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CLIC PHYSICS OVERVIEW

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On behalf of the CLICdp collaboration

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Abstract

In this paper, based on the invited talk at the 17^{th} Lomonosov Conference of Elementary Particle Physics, the physics program at the future Compact Linear Collider (CLIC) will be reviewed, with particular emphasis on the Higgs physics studies. It will be demonstrated, on the basis of detailed physics and detector studies carried out at CLIC, that the CLIC is indeed a precision tool for studies both in the Higgs sector and beyond the Standard Model.

Talk presented at the 17th Lomonosov Conference of Elementary Particle Physics, Moscow, 20–26 August, 2015.

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Abstract. In this paper, based on the invited talk at the 17^{th} Lomonosov Conference of Elementary Particle Physics, the physics program at the future Compact Linear Collider (CLIC) will be reviewed, with particular emphasis on the Higgs physics studies. It will be demonstrated, on the basis of detailed physics and detector studies carried out at CLIC, that the CLIC is indeed a precision tool for studies both in the Higgs sector and beyond the Standard Model.

1 Introduction

The future Compact Linear Collider (CLIC) offers excellent statistical potential for precision measurements in the QCD-background-free environment of e^+e^- collisions. An energy-staged approach that includes three running center-of-mass energies (380 GeV, 1.4 TeV and 3 TeV) maximizes the potential to explore the Higgs sector in a model-independent way using the favorable properties of Higgsstrahlung - a Higgs production mechanism exploitable at future lepton colliders at center-of-mass energies $\leq$1 TeV. In addition, CLIC offers excellent possibilities to study top physics, including a threshold scan at the lowest center-of-mass energy, as well as to study the Higgs self-coupling and to perform Beyond Standard Model (BSM) searches at the highest energy. Staged implementation along the described lines provides a long-term precision physics program to complement the LHC searches. In Figure 1, cross-sections are given for top-pair production and Higgs production at various center-of-mass energies.

1.1 CLIC accelerator and detector

The CLIC accelerator is based on a novel two-beam scheme, where a high-intensity beam (drive beam) is used to generate RF power for the main beam. Using normal-conducting accelerator structures, the two-beam acceleration provides gradients of 100 MV/m as has been demonstrated at the CTF3 test facility [1]. Small (σ_x=40 nm, σ_y=1 nm) and dense ($\sim 10^9$ particles) bunches lead to strong beamstrahlung effects induced by the electromagnetic fields of the opposite bunches. Consequently, beamstrahlung photons produce hadrons as often as 3.2 interactions per bunch-crossing. With a small bunch separation of 0.5 ns, the above leads to a requirement of 10 ns time stamping in order to cope with the occupancy of the central detectors. At the other hand, Beamstrahlung also deteriorates luminosity spectrum, in particular at high center-of-mass energies, however, it has been shown in [2] that the effect can be controlled at a permille level in the peak region above 80% of the nominal center-of-mass energies. The SiD [3] and ILD [4] detector concepts proposed for the International

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Linear Collider, have been adapted to the CLIC running conditions. Detector performance is driven by the physics goals requiring: Jet energy resolution better than 3.5% for high-energy jets above 100 GeV, track momentum resolution $\Delta(p_t)/(p_t)^2 \sim 10^{-5}$ GeV^{-1}, impact parameter resolution of the order of a few microns. The above comes respectively from the need to distinguish between Z, W or Higgs bosons, to reconstruct the Higgs boson from the recoil mass of the Z decay products (i.e. muons) and to provide the flavor separation i.e. for the measurement of the Higgs couplings to beauty and charm. Detector hermeticity and the ability to efficiently identify leptons (over 95%) is assumed at all energy stages. In Figure 2 [1], a schematic view of the CLIC detector models is given.

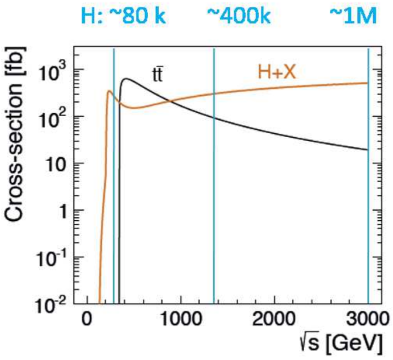

Figure 1: Higgs and top-pair production cross-sections as a function of center-of-mass energy. Approximate statistics of the produced Higgs bosons is also indicated per energy stage. Four years of nominal detector operation are assumed per stage.

