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Physics at the Compact Linear Collider

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Abstract

This paper (based on an invited talk at the 18th Lomonosov Conference on Elementary Particle Physics) provides an overview of the physics program at CLIC, including updates on the ongoing studies on t-quark precision observables, massive vector-boson scattering and di-photon processes at high energies.

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Abstract. This paper (based on an invited talk at the 18th Lomonosov Conference on Elementary Particle Physics) provides an overview of the physics program at CLIC, including updates on the ongoing studies on t-quark precision observables, massive vector-boson scattering and di-photon processes at high energies.

1 Introduction

Highlights from the topical studies ongoing at CLIC in the Higgs, top and Beyond the Standard Model (BSM) sectors are given to illustrate the capabilities of CLIC to address relevant questions in the post-LHC era. An energy-staged approach that includes three running center-of-mass energies (380 GeV, 1.4 TeV and 3 TeV) is optimized to the physics program, including the CLIC unique sensitivity at the highest center-of-mass energy to a possible extensions of the Standard Model (SM). With its full statistics of $\sim 10^6$ Higgs bosons, crucial measurements of the Higgs properties will be possible to indicate the validity scale of the Standard Model.

As at other e^+e^- colliders, the CLIC experimental environment is practically free of QCD background and thus suitable for precision measurements. As discussed in Section 1.1, machine related background can be reduced to the satisfactory level for physics analyses. Staged implementation can provide a long-term precision physics program to complement the LHC searches.

1.1 CLIC accelerator and detector

The CLIC accelerator is based on a novel two-beam acceleration scheme, where a high-intensity beam (drive beam) is used to generate RF power to the main beam. Using normal-conducting accelerator structures, the two-beam accelerations provides gradients of 100 MV/m as has been demonstrated at the CTF3 test facility [1]. Short ($\sigma_x=40$ nm, $\sigma_y=1$ nm) and dense ($\sim 10^9$ particles) bunches, lead to a strong beamstrahlung induced by the electromagnetic fields of the opposite bunches. Consequently, beamstrahlung photons convert to hadrons causing the occupancy of the central detectors. With a time-stamping window of 10 ns and appropriate cuts on the transverse momentum and reconstructed time of particles in the calorimeter, the average depositions from this type of background can be reduced to the acceptable level [2]. On the other hand, beamstrahlung severely deteriorates the luminosity spectrum, in particular at the highest center-of-mass energies. However, it has been shown in [3] that the effect can be controlled at a permille level in the peak region ($>80\%$ of the nominal center-of-mass energy).

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A new, post-CDR detector model (CLIC_det) has been proposed [4] with the consideration to the ultimate precision for physics. The detector performance is optimized to physics requirements for hermeticity, flavor tagging, jet energy resolution, p_T reconstruction, etc. Detector comprise all-silicon tracking and compact calorimetry, placed in a 4T magnetic field. High-granularity calorimeters are optimized to the particle flow performance in order to enable a jet energy resolution of $\sim 3.5\text{-}5\%$ for jet energies of 10 GeV up to 1.5 TeV. Together with the flavor separation, the above is particularly relevant to distinguish between Z , W or Higgs bosons in their hadronic decay modes.

2 Higgs studies at CLIC

2.1 Combined fit of the Higgs measurements

An extensive program of physics studies based on full simulations of detector and physics processes, together with a full event reconstruction, has been performed in the Higgs sector and documented in [5]. Higgsstrahlung and WW -fusion are dominant production mechanisms of the Higgs boson at low and high center-of-mass energies, respectively. Depending on the production mechanism, appropriate polarization could eventually double the statistics. A combined study of these two processes can be employed to probe the Higgs width and couplings in a model-independent way. This leads to a determination of the Higgs couplings at a level of $\sim 1\%$, except for the rare decays to light particles such as muons or photons. Assuming that the Higgs total width is constrained by the SM decays, the statistical precision of the Higgs couplings can be improved to a sub-percent level. Both model-independent and model-dependent fits exploit the full statistics available at all CLIC energy stages in a cumulative way. Details of the combined fits can be found in [5] and have already been discussed in [6]. Model-dependent results allow for a comparison to the LHC and HL-LHC experiments where a similar approach is employed. To illustrate the CLIC sensitivity in comparison to the HL-LHC with the full statistics of 3000 fb^{-1} , results of the model-dependent fit are given in Figure 1 [7]. As can be seen, the CLIC will be able to provide comparable or better precision of the Higgs couplings than HL-LHC.

