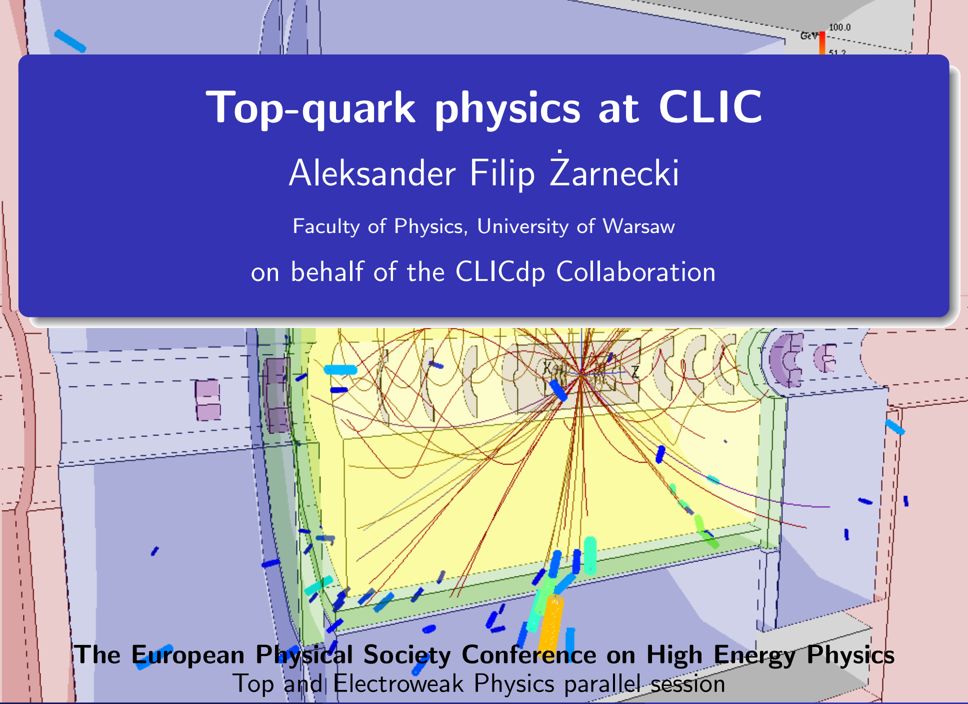


Top-quark physics at CLIC

Aleksander Filip Żarnecki

Faculty of Physics, University of Warsaw

on behalf of the CLICdp Collaboration

The European Physical Society Conference on High Energy Physics

Top and Electroweak Physics parallel session

Outline

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

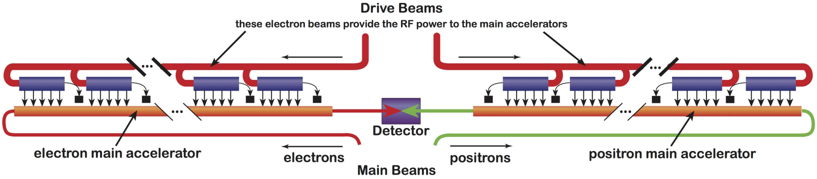
For details see:

- H.Abramowicz et al. (CLICdp Collaboration), *Top-Quark Physics at the CLIC Electron-Positron Linear Collider*, CLICdp-Pub-2018-003, arXiv:1807.02441

For more information on CLIC accelerator, detector and physics see:

- CLIC input to the European Strategy for Particle Physics Update 2018-2020

Compact LInear Collider



Conceptual Design (CDR) presented in 2012 CERN-2012-007

- 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

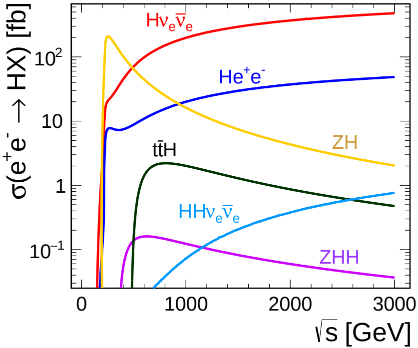
For details refer to:

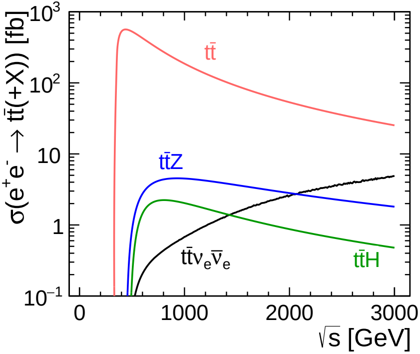
P.N.Burrows, *The CLIC accelerator project: status and plans*, *Accelerators for HEP* parallel session, tomorrow

