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Top-Quark Physics at High-Energy CLIC Operation

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The Compact Linear Collider (CLIC) is a mature option for a future electron-positron collider operating at center-of-mass energies of up to 3 TeV. CLIC will be built and operated in a staged approach with three center-of-mass energy stages currently assumed to be 380 GeV, 1.5 TeV and 3 TeV. This talk discusses the prospects for top-quark physics at the two TeV-scale CLIC energy stages based on benchmark analyses using full detector simulations. New studies of top-quark pair production at high-energy CLIC operation make use of jet-substructure techniques originally developed for the LHC. Forward-backward and polarization asymmetries, as well as so-called optimal observables, are studied. The top Yukawa coupling and the CP properties in the ttH coupling are best probed in 1.5 TeV collisions. CLIC operation at 3 TeV also enables the study of top-quark pair production through Vector Boson Fusion. The BSM sensitivity provided by the top physics program at CLIC is illustrated using Effective Field Theory (EFT).

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1. The Compact Linear Collider CLIC and its Detector Concept

The Compact Linear Collider (CLIC) is a mature option for a future e^+e^- collider at the TeV scale. The accelerator is based on radio-frequency devices using a two-beam acceleration scheme with a gradient of 100 MV/m. The CLIC CDR [2] was published in 2012. First beams can be expected in 2035. The first stage will have a center-of-mass energy of $\sqrt{s} = 380\,\text{GeV}$ with part of the run dedicated to a threshold scan at several center-of-mass energies around the $\mathrm{t\bar{t}}$ production threshold $\sqrt{s} \approx 350\,\text{GeV}$. The collider will be extended to reach 1.5 TeV and 3 TeV in the second and third stages, respectively. For the studies presented here, integrated luminosities of $\mathscr{L} = 500$, 1500, and $3000\,\text{fb}^{-1}$ have been used for the stages with collision energies of $\sqrt{s} =$ 380 GeV, 1.4 TeV, and 3 TeV, respectively, where the energy of the second stage differs from the latest baseline [1]. These proceedings present studies of top-quark measurements at the higher energy stages of CLIC which can be found in [3]. The first energy stage is also covered in [4].

The environment in electron-positron collisions is much cleaner than at hadron colliders, which allows measurements with much higher precision. At the high energies which CLIC can reach, beam-induced backgrounds, namely electron-positron pairs and $\gamma\gamma \to$ hadrons processes, have to be taken into account for the detector design and in the assessment of the physics potential.

A detector model for CLIC has been developed and optimized for high precision measurements in the CLIC beam environment [5]. The most important principle is particle flow analysis using highly granular calorimetry. Most of the studies in these proceedings are based on full simulation including the detector response, the beam energy spectrum, and beam-induced and other backgrounds.

2. Top-Quark Physics at CLIC

Top-quark physics is an important part of the CLIC physics program. The first stage is optimized for the large $\mathrm{t\bar{t}}$ production cross section and includes a top threshold scan for a high-precision top mass measurement [3]. In addition to the first stage, $\mathrm{t\bar{t}}$ production can also be measured at the higher energy stages in boosted or radiative events. The second stage is particularly suitable for $\mathrm{t\bar{t}H}$ production: The decrease of the cross section with $\sqrt{s}$ above its maximum at $\approx 800\,\text{GeV}$ is fully compensated up to $\approx 1.5\,\text{TeV}$ by the fact that the luminosity performance at linear colliders increases with energy. Processes growing with energy, e.g. $\mathrm{t\bar{t}}$ production through vector boson fusion (VBF), benefit from the $\sqrt{s} = 3\,\text{TeV}$ at the third energy stage. This program allows investigation of the top electroweak and Yukawa couplings, and the CP properties of the Higgs-top coupling, as well as sensitivity to BSM physics in the top sector.

3. Top-Quark Pair Production at High-Energy CLIC operation

3.1 Boosted Top Pair Production at 1.4 and 3 TeV

Jet substructure techniques applied to identify boosted top-quark decays benefit from the low background in e^+e^- collisions. In boosted semileptonic $t\bar{t} \to qqqq\ell\nu$ events, the lepton's charge is used to tag the top quark and anti-quark sides. The isolated lepton candidate with the highest p_T above 10 GeV is selected and a two-step jet clustering with subsequently larger radius is performed on the remaining particle flow objects. This procedure reduces the impact of soft emissions on the substructure reconstruction. Discrimination between signal and background is based on a multivariate analysis. Finally, the distribution of events according to the polar angle of the top quark and anti-quark with respect to the incoming electron is measured. From this distribution, the total cross section and the forward-backward asymmetry are extracted with a precision of $\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}} = 1.8\,\%$ (3.4 %) and $\Delta A_{FB}/A_{FB} = 2.5\,\%$ (4.7 %) at 1.4 TeV (3 TeV) for an electron beam polarization of $P(e^-) = -80\,\%$ [3].

3.2 Top-Quark Pair Production in Radiative Events at 1.4 TeV

In radiative events, the center-of-mass energy of the collision is substantially lower than the nominal collision energy. Initial state radiation and beamstrahlung lead to a significant amount of such radiative $t\bar{t}$ events. These events are thus another approach to top-pair production at the high energy stages of CLIC. A full simulation study has been performed to explore this at $\sqrt{s} = 1.4$ TeV.

