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Determination of the Higgs CPV mixing angle in ZZ-fusion at 1.4 TeV CLIC

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Abstract

CLIC is a mature project for a future staged e^-e^+ linear collider at CERN. It is designed to run at three different energy stages currently assumed to be 380 GeV, 1.5 TeV and 3 TeV. Staged energy approach enables exploring precision Higgs and top physics as well as the possibility for direct and indirect BSM searches. In this paper we present an overview of the Higgs physics together with preliminary results of the CPV study in ZZ-fusion at the intermediate energy stage.

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Determination of the Higgs CPV mixing angle in ZZ-fusion at 1.4 TeV CLIC

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CLIC is a mature project for a future staged e^-e^+ linear collider at CERN. It is designed to run at three different energy stages currently assumed to be 380 GeV, 1.5 TeV and 3 TeV. Staged energy approach enables exploring precision Higgs and top physics as well as the possibility for direct and indirect BSM searches. In this paper we present an overview of the Higgs physics together with preliminary results of the CPV study in ZZ-fusion at the intermediate energy stage.

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1. Accelerator and detector

CLIC is a mature option for a staged future e^-e^+ linear collider at CERN. It is planned to run in three energy stages: 380 GeV, 1.5 TeV and 3 TeV[1] center-of-mass energy with nominal integrated luminosities: 1 ab^{-1}, 2.5 ab^{-1} and 5 ab^{-1}, respectively [1]. The CLIC accelerator is based on a two-beam concept with acceleration gradient up to 100 MV/m. Accelerator technologies have been demonstrated at the CTF3 (now CLEAR) facility at CERN. CLIC is foreseen to operate as a Higgs factory with about 4.5 million Higgs bosons to be produced at all energy stages including beam polarization [2]. Polarization is foreseen only for the electron beam with equal amounts of run-time for -80% and +80%[2] at the initial energy stage, while at higher energy stages the run-time for -80% and +80% options is optimized in the ratio 4:1 [2]. The detector for CLIC [3] comprises an all-silicon vertex and tracking detector, compact electromagnetic and hadronic calorimeters, all placed within a magnetic field of 4 T. Excellent performances of the tracking system enable measurement of particle's transverse momentum with a resolution of σ_{p_T}/p_T^2 up to $2 \cdot 10^{-5}$ GeV^{-1} for high-energy muons (Figure 1 (left) [3]). Highly-granular calorimeters enable implementation of the Particle Flow Algorithm [4] allowing separation of jets that originate from Higgs and Z^0 and $W^\pm$ bosons decays. Jet energy resolution ranges from 5% for jet energies of 50 GeV up to about 3% for jet energies above 100 GeV (Figure 1 (right) [3]).

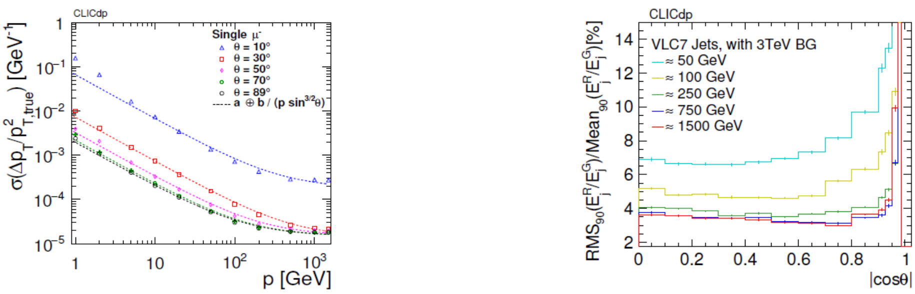


Figure 1: Transverse momentum resolution as a function of the momentum of muons, at various polar angles θ. Jet energy resolution for different jet energies as a function of the polar angle ($|\cos\theta|$), in the presence of $\gamma\gamma \to$hadron background overlaid on the $Z/\gamma^* \to q\bar{q}$ events.

2. Higgs studies

Below we highlight CLIC studies related to the Higgs couplings, Higgs self-coupling and several Beyond the Standard Models (BSM) models' realization in the Higgs sector. Most of these observables can be determined with enhanced precision w.r.t. HL-LHC, as it will be discussed further.

[1]For the first CLIC energy stage at 380 GeV center-of-mass energy is proposed with some additional running time devoted to a $t\bar{t}$ threshold scan near 350 GeV. 1.5 TeV corresponds to the maximal center-of-mass energy reach with a single drive-beam complex and thus it is used in analyses as well as the initially proposed 1.4 TeV stage.

