PROCEEDINGS OF SCIENCE

Electroweak precision measurements at CLIC

Matthias Weber on behalf of the CLICdp collaboration*
CERN, Switzerland
E-mail: matthias.artur.weber@cern.ch

Steven Green
Cavendish Laboratory, University of Cambridge, United Kingdom
E-mail: sg568@hep.phy.cam.ac.uk

Igor Boyko
JINR, Russia
E-mail: igor.boyko@cern.ch

The Compact Linear Collider (CLIC) is an option for a future electron-positron collider operating at centre-of-mass energies from a few hundred GeV up to 3 TeV. Details will be presented on two recent physics benchmark analyses of electroweak measurements at CLIC based on full detector simulations and assuming centre-of-mass energies of 1.4 and 3 TeV. Vector boson scattering gives insight into the mechanism of electroweak symmetry breaking. The processes $e^+e^- \to WW\nu\nu$ and $e^+e^- \to ZZ\nu\nu$ were studied using fully hadronic events which provide the full kinematic information on the final-state bosons. The expected precisions on anomalous gauge couplings are extracted. The process $e^+e^- \to \gamma\gamma$ allows to search for deviations from QED. The expected sensitivities to a finite electron size and other scenarios are discussed.

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*Speaker.

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1. Introduction

The Compact Linear Collider (CLIC) is an option for a future high energy linear e^+e^- collider with centre-of-mass-energies up to 3 TeV [1]. An overview of the physics potential of CLIC is given in [2, 3]. The physics program is proposed to be performed over a twenty year time span in three energy stages [4]. The first energy stage at $\sqrt{s} = 380\,\mathrm{GeV}$ focuses on Higgs [5] and top measurements with a dedicated top threshold scan for top mass determination around 350 GeV. The higher energy stages, proposed to be at $\sqrt{s} = 1.5\,\mathrm{TeV}$ and $\sqrt{s} = 3\,\mathrm{TeV}$, allow searching for beyond Standard Model (BSM) physics and can be adapted in case of discoveries by the LHC. The highest energy is motivated by limits on technology and realistic costs. Besides using direct signatures of new physics, electroweak precision measurements offer an alternative to probe BSM physics. In this contribution, we present details on two recent benchmark analyses of these type of measurements: WW and ZZ scattering and di-photon production.

2. WW and ZZ vector boson scattering at 1.4 and 3 TeV

The processes $e^+e^- \to WW\nu\nu$ and $e^+e^- \to ZZ\nu\nu$ are sensitive to anomalous gauge couplings [6]. The massive gauge-boson interactions are described by effective field theory here:

$$\mathscr{L}_{EFT} = \mathscr{L}_{SM} + \sum_{\text{dimensions}\,d} \sum_i \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathscr{O}_i^{(d)} = \mathscr{L}_{SM} + \alpha_4 \mathrm{Tr}[V^\mu V_\nu]\mathrm{Tr}[V^\nu V_\mu] + \alpha_5 \mathrm{Tr}[V^\mu V_\mu]^2,$$

where V^μ corresponds to a linear combination of massive gauge bosons $W^\pm$ and Z in a carefully chosen gauge. Signal samples are produced with WHIZARD1.97 [7]. The hadronic channel provides the largest branching fraction and sensitivity. The main background originates from $e\gamma$ processes with four quark final states. The photon is picked up from beamstrahlung or quasi-real photons emitted from the incoming electron. The latter are described using the equivalent photon approximation. The analysis is performed using the full simulation of the CLIC_ILD detector model [1]. A detailed description of the analysis will be published in the thesis [8]. Particle flow objects [9] are clustered into four jets, which are then paired into two boson candidates. The pairing is chosen, in which both candidate boson masses are closest to each other. For 1.4 TeV the clustering is performed by the k_t algorithm with radius parameter R=0.9, for 3 TeV the radius parameter is increased to 1.1. For the 3 TeV, tight selected particle flow objects, as described in [9], are used to address the larger level of beam background. Physics background events are suppressed by an isolated lepton veto and a cut on the missing transverse momentum $p_T^{\mathrm{miss}} > 100\,\mathrm{GeV}$ followed by a multivariate based selection on event shapes and other kinematic distributions. Values for α_4 and α_5 are extracted by a χ^2 fit of the invariant mass of the total system with the SM as null hypthesis ($\alpha_4 = \alpha_5 = 0$).