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 $1\,\mathrm{ab}^{-1}$ $+\ 100\ \mathrm{fb}^{-1}$ at $t\bar{t}$ threshold
  focus on precision Standard Model physics,
  in particular **Higgs boson** and **top-quark** measurements





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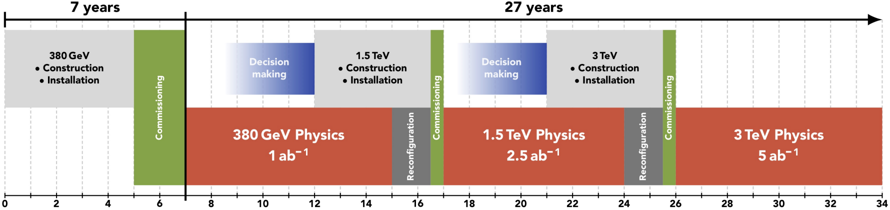
- $\sqrt{s} = 1.5$ TeV with $2.5\,\text{ab}^{-1}$
- $\sqrt{s} = 3$ TeV with $5\,\text{ab}^{-1}$
  focus on direct and indirect **BSM searches**,
  but also additional **Higgs boson** and **top-quark** studies



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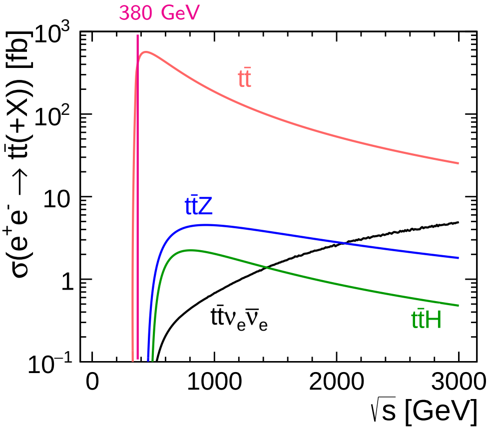
Other CLICdp contributions to EPS-HEP'2019:

- 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

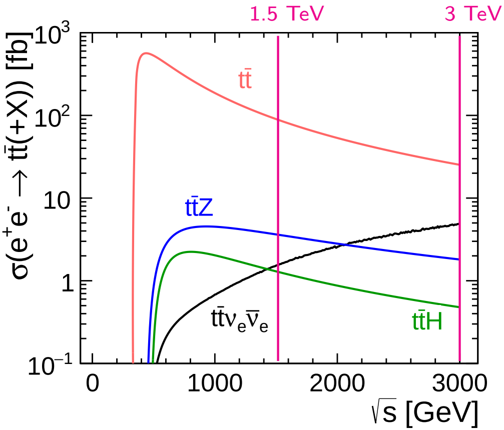


Top pair-production at and above the threshold (380 GeV)

- top-quark mass
- rare decays
- electroweak couplings

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

Top-quark processes



Top pair-production at and above the threshold (380 GeV)

- top-quark mass
- rare decays
- electroweak couplings

Additional processes open at high energies

- $t\bar{t}H \Rightarrow$ Yukawa coupling and CP properties
- $t\bar{t}\nu_e\bar{\nu}_e$ vector-boson fusion $\Rightarrow$ BSM constraints

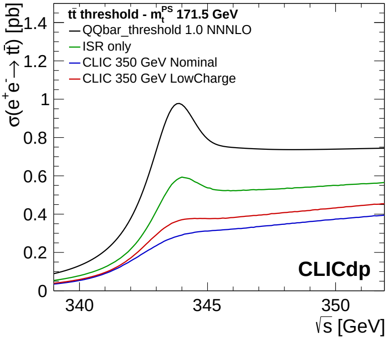
Doubled at high energy: total of over 2.8 million (anti)top quarks

Threshold scan

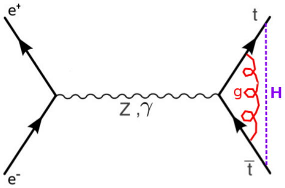
Top pair production cross section around threshold:

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 Γ_t
- strong coupling α_s
- top Yukawa coupling y_t



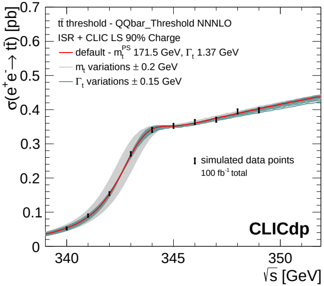
Significant cross section smearing due to luminosity spectra and ISR

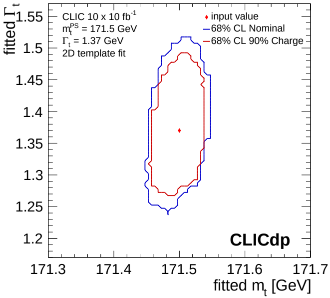
Smearing due to luminosity spectra reduced for dedicated running configuration (LowCharge)

