Beyond the Standard Model physics at CLIC

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Abstract
A summary of the recent results from CERN Yellow Report on the CLIC potential for new physics is presented, with emphasis on the direct search for new physics scenarios motivated by the open issues of the Standard Model.

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1 Introduction

The Compact Linear Collider (CLIC) [1, 2, 3, 4] is a proposed future linear $e^+e^-$ collider based on a novel two-beam accelerator scheme [5], which in recent years has reached several milestones and established the feasibility of accelerating structures necessary for a new large scale accelerator facility (see e.g. [6]). The project is foreseen to be carried out in stages which aim at precision studies of Standard Model particles such as the Higgs boson and the top quark and allow the exploration of new physics at the high energy frontier. The detailed staging of the project is presented in Ref. [7, 8], where plans for the target luminosities at each energy are outlined. These targets can be adjusted easily in case of discoveries at the Large Hadron Collider or at earlier CLIC stages. In fact the collision energy, up to 3 TeV, can be set by a suitable choice of the length of the accelerator and the duration of the data taking can also be adjusted to follow hints that the LHC may provide in the years to come. At present we consider a scheme that is a balanced choice aimed at fully exploiting the physics potential of the project in a manageable timeframe. CLIC is foreseen to deliver integrated luminosities

$$1 \text{ ab}^{-1} \text{ at } \sqrt{s} = 380 \text{ GeV}$$
$$2.5 \text{ ab}^{-1} \text{ at } \sqrt{s} = 1.5 \text{ TeV}$$
$$5 \text{ ab}^{-1} \text{ at } \sqrt{s} = 3 \text{ TeV}$$

which will be collected in an overall period of 27 years, preceded by a 7 years lead time to construct and commission the first stage of the machine [1].

The large amount of data collected at the 380 GeV stage will allow a substantial improvement of our understanding of the top quark [9] and the Higgs boson [10] compared to what the HL-LHC will be able to provide [11, 12, 13]. The later stages in the trans-TeV center-of-mass energy regime will allow to thoroughly explore new physics at the TeV scale, benefiting from the clean $e^+e^-$ collision environment. In these stages further improvements on Higgs physics and other SM properties are expected, thanks to the large number of Higgs bosons, exceeding one million, that can be detected from vector boson fusion production and the enhanced sensitivity that such high-energy collisions will enjoy to reveal new contact interactions which show up in subtle effects in reactions involving SM states and can be originated by heavy new physics.

In the following we give a detailed account of recent work [4] done for the direct search of these heavy new physics states. In many examples we will see how a trans-TeV leptonic collider can significantly extend the reach of the HL-LHC. These results clearly show how such high energy leptonic colliders can be discovery machines, as well as delivering a clean environment in which to carry out very precise measurements useful to test accurate SM theoretical predictions, as done at previous $e^+e^-$ machines like LEP and SLC.
2 Open issues in the Standard Model and Direct searches of New Physics

Several issues remain open in particle physics. Questions can be asked on the origin of the many parameters of the Standard Model and we are not able to provide satisfactory answers for the dynamics that generate them. Some of these parameters may be “just so”, and the Standard Model would be a consistent and predictive theory of fundamental interaction. Even if one takes this view, there are observed phenomena that are simply not accountable in the Standard Model, such as the astronomical observations that lead to hypothesize the presence of a new form of matter, the so-called Dark Matter of the Universe, or some deep revision of the inner workings of gravitational interactions on the largest length-scales. Either way we should expect the Standard Model to be replaced by a more fundamental theory capable of accounting for the phenomenology of Dark Matter. In the well established theory of the expanding Universe it appears that the amount of matter in excess of that of anti-matter was miraculously offset in the initial conditions of our cosmology to result in the amount of matter that we observe today. Such improbable coincidence in the history of the Universe can be made a consequence of dynamics of fundamental interactions, but requires to extend the Standard Model to find sources of baryon number violation and additional sources of CP violation. Other parameters of the Standard Model may even break the longstanding paradigm for which long-distance observables are not affected by tiny modifications of microscopic degrees of freedom [14, 15]. Establishing this sensitivity to microscopic physics or finding the mechanism that protects the Standard Model parameters from being so sensitive would settle a deep issue in the characterization of fundamental interactions. Particle colliders have a chance to shed some light on all these issues, but it should be reminded that they are not the sole type of experiments [16] capable of testing ideas to address the open issues of the Standard Model. Still they appear to be the only way forward if we want to explore the high energy frontier, at which some of the explanations of the above mentioned phenomena may be discovered. In this respect the possibility afforded by CLIC to collide point-like particles such as electrons and positrons accelerated at multi-TeV energies appears particularly interesting to directly test new physics scenarios motivated by the need to address the open issues of the Standard Model.