2.2 Higgs self-coupling

At the high center-of-mass energies of 1.4 TeV and 3 TeV, a double-Higgs production can be used to measure the Higgs boson trilinear self-coupling parameter λ that determines the shape of the Higgs potential. Several processes contribute to the double Higgs production, as illustrated in Figure 2 (left), where only one Feynman diagram (a) has the sensitivity to λ . Contribution of the non-sensitive Feynman diagrams to the double-Higgs production cross-section is taken into account with the parameterization of the double-Higgs production cross-section $\sigma(e^+e^- \rightarrow \nu_e \bar{\nu}_e HH)$ w.r.t. the

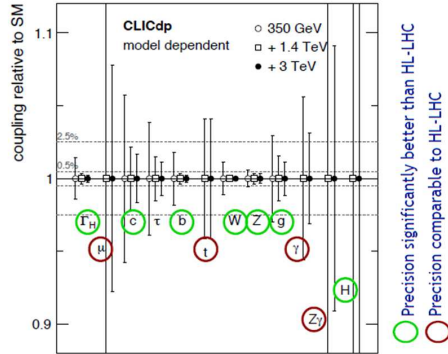


Figure 1: Higgs couplings relative statistical uncertainties in a model-dependent fit. The full statistics of 500 fb^{-1} and 1500 fb^{-1} and 2 ab^{-1} is assumed for 350 GeV, 1.4 TeV and 3 TeV CLIC, respectively, and 3000 fb^{-1} for the HL-LHC.

self-coupling parameter λ :

$$\frac{\Delta\lambda}{\lambda} \sim \kappa \frac{\Delta|\sigma(HH\nu_e\bar{\nu}_e)|}{\sigma(HH\nu_e\bar{\nu}_e)}. \quad (1)$$

Simulation at the generator level gives values of 1.22 and 1.47 for the scaling factor κ , at 1.4 TeV and 3 TeV center-of-mass energy, respectively [5]. Two signal final states are considered at both energies: $HH \rightarrow b\bar{b}b\bar{b}$ and $HH \rightarrow b\bar{b}W^+W^-$, together with a complete list of relevant background processes. Signal selection ensures that there is no overlap between the different final states of the signal, while a multivariate analysis is employed to separate each signal from background processes.

Combined results for the both Higgs decay channels, including electron polarization of -80%, leads to the relative statistical uncertainty of λ of 19% and 16% at 1.4 and 3 TeV respectively [8]. The achievable precision of λ can be improved further if multivariate analysis method would be employed to separate between λ -sensitive and non-sensitive double-Higgs production channels.

3 Top physics at CLIC

With its energy-staged implementation, CLIC offers a broad program of measurements to study the top-quark. The above includes the top mass determination from a threshold scan with the relative statistical uncertainty of $\sim 15 \text{ MeV}$ [9], direct access to the top Yukawa coupling at energies above 500 GeV and the precision studies of the top electroweak (EW) observables providing sensitivity to BSM scenarios. Excellent flavor tagging and jet reconstruction capabilities at CLIC enables precision

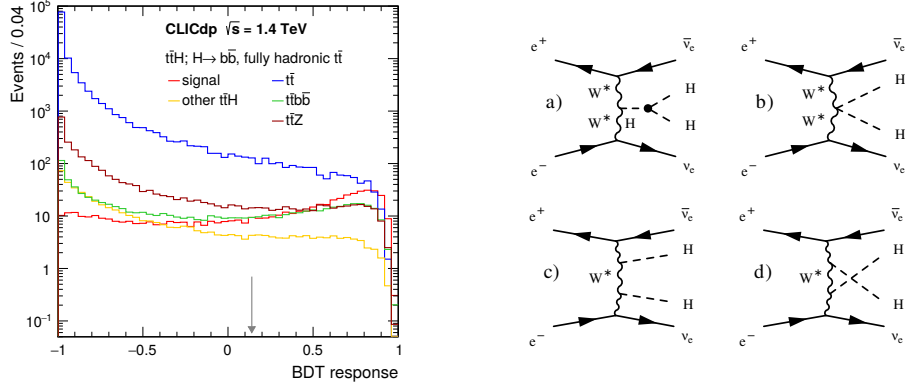


Figure 2: Left: Dominating Feynman diagrams for double-Higgs production at CLIC center-of-mass energies above 1 TeV, where only diagram (a) has a sensitivity to the Higgs self-coupling λ . Right: BDT based separation of the fully hadronic $t\bar{t}H$ signal from various background processes. The arrow denotes the BDT output value corresponding to the maximal significance.