Threshold scan

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

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





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

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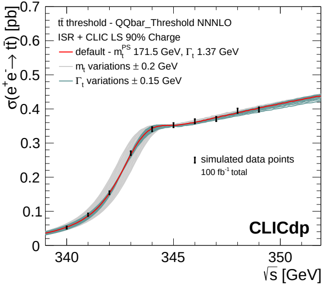
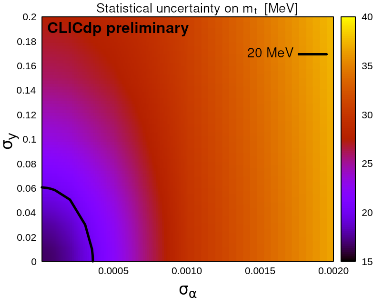




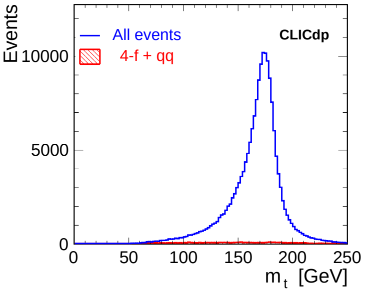
About 20 MeV uncertainty on mass expected from mass and width fit (2D)

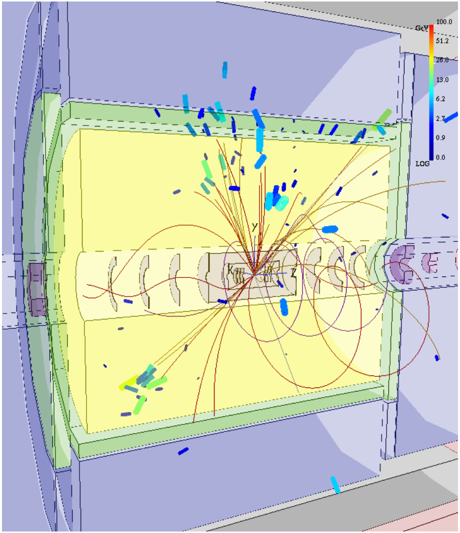
However, α_s and top-quark Yukawa coupling need to be constrained from independent measurements. Total systematic uncertainty $\sim$ 50 MeV.

Top-quark mass

Direct measurement

From reconstruction of hadronic top-quark decays





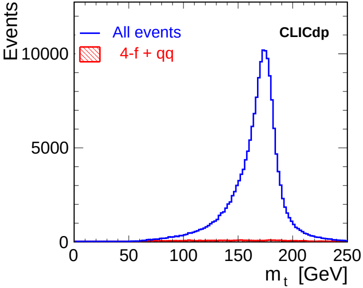
Statistical precision ∼ 30 MeV

Needs excellent control of JES
Large theoretical uncertainties

Top-quark mass

Direct measurement

From reconstruction of hadronic top-quark decays



Statistical precision $\sim$ 30 MeV

Needs excellent control of JES
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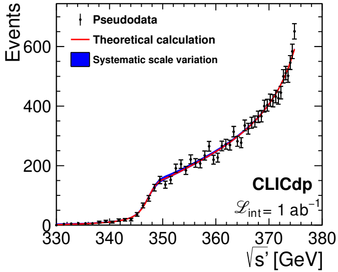
Radiative events

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

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



Statistical precision $\sim$ 100 MeV

Total uncertainty of about 140 MeV

Predictions

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

$$\begin{aligned} BR(t \rightarrow c\,\gamma) &\sim 5 \cdot 10^{-14} \\ BR(t \rightarrow c\,h) &\sim 3 \cdot 10^{-15} \\ BR(t \rightarrow c\,Z) &\sim 1 \cdot 10^{-14} \\ BR(t \rightarrow c\,g) &\sim 5 \cdot 10^{-12} \end{aligned}$$

Top-quark FCNC decays

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Significant enhancement possible in many BSM scenarios

Maximum branching fractions possible:

Model	2HDM	MSSM	$\not R$ SUSY	LH	Q singlet	RS
BR($t \rightarrow c\,\gamma$)	10^{-6}	10^{-6}	10^{-5}	10^{-7}	$8\cdot 10^{-9}$	10^{-9}
BR($t \rightarrow c\,h$)	10^{-2}	10^{-4}	10^{-6}	10^{-5}	$4\cdot 10^{-5}$	10^{-4}

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Limits expected after HL-LHC running

$BR(t \rightarrow c\gamma) < 7.4 \cdot 10^{-5}$(CMS) $\quad$ $BR(t \rightarrow ch) < 2 \cdot 10^{-4}$(ATLAS)