2 Higgs studies at CLIC

Higgsstrahlung and WW-fusion are the dominant production mechanisms of the Higgs boson at low and high energies respectively. Combined they lead to $\sim 10^6$ Higgs bosons in four years of nominal detector operation, per stage, assuming 50% data taking efficiency. Depending on the production mechanism, appropriate polarization could eventually double the statistics. Combined study of the two production mechanisms probe the Higgs width and couplings in a model-independent way. This leads to a determination of the Higgs couplings at the level of a percent (except for the rare decays to light particles such as muons or photons), employing all three stages. 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. Details of the combined fit of the Higgs measurements at all energy stages will be discussed in Section 2.2.

Figure 2: Longitudinal cross section of the top-right quadrant of the CLIC_ILD (left) and CLIC_SiD (right) detector models.

2.1 *Low and high-energy landscape*

The low-energy phase at CLIC, from the perspective of the Higgs studies is primarily motivated by the direct and model-independent measurement of the Higgs coupling to Z that can be obtained from the recoil mass distribution in Higgsstrahlung ($e^+e^- \to ZH, Z \to f\bar{f}, f = e, \mu, q$), with a statistical precision of 0.8%. The g_{HZZ} determination plays a central role in the measurement of the Higgs couplings at future e^+e^- colliders. From the Z decays to leptons, the recoil mass distribution can be used to extract the Higgs mass and the total ZH production cross section with the statistical precision of 110 MeV and 3.8%, respectively. In Figure 3 (left), reconstruction of the Higgs mass from the simulated data is given for HZ, $Z \to \mu^+\mu^-$ decays. In addition, the measurement of the recoil mass distribution from hadronic Z decays provides a direct search for invisible Higgs decays, constraining the branching ratio for $H \to invisible$ decays to 0.57% with 1σ uncertainty.

With the cross section $\sigma_{H\nu\nu}$ scaling with $log(s)$, WW-fusion becomes the dominant Higgs production channel at higher energies. This allows to probe even rare decays (BR$\leq 10^{-3}$) like $H \to \mu^+\mu^-$ (Figure 3 (right)), $H \to Z\gamma$ and $H \to \gamma\gamma$ with a statistical precision of 16%, 42% and 15% respectively. These numbers scale down by a factor ~ 0.7 if an electron polarization of -80% is applied. Excellent performance of tagging algorithms allows heavy flavor separation and the corresponding statistical uncertainty to access $\sigma_{H\nu\nu} \cdot BR(H \to b\bar{b}, c\bar{c}, gg)$ is 0.2%, 2.7% and 1.8% respectively, for the Higgs decays to b, c and gluons, yielding to a statistical precision of 1.5% on the ratio g_{Hcc}/g_{Hbb}. The latter provides a direct test of the Standard Model predictions for the up and down-type quark's couplings to the Higgs boson. Particular relevance of the high energy measurement lies in the ability to access the Higgs self-coupling λ and quartic coupling to W bosons g_{HHWW} with a relative statistical uncertainty of 12% and 3%, respectively. Beam polarization plays important role in this type of measurement

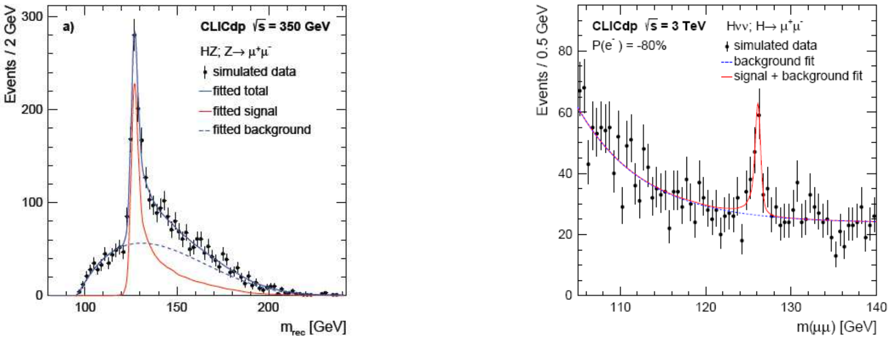

Figure 3: Recoil mass distribution from HZ, Z→ $\mu^+\mu^-$ decays at 350 GeV center-of-mass energy (left); Reconstruction of the di-muon invariant mass in Higgs decays H→ $\mu^+\mu^-$ at 3 TeV center-of-mass-energy (right).

due to the increase of the Higgs production cross-section and suppression of certain types of background.