top Yukawa coupling measurement at 1.4 TeV center-of-mass energy. The relative statistical uncertainty of the $t\bar{t}H$ production cross-section σ translates into a relative statistical uncertainty of the top Yukawa coupling y_t :

$$\frac{\Delta y_t}{y_t} = 0.53 \frac{\Delta \sigma}{\sigma}, \quad (2)$$

leading to a top Yukawa relative statistical uncertainty of $\sim 4\%$, assuming electron polarization of -80% [5]. Analysis has been performed in the Higgs dominant decay channel to $b\bar{b}$, while W bosons from the top-quark decays can either decay leptonically or hadronically, leading to 6 to 8-jet topology of the final state. The scaling factor in Eq. 2 is determined at the generator level, assuming a Standard Model value of the top Yukawa coupling. Illustration of the signal separation from various background processes, based on the multivariate method (BDT) output value, is given in Figure 2, right [5]. Multivariate approach allows to maximize a statistical significance of the signal in the presence of various physics backgrounds.

3.1 Top-quark precision EW observables

Top-pair production through the Z, γ exchange in the s-channel, provides direct access to the top EW couplings sensitive to a higher order corrections from BSM processes. The coupling associated to the top- $Z(\gamma)$ vertices is defined through a set of CP conserving and CP violating form factors that can be constrained through measurements of the sensitive EW observables (cross-section, forward-backward asymmetry, helicity angle distribution in top decays). Beam polarization allows to access different

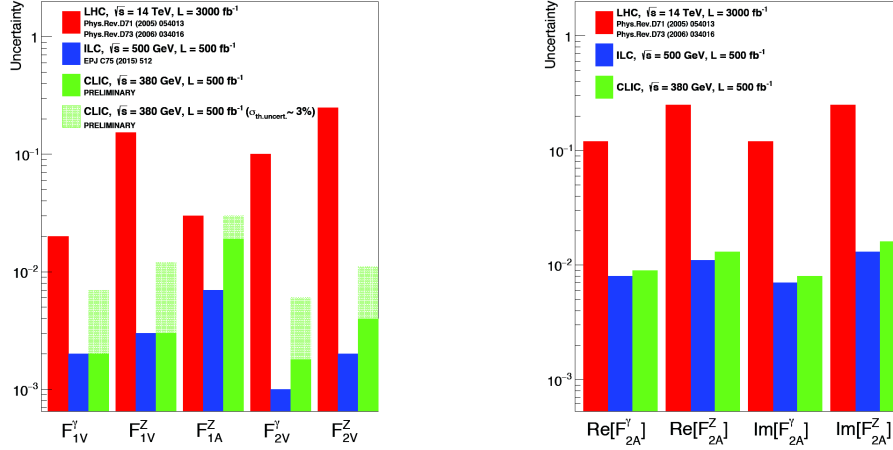


Figure 3: Expected precision on the top-quark EW form factors at different experiments.

form factors independently. Figure 3 [9] gives the relative statistical precision of the top-quark CP conserving and CP violating form factors at different experiments. It demonstrates that future electron-positron colliders (in example of ILC and CLIC) are powerful instruments to study Higgs CP properties.

4 BSM searches

Potential signatures of BSM physics can be searched for at CLIC either through direct reconstruction of new particles, with an approximate mass reach of $\sqrt{s}/2$, or indirectly through the possible deviations in precision observables (cross sections, asymmetries, couplings, etc.). Indirect searches extend the sensitivity for BSM physics beyond the direct kinematic reach of the machine, up to (model-dependent) scales of several tens of TeV. In this paper, two examples of novel CLIC studies are given in Sections 4.1 and 4.2, to illustrate the possible constraints on BSM physics through indirect searches.