Sensitivity @ 380 GeV

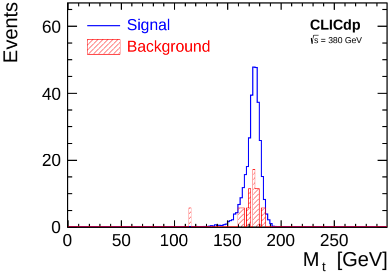
Expected limits for $1\,\mathrm{ab}^{-1}$ collected at 380 GeV CLIC — $\mathrm{CL_s}$ approach

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

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

Reconstructed cγ invariant mass after BDT selection



Sensitivity @ 380 GeV

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

$\mathrm{CL_s}$ approach

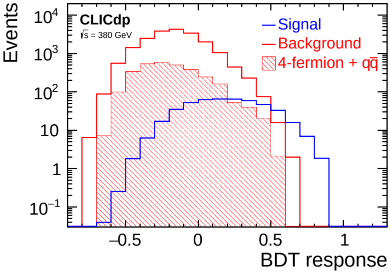
$$\mathrm{BR}(t \to c\gamma) < 2.6 \cdot 10^{-5}$$

$$\mathrm{BR}(t \to cH) \times \mathrm{BR}(H \to b\bar{b}) < 8.8 \cdot 10^{-5}$$

Signature:

- final state compatible with SM $t\bar{t}$ events
- three b-quark jets in the finals 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



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

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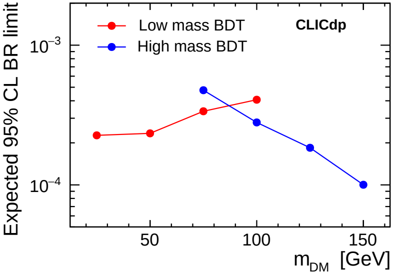
$$\begin{aligned} \mathrm{BR}(t \to c\gamma) &< 2.6 \cdot 10^{-5} \\ \mathrm{BR}(t \to cH) \times \mathrm{BR}(H \to b\bar{b}) &< 8.8 \cdot 10^{-5} \\ \mathrm{BR}(t \to c\not{E}) &< 1.0 - 3.4 \cdot 10^{-4} \end{aligned}$$

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 $\mathrm{BR}(t \to c\not{E})$ as a function of DM particle mass



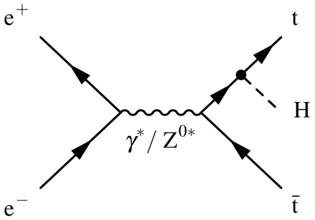
Yukawa coupling

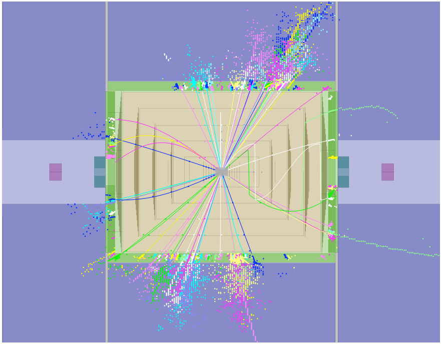
Threshold scan

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





$e^+e^- \rightarrow ttH \rightarrow bbbbqq\tau\nu_\tau$

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Direct measurement

From the measurement of the
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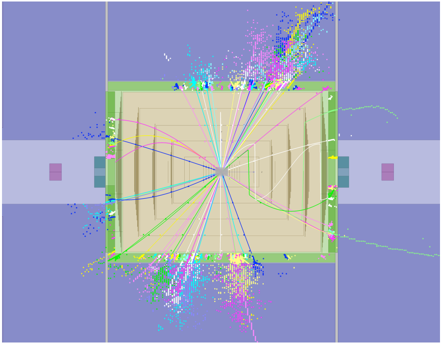
Difficult measurement:

- very low statistics
- large backgrounds
- requires perfect detector performance (6-8 jets, 4 *b*-tags)