Direct discoveries of new particles. CLIC can probe TeV scale electroweak charged particles well above the HL-LHC reach. Such new particles are naturally expected because many of the issues that need to be addressed in the Standard Model are inherent to the electroweak sector of the theory. For example particle dark matter candidates can hardly carry any other SM charge than electroweak. Furthermore the electroweak sector may be able to accommodate the violation of baryon number, C and CP necessary for the generation of a net baryon number of the Universe as well as provide a phase transition and the necessary boundaries between phases at which to generate the net baryon number. All
the problems about the origin of the masses and mixings of neutrinos and of the other fermions of the SM are related to the weak interactions. In addition, the Naturalness Problem is genuinely a question about the peculiarity of weak interactions. A complete exploration of TeV scale electroweak particles is thus a priority for particle physics.

Any such new particle can be produced at CLIC with sizable rate up to the kinematic limit of 1.5 TeV, and in some cases up to 3 TeV via single production mechanisms. Depending on the decay channels, different detection strategies are possible.

When new particles decay into standard final states featuring prompt jets, leptons and photons they give rise to signatures which can be relatively easily be distinguished from backgrounds. Indeed, background from SM processes usually have cross-section comparable with that of the signal, as they are produced via the same electroweak interactions. This is the key advantage of lepton colliders over hadron colliders that makes CLIC out-perform the HL-LHC. In most cases the signals can be isolated so clearly that it is possible to measure the properties of new particles, such as mass and spin, and even test concrete models of physics beyond the Standard Model by checking some of their key predictions on new physics particles properties. Examples of reach for direct discoveries are discussed in detail in Ref. [4], e.g. for new scalars and for several examples from supersymmetric models. We highlight Section 4.4 of Ref. [4] which contains studies, not summarized here for brevity of this contribution, on the test of models which predict the Higgs boson mass from other model parameters, such as the MSSM, and tests of other predictions from models of Neutral Naturalness such as Twin Higgs models [17]. Other examples of direct reach for discovery for models of particle Dark Matter, baryogenesis and neutrino mass generations are discussed in detail in the following. We should recall that the CLIC potential to directly explore new physics is extensively documented in the literature, and in particular in early Refs. [18, 19], often taking supersymmetric particles as benchmarks. These were studies from before the Run2 of the LHC, hence cannot profit from the vantage point we reached today in the exploration of the TeV scale. In the following we will try to use as much as possible simplified models that extend the SM in the spirit of well known BSM models, but do not necessarily carry the whole bag of phenomenological consequences. For instance we will discuss WIMP-like Dark Matter searches by just adding a new electroweak state to the SM matter content, or we will study generic singlet scalar particles without attaching them to any particular model of the large class in which they may arise (e.g. in models of electroweak symmetry breaking or baryogenesis scenarios).

When the new particles give rise to non-standard signatures, e.g. because they decay at a macroscopic distance in the detector volume, it is still possible to isolate these signals thanks to the clean environment typical of $e^+e^-$ colliders. Relevant examples of this kind of signatures include Higgs boson rare decays to long-lived particles, Higgsino Dark Matter and the search for WIMP baryogenesis models which are further discussed below. In this case as well the models we present are representative models of some large class of BSM scenarios and
Figure 1: CLIC reach for new scalar singlets direct observation (blue and green solid lines)\[20\]. Constraints from measurements of 125 GeV Higgs boson couplings are reported as horizontal lines. LHC expectations for both direct and indirect sensitivity are reported as well.

the results we present allow recasts of the provided information for other new physics scenarios.

**Extended Higgs Sector** Understanding the nature of the Higgs boson is one of the key elements for a full understanding of the electroweak interactions and in particular of the breaking of electroweak symmetry. A very important question is if the Higgs is the unique scalar particle at the weak scale, or if instead an extended scalar sector exists. For this reason it is a key target for future colliders to investigate the existence of additional Higgs bosons at the TeV scale, which may be the first important step to unravel the mystery of electroweak symmetry breaking and the origin of the weak scale.

A prototypical example of extended Higgs sector is the extension of the SM with a new scalar. A particularly challenging case is the one in which the new scalar has no gauge interactions and interacts with SM only through the Higgs boson portal. This kind of scalar is usually referred as a “singlet” scalar and arises in concrete models such as the Next-to-Minimal Supersymmetric Standard Model (NMSSM), non minimal Composite Higgs models as well as Twin Higgs models from “neutral naturalness” solution to the hierarchy problem of the weak scale. In addition, a new such scalar may affect the Higgs boson potential and alter the nature of the phase transition between broken and unbroken electroweak symmetry in the early Universe, thus playing a role in the generation of a net baryon number.