The invariant mass of the system for the different values of α_4 and α_5 is shown in Fig. 1 for signal events, together with a multi-boson interaction confidence limit summary plot from ATLAS based on the full 8 TeV LHC data of $20.2\,\mathrm{fb}^{-1}$ [10]. Fig. 2 shows the expected precision of CLIC to anomalous gauge couplings in the fully hadronic decay channel of WW and ZZ events. It can be seen that CLIC operating at 1.4 and 3 TeV has better sensitivity to anomalous gauge couplings than the LHC after the completion of Run I. The 3 TeV result leads to an increased sensitivity compared to 1.4 TeV by an order of magnitude.

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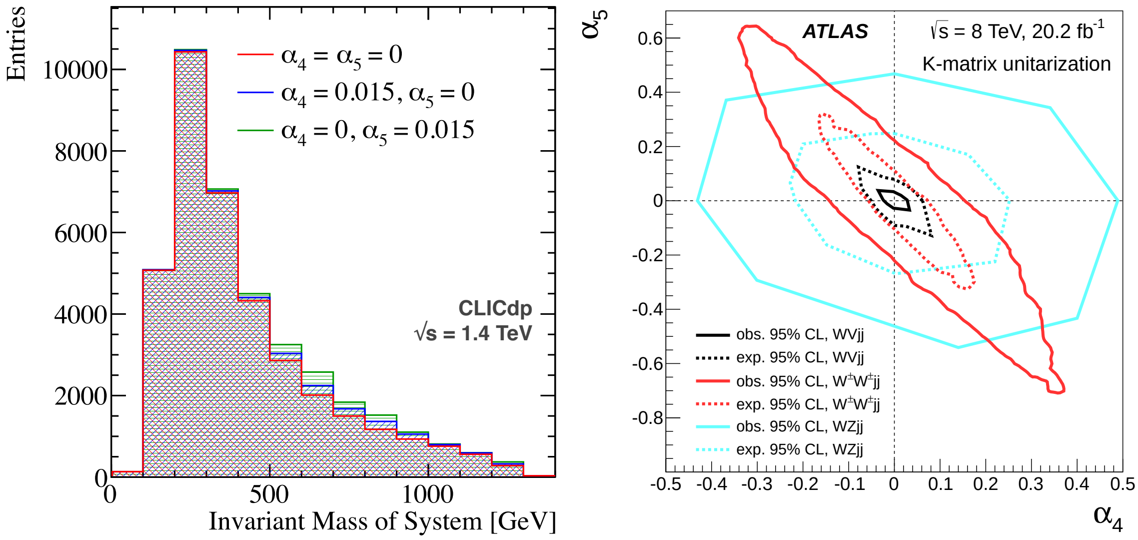

Figure 1: The invariant mass of the four jet system for different values of α_4 and α_5 for CLIC running at 1.4 TeV (left) and limits on anomalous electroweak production of WW and WZ by ATLAS using the full 8 TeV LHC Run I data of 20.2 fb^{-1} [10] (right).

