PROCEEDINGS OF SCIENCE

CLIC BSM (in)direct searches

Roberto Franceschini[*†]
Dipartimento di Matematica e Fisica
Università degli Studi Roma Tre and INFN Roma Tre
Via della Vasca Navale 84, IT-00146, Roma, Italy
E-mail: roberto.franceschini@uniroma3.it

We review recent progress in the assessment of CLIC physics potential to uncover physics beyond the Standard Model. Particular emphasis is put on the work in progress for the CERN Yellow Report "The CLIC New Physics Potential" and a selection of new results from the CLICdp collaboration. The physics case for the study of electro-weak symmetry breaking sector, dark matter particles candidates, and model independent explorations of the physics of the TeV scale is presented.

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*Speaker.

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Several motivations for physics beyond the Standard Model exist from observed phenomena that cannot be explained by the interactions and matter of the Standard Model, e.g. the dark matter of the Universe, the striking imbalance between matter and antimatter around us, the non-zero mass of neutrinos. In addition, the Standard Model itself has several mysterious aspects, such as the existence of well separate length scales for electro-weak interactions and gravity and peculiar patterns of masses and mixings of quarks and leptons.

All of these call for the most thorough theoretical and experimental exploration of extensions of the Standard Model. A most interesting class of such explorations can be carried out at high energy colliders, which probe the structure of fundamental interactions at the shortest length-scales. Leptonic colliders, such as the e^+e^- collider CLIC, use point-like particles as projectiles, so that the full power of the collisions is used to magnify the short scale physics to a scale observable with our detectors. Furthermore, it is important to stress that all the puzzles within the Standard Model, and the motivations for physics that goes beyond it, are tightly related to the electro-weak sector of the Standard Model. As leptons carry only electro-weak charges, they offer a direct probe of the electro-weak sector of the Standard Model. Such a direct probe of the electro-weak sector of the Standard Model is a prime tool to seek answers to the puzzles that motivate physics beyond the Standard Model. It is also very important to remark that the results of leptonic collisions can be recorded very accurately and finely by particles detectors, therefore even very subtle phenomena can be highlighted by the experiments running at leptonic colliders. For this reason lepton colliders can tackle the most obvious as well as the most subtle signals of new physics. This is true even for completely unexpected signals, thanks to the capability of experiments at lepton colliders to keep full records of each collision, without pre-selecting during data-taking on the type of signal to be sought at later time in data analysis.

In this context, CLIC has the notable feature of being able to provide collisions at a center-of-mass energy more than 10 times higher than anything ever realized in past leptonic colliders. This allows for a thorough study of completely unexplored length-scales, at which fundamental interactions may operate in a completely new way, showing up new symmetries or new interactions, that a leptonic collider such as CLIC is able to study with extraordinary accuracy.

A key issue in raising the energy of particles collisions to explore ever shorter length scales is the systematic reduction of collisions rate expected from the simple geometric scaling of cross-sections, which in normal conditions scales as $\sigma \propto \frac{1}{E^2}$. For this reason it is of utmost importance to build particle accelerators capable of *both* larger energies *and* larger instantaneous luminosity. The latter challenge has been clearly met in the step from TeVatron to the Large Hadron Collider, but seems to be a bottleneck for all the options for future colliders at the energy frontier [1]. The innovative two-beams acceleration schemes of CLIC [2], plus the (linear) growth of luminosity with energy due to relativistic contraction of colliding beams, allows CLIC to deliver an instantaneous luminosity in excess of $10^{34}/(cm^2 \cdot s)$. This makes CLIC able to produce a fraction of a million of Higgs bosons in the first operation stages and in excess of a million in the later operation stages. The later stages of CLIC have such large beam energy that the e^+e^- cross-section is significantly affected by collisions of virtual particles belonging to the quantum structure of the electrons and positrons, resulting in a *growth* of the cross-section at higher energies $\sigma \propto \log(E)$. The access to collisions of "electron constituents" in e^+e^- is also a trademark of CLIC, which will be put to use in the later sections to explore new physics both indirectly and directly.

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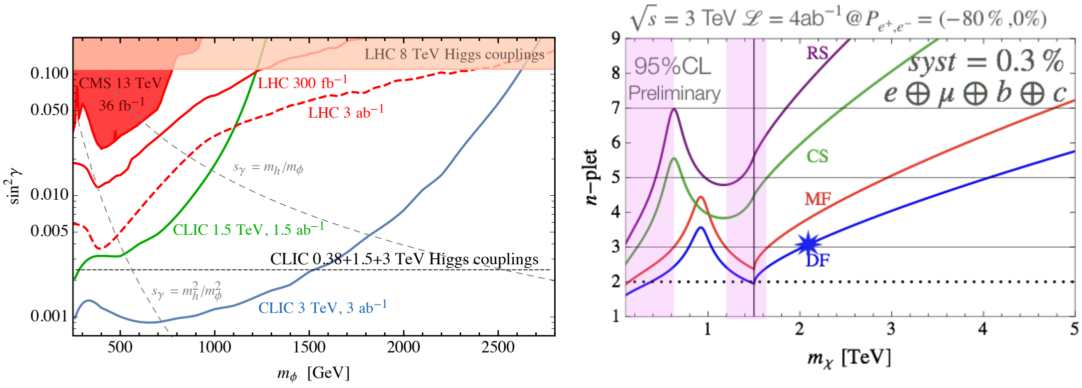

Figure 1: CLIC reach on singlet extensions of the Standard Model and new electro-weak n-plets.