[2]'+' and '-' stand for right-handed and left-handed polarization, respectively.

2.1 Higgs couplings

A unique feature of e^-e^+ colliders is a model independent determination of the Higgsstrahlung cross section via the recoil mass technique. The total cross section is proportional to g^2_{HZZ}, where g_{HZZ} is the Higgs coupling to Z bosons. g_{HZZ} serves as an input to the global fit of energy staged measurements of the Higgs couplings in a model independent way. Figure 2 (left) [5] illustrates the statistical precision of such a measurement with cumulative data from all energy stages. It can be seen that most of the couplings can be determined with a statistical uncertainty below 1%. Other global fits are also studied, within κ or an EFT framework and documented in [6].

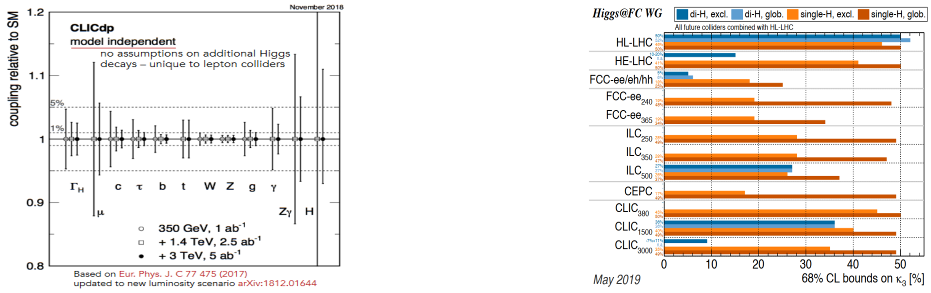


Figure 2: Illustration of the precision of the Higgs couplings measurements within the three-stage CLIC programme, determined in a model independent fit (left). 68% CL on the Higgs self-coupling in single and double Higgs production at future Higgs factories (right).

2.2 Higgs self-coupling

The Higgs self-coupling λ is the shaping parameter of the Higgs potential, also being a sensitive probe to various BSM realizations in the Higgs sector. At CLIC there is a possibility for direct double-Higgs production in vector boson fusion ($e^-e^+ \rightarrow \mathrm{HH}\nu\bar{\nu}$) as well as in double Higgsstrahlung ($e^-e^+ \rightarrow \mathrm{ZHH}$). Favoured at higher center-of-mass energies (above 500 GeV), double-Higgs production in WW-fusion is the most sensitive process to non-Standard Model values of λ. Having the advantage to run at high energies (1.4 TeV and 3 TeV) CLIC has excellent sensitivity to measure the Higgs self-coupling (Figure 2 (right) [7]). On the other side, precision of λ measurement is not challenged by theoretical uncertainty like at hadron colliders. Combined result from di-Higgs production at 1.4 TeV and 3 TeV gives for the relative statistical uncertainty of λ the values (-8%, + 11%) at 68% CL [8].

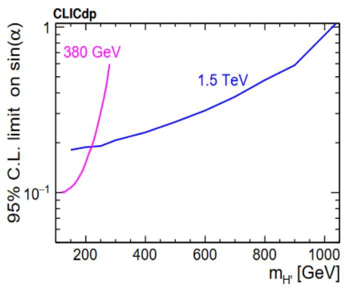
2.3 Higgs BSM studies

Several Higgs BSM realizations with impact on the Higgs sector will be illustrated, such as Vector-Fermion Dark Matter model (VFDM), Composite Higgs model and CP violating (CPV) mixture of scalar and pseudoscalar states.

2.3.1 VFDM

The Vector-fermion dark matter model [9] is an extension of the SM with one additional scalar ϕ that mixes with the SM Higgs boson h via a mixing angle α. This mixing implies the existence of two electroweak eigenstates H and H' (H = h $\cdot \cos\alpha + \phi \cdot \sin\alpha$ and H' = - h $\cdot \sin\alpha + \phi \cdot \cos\alpha$) [9].

Under the assumption that the new state H' decays invisibly 100%, BR(H→inv) $\sim \sin^2\alpha$. Figure 3 (left) presents the 95% CL on sinα as a function of the H' mass to be reconstructed at 380 GeV and 1.5 TeV. Mass of the new state H' is determined from the Higgsstrahlung process, as the mass recoiling against the di-jet system from the primary Z boson. The scalar sector mixing angle (sinα) can be determined with a 95% CL limit when the new scalar mass reaches about 300 GeV (1 TeV) at 380 GeV (1.5 TeV) center-of-mass energy.