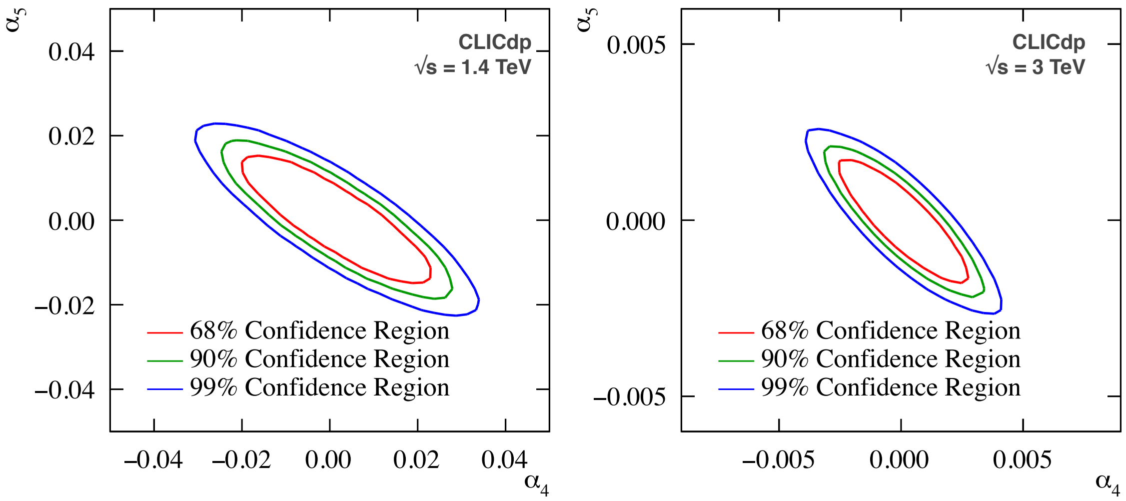

Figure 2: Projected sensitivity to α_4 and α_5 for CLIC after completion of the 1.4 TeV run with 1.5 ab^{-1} integrated luminosity (left) and using a 3 TeV dataset of 2 ab^{-1}.

3. Di-Photon production at 3 TeV

Di-photon production offers a clean experimental signature at very high energies. In combination with available precise theory calculations this process allows searching for deviations from the SM. The analysis flow starts with selecting two high energetic photons $E_{\gamma,1} > 1.3\,\text{TeV}$ and $E_{\gamma,2} > 1.2\,\text{TeV}$ in anti-parallel configuration within 10°. Physics background are rejected by applying a veto on a third photon ($E_{\gamma 3} > 50\,\text{GeV}$). Background contributions involving electrons, mainly from Bhabha scattering, are suppressed by vetoing events with tracks with $p > 300\,\text{GeV}$ within 20° around both photon candidates. The reconstructed polar angle distribution is shown in Figure 3 for signal and background events using the full simulation of the CLIC_SiD detector model.

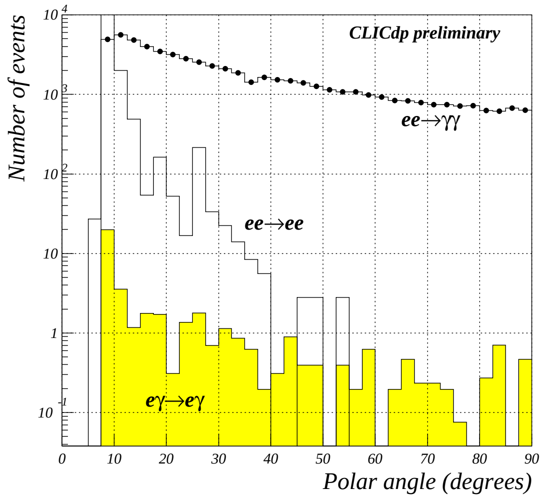

Figure 3: Signal and background contributions to the reconstructed di-photon spectrum at CLIC as function of the photon polar angle for an integrated luminosity of $2\,\mathrm{ab}^{-1}$ at 3 TeV. The photon in the $e\gamma \to e\gamma$ background (yellow) is picked up from beamstrahlung or quasi-real photons emitted from the incoming electron.

Four different new physics models are tested:

- a QED cutoff model with a non point like electron with a slope parameter of the charge distribution Λ_{QED}
- a contact interaction model introduced with a dimension-7 Lagrangian with an effective scale Λ'
- gravity in extra dimensions, which allows for a Planck mass M_{S} at the TeV scale, checking the sensitivity to $M_{\mathrm{S}}/\lambda^{1/4}$
- excited electrons e^*, where the $ee \to \gamma\gamma$ spectrum can be distorted via t-channel exchange, even if the e^* mass cannot be detected directly.

The signals are rather flat in $\cos\theta$ and thus lead to sizeable deviations in the very central part of the detector, illustrated in Fig. 4 for a QED cut-off with $\Lambda_{\mathrm{QED}} = 3\,\mathrm{TeV}$ and extra dimensions with $M_{\mathrm{S}} = 8\,\mathrm{TeV}$.