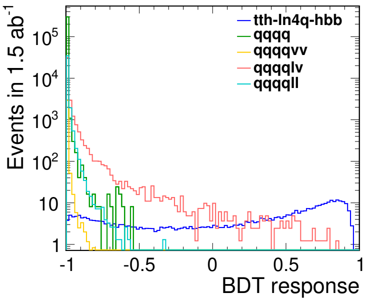


$e^+e^- \rightarrow ttH \rightarrow bbbbqq\tau\nu_\tau$

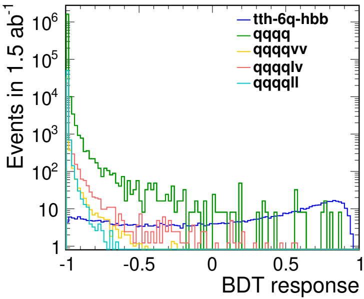
Direct measurement

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

Semi-leptonic event selection



Hadronic event selection



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

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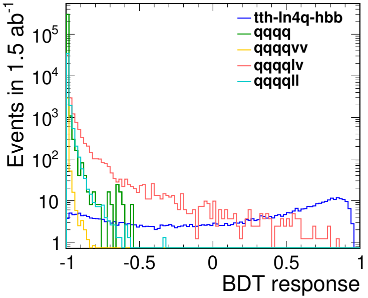
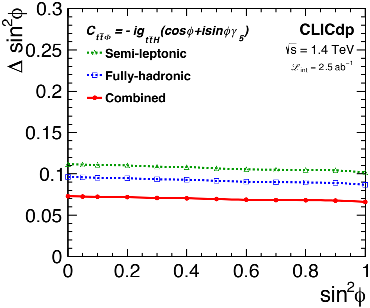


Sensitivity to the CP mixing angle

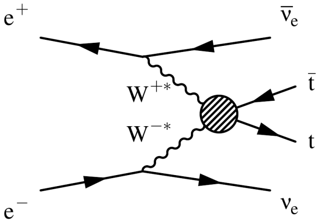


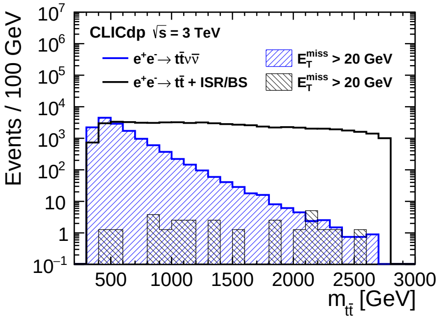
Expected precision from combined measurement: $\frac{\Delta y_t}{y_t} = 2.7\%$

$\Rightarrow$ uncertainty of $\sim$0.07 on $\sin^2\phi$ describing CP violation in ttH coupling

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, $E_T^{miss} > 20$ GeV

Measurement of $e^+e^- \to t\bar{t}\nu_e\bar{\nu}_e$ production

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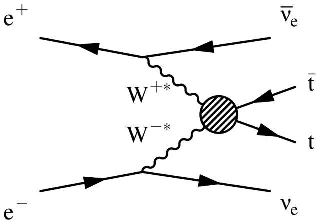
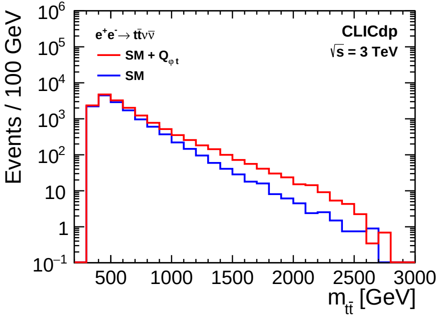


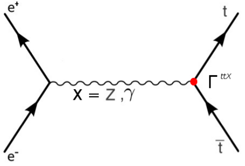


Reconstructed $t\bar{t}$ invariant mass distribution is sensitive to possible new physics contributions. Shown as an example is the EFT operator $\mathcal{Q}_{\phi t}$

Top-quark pair production

Pair production provides direct access to top electroweak couplings

Possible higher order corrections
⇒ sensitive to "new physics" contribution



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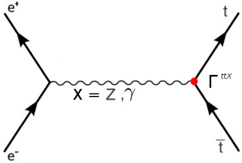


New physics effects can be constrained through measurement of:

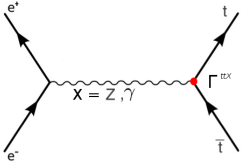
- total cross-section
- forward-backward asymmetry
- helicity angle distribution in top decays

Electroweak couplings

Top-quark pair production

Pair production provides direct access to top electroweak couplings

Possible higher order corrections
⇒ 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

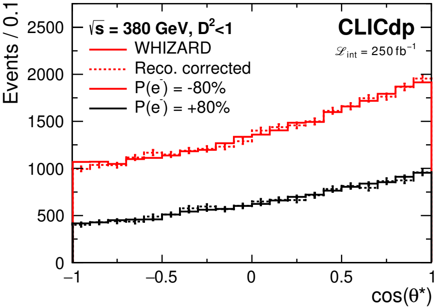
Additional constraints obtained by:

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

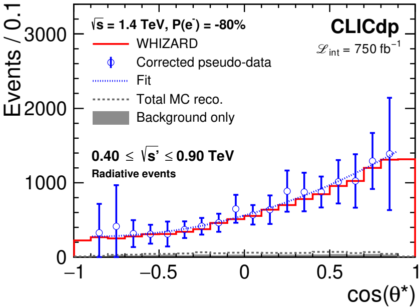
Top-quark pair production

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

380 GeV



Radiative events at 1.4 TeV



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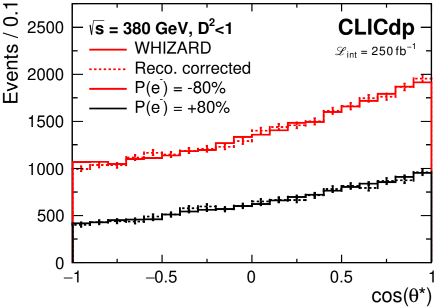
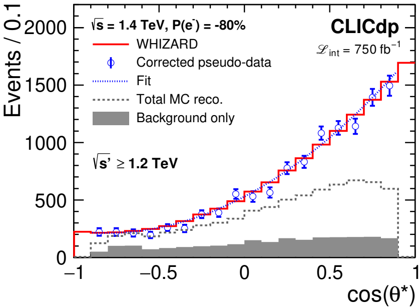


Boosted top decays at 1.4 TeV



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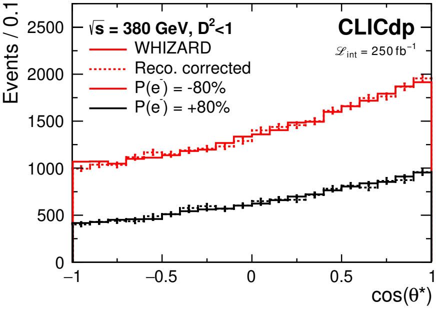
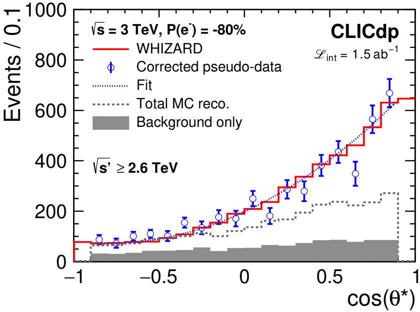


Boosted top decays at 3 TeV



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).

$Q_{\varphi t} = (\varphi^\dagger i_\mu \varphi)(\bar{t}\gamma^\mu t)$
$Q_{tB} = (\bar{q}\sigma^{\mu\nu} t)\tilde{\varphi} B_{\mu\nu}$
$Q_{tW} = (\bar{q}\sigma^{\mu\nu} t)\tau^I \tilde{\varphi} W^I_{\mu\nu}$

$Q^-_{\varphi q} = Q^{(1)}_{\varphi q} - Q^{(3)}_{\varphi q} = (\varphi^\dagger i_\mu \varphi)(\bar{q}\gamma^\mu q) - (\varphi^\dagger i^I_\mu \varphi)(\bar{q}\,\tau^I \gamma^\mu q)$
$Q_{lt,B} = (\bar{t}\gamma^\mu t)(\bar{e}\gamma_\mu e + \frac{1}{2}\bar{l}\gamma_\mu l) \overset{\mathrm{EOM}}{=} \frac{1}{2} Q_{\varphi t} + \frac{1}{g'}\bar{t}\gamma^\mu t\, D^\nu B_{\mu\nu} + \ldots$
$Q_{lq,B} = (\bar{q}\gamma^\mu q)(\bar{e}\gamma_\mu e + \frac{1}{2}\bar{l}\gamma_\mu l) \overset{\mathrm{EOM}}{=} \frac{1}{2} Q^{(1)}_{\varphi q} + \frac{1}{g'}\bar{q}\gamma^\mu q\, D^\nu B_{\mu\nu} + \ldots$
$Q_{lq,W} = (\bar{q}\tau^I \gamma^\mu q)(\bar{l}\tau^I \gamma_\mu l) \overset{\mathrm{EOM}}{=} -Q^{(3)}_{\varphi q} - \frac{2}{g}\bar{q}\tau^I \gamma^\mu q\, D^\nu W^I_{\mu\nu} + \ldots$

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).

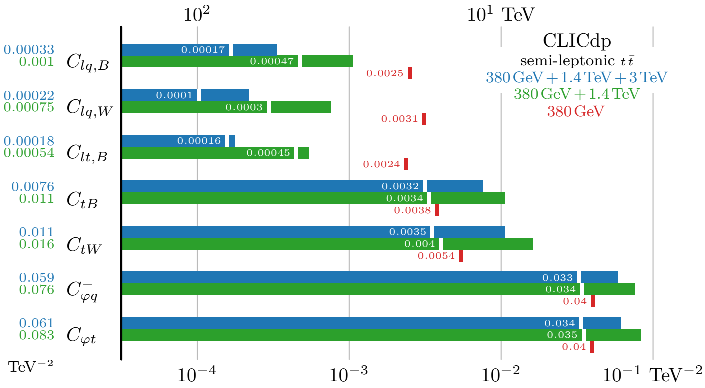
Measurements at one energy stage are insufficient to simultaneously constrain all couplings in the seven-dimensional EFT parameter space.