2.2 *Combined fit of the Higgs measurements*

The full statistics of data (0.5 ab^{-1} at 380 GeV, 1.5 ab^{-1} at 1.4 TeV, 2 ab^{-1} at 3 TeV) can be used in a global fit in order to reach the ultimate precision on the Higgs couplings. Direct access to g_{HZZ}, in a model-independent way, through Higgsstrahlung at the lowest center-of-mass energy, allows a fit with minimal theoretical assumptions where the Higgs couplings and the Higgs total width enter as free parameters:

$$\frac{{g_{HZZ}}^2 \cdot {g_{Hbb}}^2}{\Gamma_H} = C_{HZ,H\to b\bar{b}} \tag{1}$$

and, similarly for other processes, fit parameters C$_i$ can be defined where *i*=1,10. Then, the overall χ^2 can be built:

$$\chi^2 = \sum_{i=1,10} \frac{(C_i/C_i^{SM} - 1)^2}{\delta F_i^2} \tag{2}$$

where δF_i stands for the relative statistical uncertainty of the σ·BR measurement for the considered Higgs decay *i* and σ is the Higgs production cross-section. The above leads to the determination of the Higgs total width with a relative statistical uncertainty of 3.4%, while most of the couplings can be determined at a percent level. On the other hand, assuming that the total (model-dependent) width is determined from the SM branching ratios, a global fit can be performed in a model-dependent way, with the relative partial widths κ_i (i=1,9) as free parameters:

$$\Gamma_H^{md} = \sum_{i=1,9} \kappa_i^2 BR_i^{SM} \qquad\qquad \kappa_i^2 = \Gamma_i/\Gamma_i^{SM} \tag{3}$$

Then, instead of couplings, the corresponding relative partial width is defining C_i in (2), as in example:

$$\frac{\kappa_{HZZ}^2 \cdot \kappa_{Hbb}^2}{\Gamma_H^{md}} = C_{HZ,H\to b\bar{b}} \tag{4}$$

The above, LHC-style approach, leads to a sub-percent precision for most of the couplings. Precision of the Higgs couplings at the three-stage CLIC program is illustrated in Figure 4, for a model-independent and dependent fit.

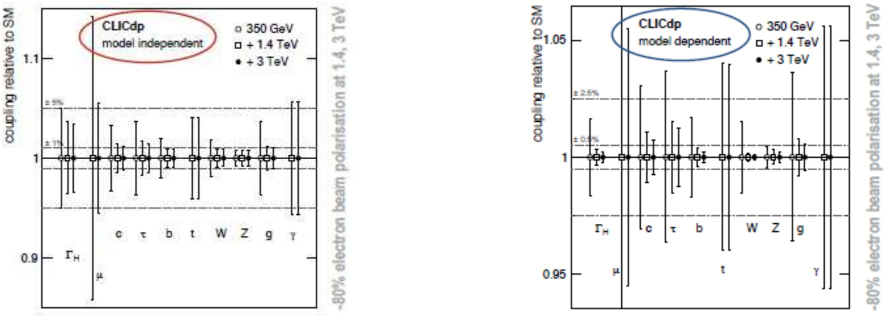

Figure 4: Precision of the Higgs couplings of the three-stage CLIC program for a model-independent (left) and model-dependent fit (right).

3 Top benchmark studies

As an e^+e^- collider, CLIC offers two complementary ways of the top mass measurement. One is by direct reconstruction of the invariant mass of the top decay products and can be performed at arbitrary center-of-mass energy and the other is based on a cross-section scan around the top-pair production threshold. Interpretation of the first method depends on higher order theoretical corrections. The invariant mass approach leads to the statistical uncertainty of 80 MeV, while the threshold scan provides 30 MeV statistical uncertainty, within the total error of 100 MeV dominated by the theoretical uncertainty. Excellent flavor tagging and possibility to separate between jets originating from Z, W and H, enables the measurement of the top Yukawa coupling at 1.4 TeV centre-of-mass energy. With electron polarization of -80%, it is possible to achieve a relative statistical uncertainty of the top Yukawa coupling below 4% [5]. In Figure 5 (left) [5], the top threshold scan is illustrated for 174 GeV top mass.