Table 1 lists for each of the models the expected sensitivity at 95% confidence level (CL) for an integrated luminosity of $L = 2\,\mathrm{ab}^{-1}$ for different assumptions on the uncertainty of the total luminosity of 0.2%, 0.5% and 1.0% scenarios. Systematic effects due to polar angle misalignment by 1 mrad and an uncertainty on the residual background level by 15 % have been included. The expected sensitivities are about 15-20 times better than limits set by the Large Electron-Positron (LEP) Collider [11].

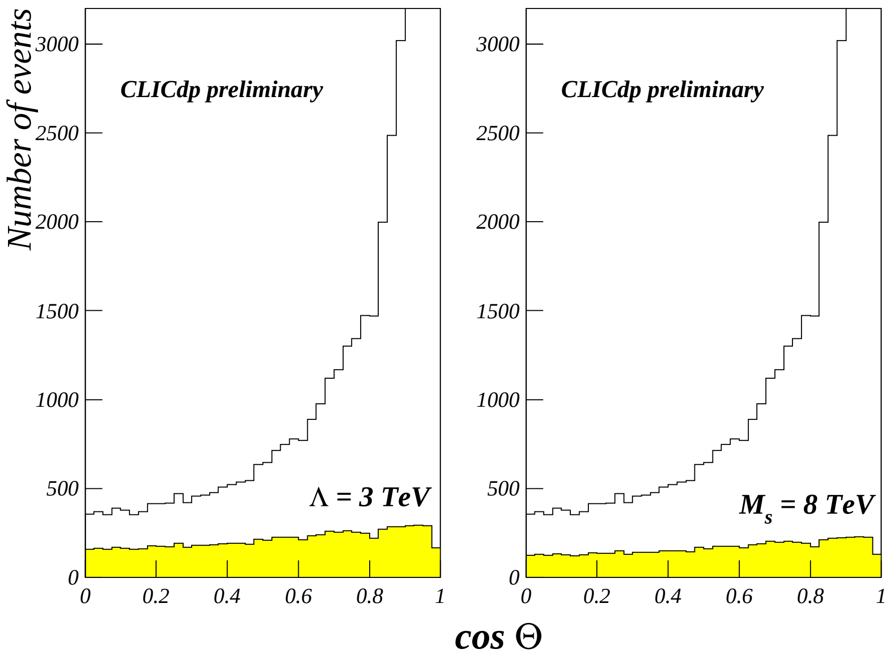

Figure 4: The expected number of signal events for a QED cut-off model with $\Lambda_{\mathrm{QED}} = 3\,\mathrm{TeV}$ (left) and extra dimensions with $M_{\mathrm{S}} = 8\,\mathrm{TeV}$ (right) together with the expected number of events from SM di-photon production as function of $cos\theta$ for an integrated luminosity of $L = 2\,\mathrm{ab}^{-1}$ at $\sqrt{s} = 3\,\mathrm{TeV}$.

Table 1: Expected sensitivity of the Di-Photon production cross-section measurement to four new physics models for three different luminosity uncertainty scenarios:

Scenario	$\Delta\mathrm{L} = 0.2\%$	$\Delta\mathrm{L} = 0.5\%$	$\Delta\mathrm{L} = 1.0\%$	LEP limit [11]
QED cut-off (finite electron size) $\Lambda_{\mathrm{QED}}(95\%\,\mathrm{CL})$	6.52 TeV	6.33 TeV	6.01 TeV	∼431 GeV
Contact interactions $\Lambda'(95\%\,\mathrm{CL})$	20.7 TeV	20.1 TeV	18.9 TeV	∼880 GeV
Extra dimensions $M_{\mathrm{S}}/\lambda^{1/4}(95\%\,\mathrm{CL})$	16.3 TeV	15.9 TeV	15.2 TeV	∼1.1 TeV
Excited electron $M_{\mathrm{e}^*}(95\%\,\mathrm{CL})$	5.03 TeV	4.87 TeV	4.7 TeV	∼366 GeV

4. Summary

Two benchmark precision electroweak physics analyses at CLIC have been discussed. The sensitivity of WW and ZZ vector boson scattering to anomalous gauge couplings exceeds current LHC limits. The sensitivity is increased by an order of magnitude using e^+e^- collisions at the highest energy stage compared to the first two energy stages of CLIC. The ability to search for new physics models in di-photon production exceeds LEP limits by an order of magnitude.

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