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

Constraints on BSM effects

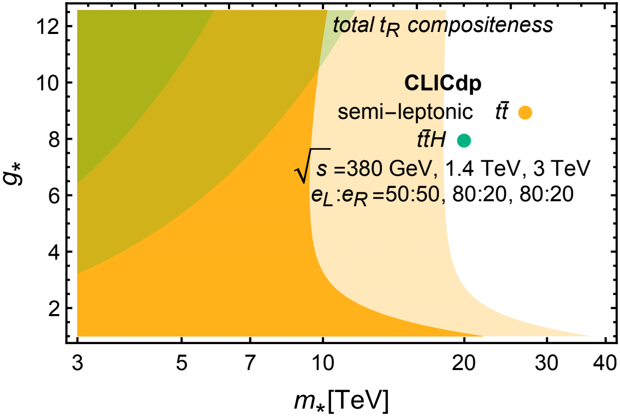
Summary of the global EFT analysis of measurements involving top quark
Results based on statistically optimal observables



High energy CLIC can reach "new physics" scales in the 100 TeV range

Discovery reach

5σ discovery range for top compositeness from global EFT analysis



top-quark compositeness can be discovered at CLIC up to ∼10 TeV

more than 20 TeV can be reached in favourable configurations

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

For details see: • H.Abramowicz et al. (CLICdp Collaboration), *Top-Quark Physics at the CLIC Electron-Positron Linear Collider*, CLICdp-Pub-2018-003, arXiv:1807.02441

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

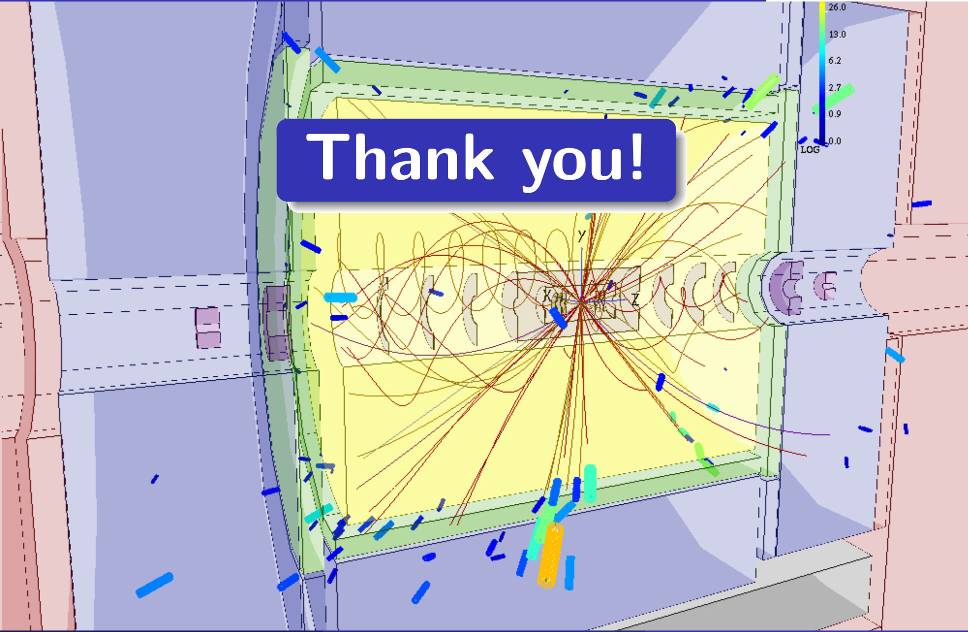
Subsequent CLIC stages:

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: • H.Abramowicz et al. (CLICdp Collaboration), *Top-Quark Physics at the CLIC Electron-Positron Linear Collider*, CLICdp-Pub-2018-003, arXiv:1807.02441

Thank you!



References

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

- CLIC 2018 Summary Report, CERN-2018-005-M, arXiv:1812.06018
- CLIC Project Implementation Plan, CERN-2018-010-M, arXiv:1903.08655
- The CLIC potential for new physics, CERN-2018-009-M, arXiv:1812.02093