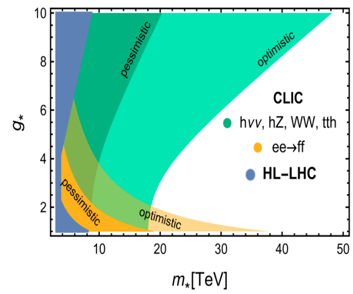


Figure 3: 95% CL limit on the scalar sector mixing angle (sinα) as a function of a new scalar mass ($m_{H'}$); Discovery (5σ) reach on composite Higgs at CLIC and projected exclusion (2σ) regions at the HL-LHC, given in the compositeness coupling-mass phase space.

2.3.2 Composite Higgs

If the Higgs boson is composite, it will be a manifestation of a pseudo-Nambu-Goldstone boson of the underlying strongly-interacting sector. Higgs compositeness would modify the SM Lagrangian through EFT operators enabling determination of the compositeness scale m* and the coupling strength g*. In Figure 3 (right) [6] CLIC and HL-LHC projected sensitivities to composite Higgs parameter space are illustrated assuming the full CLIC operation with polarized electron beams. Projections are based on the combined fit from h$\nu\nu$, hZ, WW-fusion and tth production channels and fermion pair production. Two shades of colour filling correspond to the strongest and the weakest sensitivities obtained for a factor of 2 increase and decrease of the EFT operators' coefficients. One may observe that CLIC has a potential to discover Higgs compositeness up to ~10 TeV scale even in the most pessimistic case considered. This is far beyond the HL-LHC exclusion region.

2.4 CPV in the Higgs sector

In the extended Higgs sector, the Higgs boson could be a mixture of scalar (H) and pseudoscalar (A) states:

$$h = H \cdot \cos \Psi_{\rm CP} + A \cdot \sin \Psi_{\rm CP}, \quad (1)$$

where $\Psi_{\rm CP}$ is the CPV mixing angle.

At future linear e^-e^+ colliders CPV can be probed in HVV and Hff vertices in various Higgs production and decay processes. Most of the results are obtained in fermionic vertices ($H \to \tau^+\tau^-$ decay and $t\bar{t}H$ production) where the CPV occurs at the Born level [10]. ILC estimates the sensitivity to $\Psi_{\rm CP}$ measurement in $H \to \tau^+\tau^-$ decay at 250 GeV, where $\Psi_{\rm CP}$ can be determined with the absolute statistical uncertainty target of 4° [11], reaching the aimed theoretical limit of

10^{-2} [12]. According to [12], there are no predictions for CPV mixing angle determination in vector boson fusion at e^-e^+ colliders, where the CPV effect is much weaker, calling for a precision of 10^{-5} for the CPV factor f_{CP}^{HVV},

$$f_{CP}^{HVV} = sin^2(\Delta\Psi_{CP}), \tag{2}$$

where

$$g_{HVV}^2 = \frac{1}{(1 - f_{CP}^{HVV})}, \tag{3}$$

and g_{HVV} stands for the effective Higgs to vector boson coupling. Details of the ongoing analysis at 1.4 TeV CLIC where Higgs bosons are produced in ZZ-fusion are discussed below.

2.4.1 Method of the analysis

While the Higgs boson is produced in ZZ-fusion, we consider the exclusive $H \to b\bar{b}$ decay channel to avoid the high cross section $e^-e^+ \to e^-e^+\gamma$ background that will be present in the inclusive analysis. The CP sensitive observable is defined as the angle $\Delta\Phi$ between the production planes illustrated in Figure 4 (left). The analysis comprises several steps: events with two isolated electrons (positrons) are preselected. The background is CP insensitive as illustrated in Figure 4 (middle). Multi Variant Analysis (MVA) is further employed for the suppression of background, where the signal efficiency is 81% and the overall background rejection rate is 99.9%. The selection efficiency is unbiased towards $\Delta\Phi$. The reconstructed observable $\Delta\Phi$ is corrected for acceptance effects of the central tracker (Figure 4 (right)). Detector reconstruction effects are negligible. There is an ongoing optimization of the fit to extract Ψ_{CP} from the $\Delta\Phi$ distribution illustrated in Figure 4 (right).