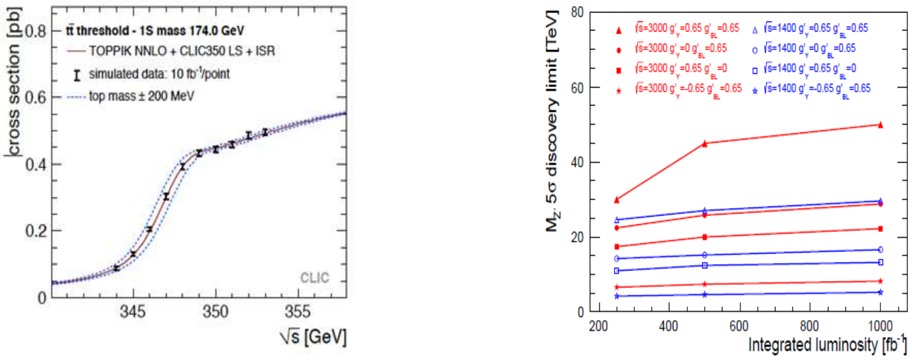

Figure 5: Illustration of the top-pair production cross-section sensitivity to the top mass performed around the production threshold (left); 5σ discovery limit on Z$'$ mass as a function of integrated luminosity (right).

4 BSM searches

At CLIC, potential signatures of BSM physics can be searched for either through direct reconstruction of new particles, with an approximate mass reach of $\sqrt{s}/2$, and indirectly, in a model-dependent way, using evidence of deviations in precision observables (like cross-sections, FB and LR asymmetries, etc.). Indirect searches extend the sensitivity for BSM physics beyond the direct kinematic reach of the machine. As showed in [1], mass measurements at a percent level or better are possible for most particles in the accessible SUSY scenarios. In indirect searches, fermion-pair production can be used to test extended gauge theories (i.e. with Z$'$) where sensitive observables receive higher order corrections due to the appearance of new gauge bosons. Figure 5 (right) [5] illustrates 5 σ discovery limits on Z$'$ mass, as a function of integrated luminosity. It is clear that the sensitivity is extended far beyond the operational center-of-mass energy. The same is true for probing the fundamental scale in models with extra dimensions and for many other indirect searches.

5 Complementarity with the LHC program

The capacity for precision studies of either SM processes, or particles discovered at LHC, together with a stand-alone discovery reach, makes CLIC complementary to the LHC physics program. The ability to measure the Higgs couplings to a percent level or better is, in principal, more precise than what can be done by LHC or its high luminosity upgrade HL-LHC. This is of particular importance for measurement of the Higgs self-coupling λ, defining the shape of the Higgs potential. The same is true for probing the Higgs compositeness - very similar in phenomenology to the SM Higgs. In the later case, the only difference comes from the relative correction proportional to ξ where $\xi = (v/f)^2$ and v is the vacuum expectation value of the SM Higgs and f

is the scale of compositeness. Figure 6 [5] illustrates current constraints and the reach on ξ at LHC and CLIC. With the double-Higgs production included, the estimated reach at CLIC is around ξ=0.002 corresponding to the scale of compositeness of 70 TeV. For comparison, the estimates for HL-LHC reach on the scale of compositeness f, with an integrated luminosity of 3000 fb^{-1}, are $f \leq$1.2 TeV at 95% CL [6].

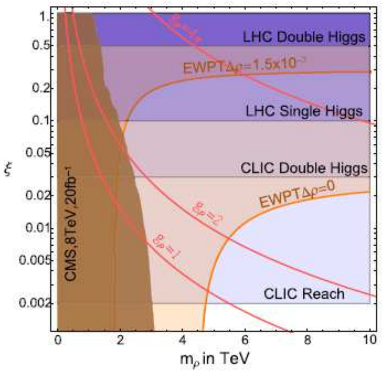

Figure 6: Summary plot on the current constraints and prospects on Higgs compositeness probe. Correction factor to the strength of the Higgs interactions ξ is given as function of the mass of the vector resonance of the composite theory.

6 Summary

The CLIC accelerator is an attractive option for a future e^+e^- collider, with the demonstrated feasibility through the extensive simulation and prototyping, comprehending physics and accelerator and detector R&D [1]. Staged implementation results in a broad physics program, from precision studies of Higgs physics to BSM probes. The most of Higgs couplings can be probed at a percent or sub-percent level. Rare Higgs decays to the lightest particles such as muons and photons can be accessed with a statistical precision of several percent, while the Higgs self-coupling can be determined with 12% uncertainty at the highest energy. Composite Higgs can be indirectly probed up to the scale of 70 TeV. A scan of the top mass at the production threshold allows the top mass to be determinated with a statistical uncertainty smaller than the theoretical error. Employment of beam polarisation enables determination of the top Yukawa coupling below 4%. BSM physics can be accessed through direct and indirect searches. The first ones give access to SUSY masses at a percent level, in most of the available scenarios, while the indirect searches extend the energy scale far beyond the kinematic reach of the machine (as in the case of extended gauge theories, theories with extra-dimensions, etc.) The foreseen physics program at CLIC extends and complements the physics studies planned for LHC and HL-LHC.

Acknowledgments

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