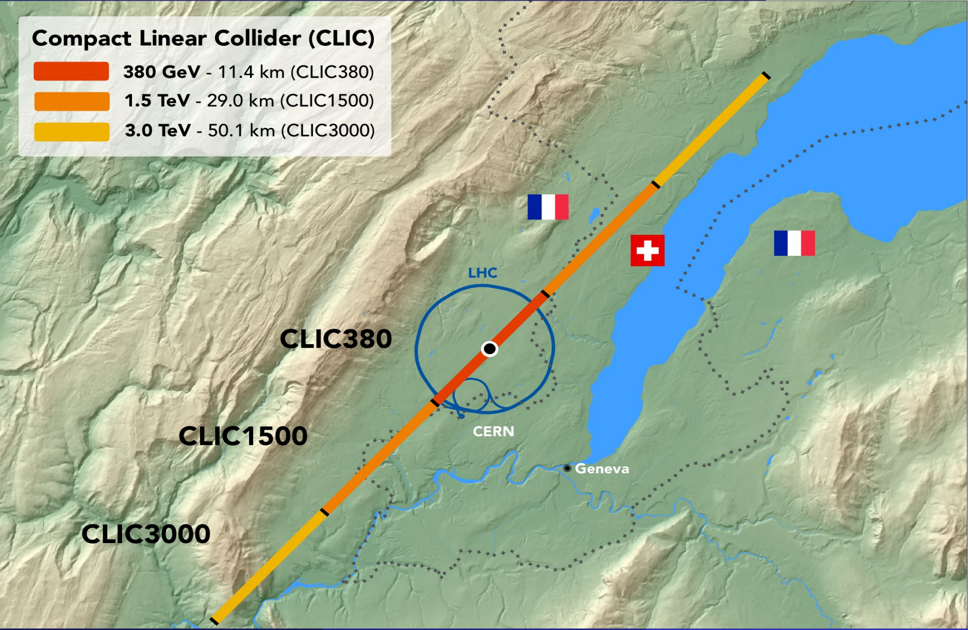
Journal publications

- 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
- A detector for CLIC: main parameters and performance arXiv:1812.07337

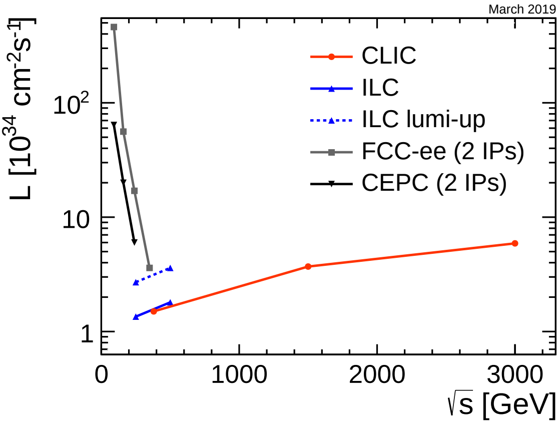
CLIC stages



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

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

CLICdp Collaboration

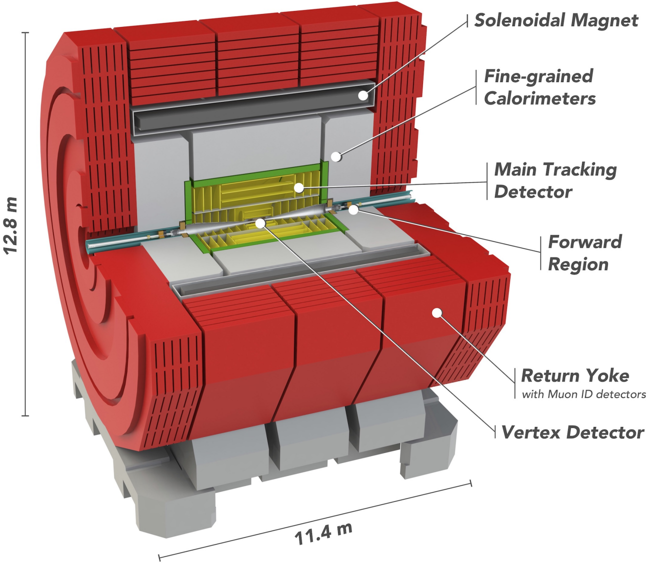
CLICdet

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

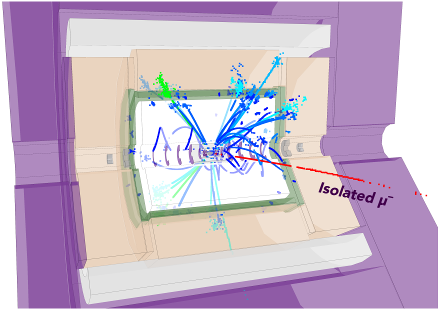


Detector performance

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.

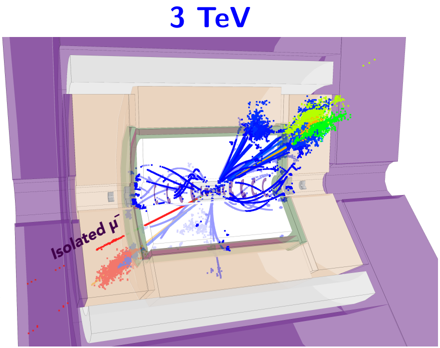
Based on high calorimeter granularity and precise tracking.

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

Detector performance

Top-quark event reconstruction

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



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.