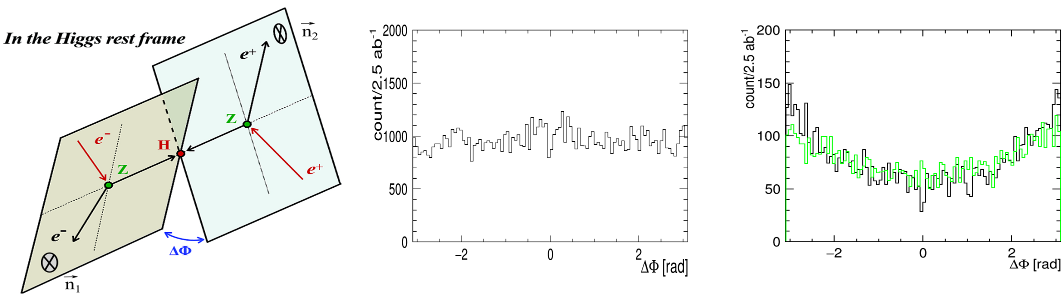


Figure 4: Illustration of the CP sensitive angle $\Delta\Phi$ (left), $\Delta\Phi$ distribution for background after preselection (middle) and $\Delta\Phi$ for signal after full simulation, reconstruction and selection (black) vs. generated (green) (right).

3. Conclusion

It is clear that high-energy operation of CLIC (i.e. above 1 TeV centre-of-mass energy) enables superior sensitivity to probe various BSM realizations in the Higgs sector, including models like VFDM or compositeness. In particluar, due to relevant statistics of double-Higgs production at highest energies, the Higgs self-coupling parameter λ can be measured with a relative precision $\lesssim$ 10%. Also, preliminar findings of the CPV measurement in the Higgs sector in ZZ-fusion at 1.4

TeV CLIC are promising in terms of background suppression and unbiased reconstruction of CP sensitive angular observable.

4. Acknowledgments

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References

[1] M. Aicheler, P.N. Burrows, N. Catalan Lasheras, R. Corsini, M. Draper, J. Osborne, D. Schulte, S. Stapnes, and M.J. Stuart, *The Compact Linear Collider (CLIC) Project Implementation Plan*, (CERN Yellow Reports: Monographs), CERN-2018-010-M (2018).

[2] P. Roloff, R. Franceschini, U. Schnoor, and A. Wulzer, *The Compact Linear e^-e^+ Collider (CLIC): Physics Potential*, (Input to the European Particle Physics Strategy Update on behalf of the CLIC and CLICdp Collaborations), arXiv:1812.07986v1 [hep-ex] (2018).

[3] D. Arominski et. al [CLICdp Collaboration], *A detector for CLIC: main parameters and performance*, CLICdp-Note-2018-005 (CERN, Geneva, 2018).

[4] M. A. Thomson, *Particle flow calorimetry and the pandora PFA algorithm*, *Nucl. Instrum. Methods Phys. Res., Sect.* **A 611**, 25 (2009).

[5] P. Roloff and A. Robson, *Updated CLIC luminosity staging baseline and Higgs coupling prospects*, CLICdp-Note-2018-002 (CERN, Geneva, 2018).

[6] J. De Blas et. al, *The CLIC potential for new physics*, (CERN Yellow Reports: Monographs), CERN-2018-009-M (2018).

[7] M. Cepeda (for the Higgs@Future Colliders WG), in *Proceedings of the CERN Council Open Symposium on the Update of European Strategy for Particle Physics*, (Granada, May 2019).

[8] P. Roloff, U. Schnoor, R. Simoniello and B. Xu, *Double Higgs boson production and Higgs self-coupling extraction at CLIC*, *Eur. Phys. J.* **C 80**, 1010 (2020).

[9] K. Mekala, A. F. Zarnecki, B. Grzadkowski and M. Iglicki, *Sensitivity to invisible Higgs boson decays at CLIC*, *Eur. Phys. J.* **Plus 136**, 2 (2020).

[10] J. de Blas, M. Cepeda, et. al, *Higgs Boson studies at future particle colliders*, *J. High Energ. Phys.* **2020** 139 (2020).

[11] D. Jeans and G. W. Wilson, *Measuring the CP state of tau lepton pairs from Higgs decay at the ILC*, *Phys. Rev.* **D 98** 013007 (2018).

[12] A. V. Gritsan et. al, *Snowmass White Paper: Prospects of CP-violation measurements with the Higgs boson at future experiments*, arXiv:2205.07715v2 [hep-ex] (2022).