1. Electro-weak symmetry breaking

A concrete possibility to understand the symmetry breaking sector of the Standard Model is to embed the Higgs boson, so far the only observed member or the symmetry breaking sector, in a bigger context in which a sector of scalars exists. These scalars are part of a larger dynamics that can help to understand the enormous size of the length-scale characteristic of the electro-weak interactions compared to Planck length characteristic of gravitational ones. A sector of scalars is generically predicted in supersymmetric extensions of the Standard Model and in models of composite Higgs bosons. Reference [3] has studied how to parametrize these large classes of models into an effective model where only the Higgs boson and a scalar with no gauge interactions are kept as effective degrees of freedom. The mass eigenstates of the scalar sector are then expected to be a superposition of interaction eigenstates, namely the Higgs boson and the new scalar. The fraction γ of the new scalar in the lightest mass eigenstate, assumed to be at 125 GeV, and the mass of the second mass eigenstate are the two only parameter needed to describe the phenomenology of this model. CLIC can probe this model via the measurement of 125 GeV Higgs boson rates as well as directly searching for the production of the heavier scalar, that is expected to decay in a pair of Higgs bosons and give rise to jetty final states $e^+e^- \to S \to hh \to 4b$. We remark that a large fraction of the cross-section may come from collisions of W bosons that appear as electron beam constituents and have cross-sections log-enhanced by the large e^+e^- center-of-mass energy.

From a thorough study of backgrounds and signal events with N=4 exclusive Valencia-style jets [4], taking into account detector effects by Delphes [5] with a CLIC-specific parametrization, the reach for new scalars of given mixing angle γ is shown in Figure 1. It can be seen that the direct reach of CLIC 3 TeV (blue line) improves more than one order of magnitude compared to the High-Luminosity LHC reach. In particular, if one is interested in the theoretically most motivated case of mixing γ inversely proportional to the mass of the new heavy scalar, CLIC 3 TeV will probe masses up to 1.8 TeV. From the mixing γ one also expects a consistent reduction of the rates of the Higgs boson in all its decay modes and production channels. Precision measurements of the Higgs boson rates are expected to probe this model indirectly and exclude any mixing above the dashed black line in Figure 1. Evidently CLIC can probe scalar masses up to beyond 2.5 TeV.

2. Dark Matter and beyond

Several astrophysical and cosmological observation seem to require some form of matter in the Universe with gravitational effects on a range of distance scales and possibly interaction with the Standard Model. This form of matter has visible effects in probes of the early Universe till present day, so it is usually assumed to be stable. A simple explanation for the stability of Dark Matter may be that its decay is forbidden by some accidental symmetry of the Standard Model, similarly to the stability of the proton. Ref. [6] has studied possible candidate extensions of the Standard Model that can provide such "accidental" dark matter and found several candidates n-plets of the weak interactions $SU(2)$ with mass in the TeV or multi-TeV range. The presence of new matter carrying weak charge at the TeV scale can be probed at CLIC with precision studies of the Drell-Yan process $e^+e^- \to \gamma^*/Z^* \to f\bar{f}$. Modifications to the total and differential cross-section of this process are induced by modified propagators for the gauge bosons, that reflect self-energy corrections from the new electro-weak states. A study of the reach of CLIC 3 TeV is presented in Figure 1 for a generic n-plet. The star denotes a thermal dark matter candidate Dirac fermion 3-plet for which CLIC 3 TeV can put a 95% C.L. exclusion. The figure also reports pink shaded areas, which denote masses excluded for a Wino-like 3-plet (Majorana fermion), possibly coming from "split SUSY". In this study it has been assumed that the 3 TeV stage of CLIC will accumulate in total $5/ab$ of data, of which $4/ab$ are taken with beam polarization $P_{e^-,e^+} = (-80\%, 0\%)$, as per the latest revision of the CLIC staging. Due to the importance of corrections to the Z boson propagator this study benefits substantially from the possibility to polarize the beams to collide left-handed electrons; the polarization of positrons may further enhance the reach of CLIC.

Recently the CLICdp collaboration has produced a result [7] for an exotic decay of the 125 GeV Higgs boson $e^+e^- \to h\nu\bar{\nu} \to XX \to 4b$, where X is a meta-stable particle. Thanks to dedicated vertex-fidinder algorithms and the relatively clean environment of e^+e^- collisions it is possible to test X life-time from 1 to few 100 ps and put bounds for this exotic branching fraction of the Higgs at the 10^{-4} level. These results open the way for a number of searches that deal with displaced vertex as signature from new physics related to baryogenesis, electro-weak symmetry breaking, and other scenarios of physics beyond the Standard Model.

In conclusion these results qualify the multi-TeV e^+e^- collider CLIC as an excellent probe of a variety of well motivated scenarios of physics beyond the Standard Model, capable of probing interesting parameters space over a large range of different signatures.

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