The effective collision energy of the hard interaction, $\sqrt{s'}$, is reconstructed with a kinematic fit in the semileptonic decay channel of $t\bar{t}$. The signal is extracted with a multivariate analysis based on measures of the jet substructure and kinematics. Similar to the approach described in 3.1, the polar angle distribution is used to measure the cross section and the forward-backward asymmetry.

4. Associated Top-Quark Pair and Higgs Production at 1.4 TeV

Associated $t\bar{t}H$ production is accessible at the second CLIC stage. The most promising final state is $H \to b\bar{b}$ together with fully hadronic as well as semi-leptonic $t\bar{t}$ decays. Events are classified according to the reconstructed top decay. Then, the jet combinatorics are assigned according to a χ^2 minimization. A multivariate analysis is used for the event selection.

The expected precision on the cross-section for the combination of these channels at 1.4 TeV with 1.5 ab^{-1} luminosity is 7.3 %, translating into a precision of the Yukawa coupling of 3.8 %.

4.1 CP Mixing in $t\bar{t}H$ Production

The $t\bar{t}H$ final state is also suitable for investigating the CP property of the Higgs sector. A CP-odd admixture to the $t\bar{t}H$ coupling is parametrized with a mixing angle ϕ as $ig_{t\bar{t}H}(\cos\phi + i\sin\phi\;\gamma_5)$. The cross section dependence on the mixing angle is exploited to set limits on the CP-odd admixture. The expected sensitivity is $\Delta\sin^2\phi \approx 0.1$ for the full range of $0 < \sin^2\phi < 1$. This result can be further improved by making use of polarized beams and differential distributions.

5. Vector Boson Fusion Production of Top-Quark Pairs at 3 TeV

VBF $t\bar{t}$ production probes the coupling of longitudinal W bosons to top quarks, giving insight into the electroweak symmetry breaking mechanism. For this study, the contribution of new physics is parametrized in terms of those top-philic EFT operators [3] whose contribution to $WW \to t\bar{t}$ grows quadratically with energy, namely $Q_{\varphi t}$, $Q^{(1)}_{\varphi q}$, $Q^{(3)}_{\varphi q}$, and Q_{tW}. The analysis is based on a parton-level study with a realistic top-tagging efficiency applied. Backgrounds are suppressed by applying a cut on the missing energy. The scattering angle and the invariant mass of the $t\bar{t}$ system are used to set limits on the EFT operator coefficients. The scale of new physics expected to be reached at CLIC from this analysis is between 1 and 10 TeV for the operators considered.

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6. Top-Philic EFT Interpretation

A global EFT interpretation [6] can be performed by measuring statistically optimal observables for the top-philic operator basis. Realistic overall efficiencies for semi-leptonic final states [3, Ch. 7] are applied. The prospects for limits to be set by CLIC measurements are evaluated by analysing top-pair production in the $e^+e^- \to t\bar{t} \to bW^+\bar{b}W^-$ final state at parton level including the total rate information. An equal share of $P(e^-) = \pm 80\,\%$ is assumed for all three stages. Figure 1 illustrates the limits. In particular, for the operators whose effects grow with energy, the addition of the third stage brings the scale of new physics close to 100 TeV.

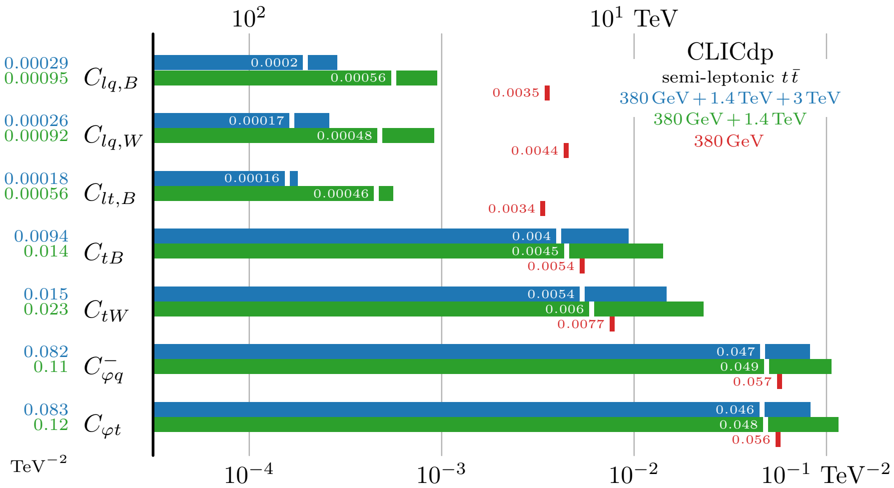

Figure 1: Limits on the top-philic EFT operator coefficients defined in [3]. Solid bars indicate limits from a global fit, green including the first two and blue including all energy stages. Ticks mark individual operator limits indicating in red the results based on the first energy stage only and in white on green (blue) the combination of the first two (all three) stages.

7. Conclusions

Top-quark physics is an important part of the high-energy operation of CLIC, giving unprecedented access to the top Yukawa coupling and the CP property of the $t\bar{t}$H coupling, the top electroweak couplings as well as sensitivity to potential BSM physics in the top sector embodied by significantly enhanced sensitivity to some top-philic EFT operators.

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