}) = \pm 0.8\% \]
Simultaneous $H \rightarrow b \bar{b}, c \bar{c}, g g$ @ 350 GeV

Compare $b \bar{b}$ likelihood versus $c \bar{c}$ likelihood for different event classes.

$H \rightarrow b \bar{b}$

$H \rightarrow c \bar{c}$

$H \rightarrow g g$

2 production and 3 decay modes

$\Delta(\sigma \times \text{BR})_{\text{SM}}/(\sigma \times \text{BR})_{\text{SM}}$ at 350 GeV, 500 fb$^{-1}$

<table>
<thead>
<tr>
<th>Decay</th>
<th>Statistical uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Higgsstrahlung</td>
</tr>
<tr>
<td>$H \rightarrow b \bar{b}$</td>
<td>0.84 %</td>
</tr>
<tr>
<td>$H \rightarrow c \bar{c}$</td>
<td>10.3 %</td>
</tr>
<tr>
<td>$H \rightarrow g g$</td>
<td>4.5 %</td>
</tr>
</tbody>
</table>
Higgs physics above 1 TeV

Vector boson fusion:
\( e^+e^- \rightarrow H\nu\nu, \; e^+e^- \rightarrow H^+H^- \)
High \( \sigma + \) increased luminosity
Access to rare Higgs decays

\( \ttH \) production:
- Extraction of Yukawa coupling \( \gamma_t \)
- Best at \( \sqrt{s} \) above 700 GeV

Studied at 1.4 TeV, 1.5 ab\(^{-1}\)
- Fully hadronic (8 jets)
- Semi-leptonic (6 jets + lepton + \( \nu \))

Statistical accuracy:
- \( \Delta(g_{Htt}) = \pm 4.4\% \) at 1.4 TeV
Higgs coupling precision

- Full CLIC programme, 5 years each stage
  ▶ Assumes 80% e- pol., >1 TeV
- Recoil mass approach
  ▶ Model independent analysis
  ▶ ~1% level for most couplings
  ▶ H width free, allows extra non-SM decays,
  ▶ H width to ±3.6%
- Full simulation study, details

CLIC has unique sensitivity and energy reach
Summary

• e^+e^- machine at few 10^2 GeV will measure Higgs and top properties
  ▶ Precision >> HL-LHC and less model dependent

• First CLIC stage at 350/380 GeV allows
  ▶ Higgs production: Higgsstrahlung and WW fusion
  ▶ Top quark: threshold and continuum regions
  ▶ Rare decays

• Higher-energy e^+e^- collider has more BSM discovery potential
  ▶ Direct detection up to kinematic limit
  ▶ Indirect discovery via precise EW measurements up to ~few x10 TeV
  ▶ Sensitivity often rises steeply with the centre-of-mass energy

CLIC is unique, only proposed multi-TeV e^+e^- machine
Backup material
### Motivation: why $e^+e^-$?

#### p-p collisions

<table>
<thead>
<tr>
<th>Initial state for hard scatter?</th>
</tr>
</thead>
<tbody>
<tr>
<td>→ Initial state/event unknown</td>
</tr>
<tr>
<td>→ Limits achievable precision</td>
</tr>
<tr>
<td>→ Proton are complicated...</td>
</tr>
</tbody>
</table>

#### e$^+$e$^-$ collisions

<table>
<thead>
<tr>
<th>Initial state</th>
</tr>
</thead>
<tbody>
<tr>
<td>→ Initial state ~well defined</td>
</tr>
<tr>
<td>→ High-precision measurements</td>
</tr>
<tr>
<td>→ e$^+$/e$^-$ are point-like</td>
</tr>
</tbody>
</table>

- High rates of QCD backgrounds
  - → Complex triggering schemes
  - → High radiation levels

- Cleaner experimental environment
  - → Simple trigger scheme/readout
  - → Low radiation levels

- High cross-sections for colored-states

- Superior sensitivity for electro-weak states

- High-energy circular colliders feasible

- $\geq 350$ GeV needs a linear collider
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
Costings

![Chart of costings for different energy levels: 500 GeV A, 500 GeV B, 380 GeV. The chart shows the breakdown of costs by category: Accelerator control & op. infra., Civil engineering & services, Interaction region, Two-beam accelerators, Drive beam production, Main beam production.](Image)

- **500 GeV A**:
  - Accelerator control & op. infra.: 1000 MCHF
  - Civil engineering & services: 4000 MCHF
  - Interaction region: 100 MCHF
  - Two-beam accelerators: 2000 MCHF
  - Drive beam production: 1000 MCHF
  - Main beam production: 1000 MCHF

- **500 GeV B**:
  - Accelerator control & op. infra.: 1200 MCHF
  - Civil engineering & services: 3800 MCHF
  - Interaction region: 200 MCHF
  - Two-beam accelerators: 2200 MCHF
  - Drive beam production: 100 MCHF
  - Main beam production: 1000 MCHF

- **380 GeV**:
  - Accelerator control & op. infra.: 1000 MCHF
  - Civil engineering & services: 4800 MCHF
  - Interaction region: 100 MCHF
  - Two-beam accelerators: 2000 MCHF
  - Drive beam production: 1000 MCHF
  - Main beam production: 1000 MCHF

Total costs for:
- **500 GeV A**: 8000 MCHF
- **500 GeV B**: 8200 MCHF
- **380 GeV**: 8000 MCHF
Initial energy
Higher energy