4.1 Massive vector boson scattering at high energies

Massive vector boson scattering, and W^+W^- scattering in particular, are sensitive probes to the higher-dimension operators in the Effective Field Theory (EFT) approach. Such a scattering process $W^+W^- \rightarrow VV$, with $V = W, Z$ is illustrated in Figure 4, left. Anomalous couplings at the quartic vertex (i.e. $\alpha_4, \alpha_5 \neq 0$) result in modification of the sensitive observables like the cross-section and invariant mass of the VV system. Fully hadronic final state of the VV system is separated from the background processes in a multivariate analysis approach. A chi squared (χ^2) fit is employed to extract the couplings α_4 and α_5 , and the corresponding confidence inter-

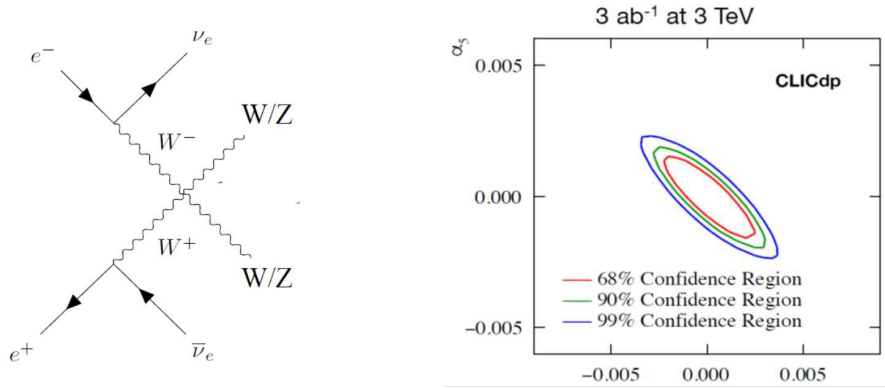


Figure 4: Left: Feynman diagram for W^+W^- scattering. Right: Confidence intervals for the quartic couplings α_4 and α_5 , simulated at 3 TeV CLIC with 3 ab^{-1} of the integrated luminosity.

vals have been derived. Due to a larger statistics, coupling determination precision at 3 TeV CLIC (Figure 4, right) is improved for an order of magnitude in comparison to the measurement at 1.4 TeV center-of-mass energy [8]. As for the top-physics studies, this measurement also relies on the excellent jet reconstruction.

4.2 Di-photon production

Di-photon production is a well described QED process that can be exploited to search for the possible deviations of the sensitive observables (cross-section, photon polar angle distribution) from the Standard Model predictions. Depending on the relative uncertainty of the integrated luminosity, various BSM models can be probed at a kinematic limit 10-20 times higher than at LEP. This is illustrated in Table 1 [8]. Forward electron tagging is crucial for this measurement in order to suppress background from the Bhabha scattering.

Table 1: 95% CL exclusion limits for various BSM models, obtained from di-photon production at 3 TeV CLIC with 2 ab^{-1} and at LEP.

Scenario	$\Delta L = 0.2\%$	$\Delta L = 0.5\%$	$\Delta L = 0.1\%$	LEP limit
QED cut-off (finite electron size) Λ_{QED}	6.52 TeV	6.33 TeV	6.01 TeV	$\sim 390 \text{ GeV}$
Contact interactions Λ'	20.7 TeV	20.1 TeV	18.9 TeV	$\sim 830 \text{ GeV}$
Extra dimensions $M_s/\Lambda^{1/4}$	16.3 TeV	15.9 TeV	15.3 TeV	$\sim 1 \text{ TeV}$
Excited electron M_{e^+}	5.03 TeV	4.87 TeV	4.7 TeV	$\sim 250 \text{ GeV}$

5 Summary

CLIC is a mature future linear collider option with the physics program combining precision measurements with direct and indirect discovery potential. The CLIC detector model is being optimized to meet the performance requirements from the physics studies, in terms of multi-jet final state reconstruction, photon reconstruction, missing-momentum measurement, forward electron tagging and many more. Staged implementation results in a broad physics program, from precision studies of the Higgs and top-quark physics to BSM probes. At the lowest center-of-mass energy, CLIC features model independence in the Higgs coupling measurements, achievable with a statistical precision at the percent level for most of the couplings. Operation at high energies enables precision measurement of rare Higgs decays, Higgs self-coupling, Higgs mass and CP properties. BSM measurements also benefits from the high-energy operation, with the sensitivity extended far beyond the available center-of-mass energy. Top-quark measurements serve as additional probe to the EW and BSM sectors.

Acknowledgments

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