A concrete study of direct production of new scalar singlet at CLIC is summarized in Fig. 1. CLIC sensitivity to direct production of a new scalar singlet extends well beyond the TeV mass scale at which these new singlets are most motivated. For a mixing between the singlet and the Higgs $\sin^2 \gamma < 0.24\%$ the new singlet has to be heavier than 1.5 TeV. Furthermore if a singlet of any mass has mixing $\sin^2 \gamma > 0.24\%$ it would result in deviation in the single Higgs couplings to SM gauge bosons and fermions in excess of 2 standard deviations for the expected accuracy of Higgs couplings determinations at CLIC. These studies are discussed in detail in Sec. 4.2 of Ref. \[4\], where their implications on
concrete models are also worked out. It is found that in the case of the NMSSM CLIC can exclude a new scalar lighter than 1.5 TeV for values of $\tan \beta < 4$, where the NMSSM is most motivated. For Twin Higgs models direct search bounds generically rule out new scalars below 2 TeV for values of the dynamical scale of the model $f < 2$ TeV where the model is most motivated. Furthermore, the study of Higgs boson couplings excludes $f < 4.5$ TeV if one assumes that the mass of the scalar is equal or greater than $f$, as expected for a composite scalar. Similarly to what happens for the NMSSM bound, such a constraint on the Higgs compositeness scale $f$ would push the model out of its most motivated region of parameters space. We point out to the reader that further studies on extended Higgs sectors can be found in Sec. 4.3 of Ref. [4], which reports results from Ref. [21] on several concrete models featuring extended scalar sectors with multiple doublets and singlets fields, e.g. the 2-Higgs-Doublets model (2HDM).

CLIC can probe the existence of such new scalars both by direct production of new scalars and by indirect effects they have on the 125 GeV Higgs boson couplings. The expected reach extends up to and beyond 1 TeV, improving dramatically on the HL-LHC searches. Also for light singlet scalars, studied in Ref. [22] and presented in [4], it is found that the HL-LHC reach is significantly extended by each stage of CLIC. In particular these studies for light scalar searches highlight the importance of scalar-strahlung searches at the first stage of CLIC (and/or lower energies lepton colliders [23, 24]) as well as the direct searches for specific final states in the 125 GeV Higgs boson decays, such as $h \rightarrow 4b$ [25]. All in all CLIC is able to thoroughly test extended Higgs sectors and rule out new scalars up to multi-TeV masses. Both direct and indirect signatures can be successfully pursued yielding stringent bounds on new scalar particles that improve by almost one order of magnitude in mass scale compared to the HL-LHC.

**Composite Higgs** The Higgs boson is the only scalar particle that is predicted in the SM to be exactly point-like. Therefore it is interesting to investigate if instead it is an extended composite object and, if it is, to determine its geometric size $l_H$. Discovering the composite nature of the Higgs would be a crucial step towards the understanding of the microscopic origin of the electroweak symmetry breaking phenomenon. Higgs compositeness might also provide a screening of SM Higgs mass parameter from details of the ultra high energy modes, as the Standard Model would be replaced by a whole new fundamental theory of the electroweak sector at distances shorter than the size of the Higgs boson. At a phenomenological level a composite Higgs would manifest itself at CLIC through contact interactions, e.g. the $d = 6$ SMEFT operators, suppressed by two powers of the Higgs compositeness scale $m_s \sim 1/l_H^2$. The operator coefficients are enhanced or suppressed, relative to the naive $1/m_s^2$ scaling, by positive or negative powers of a parameter “$g_*$” representing the coupling strength of the composite sector the Higgs emerges from [26]. These rules provide estimates for the operator coefficients in the $(m_s, g_*)$ plane and allow us to translate the CLIC sensitivity to the SMEFT into the discovery reach on Higgs
compositeness, as displayed in Figure 2a from Ref. [4]. The projected HL-LHC exclusion (as opposite to discovery lines shown for CLIC) reach is also shown in the figure for unit $c$-coefficients. The dramatic improvement achieved by CLIC at small and intermediate $g_*$ is due to the high-energy stages that allow for a very precise determination of the $c_{HW}$, $c_{HB}$, $c_{2W}$ and $c_{2B}$ SMEFT Wilson coefficients. Single Higgs boson couplings measurements are instead provide the most stringent constraints at large $g_*$.

This example shows magnificently the complementarity of the searches for new physics that can be attained at CLIC by exploiting the precision and the mass reach that CLIC will provide. Measurements from high-intensity studies, in this case studies of copiously produced Higgs bosons, probe one combination of the two characteristic parameters of this scenario, while the other combination is probed by less copious events at high invariant mass in the later stages of CLIC. It should be remarked that a similar conclusion can be reached in the study of the general $d = 6$ SMEFT for universal theories, in which the study of high energy processes allows to put constraints on quantities such as the “S parameter” [27, 28, 29, 30, 31] that is traditionally measured in high-intensity experiments at the $Z$ pole [32, 33]. This complementarity of approaches is a great advantage of high energy lepton colliders.

Within the compositeness context, and in connection with the Naturalness Problem, top quark compositeness can also be considered. It produces SMEFT operators in the top sector that can be probed by measuring the top Yukawa coupling and, very effectively, by $t\bar{t}$ production at high-energy CLIC. The reach in the “total $t_R$ compositeness” scenario is displayed on Figure 2b. For further details, and for a similar result in the case of “partial top compositeness”, see
Dark Matter The nature of dark matter in the Universe is a great mystery. Very little is known about the particle properties of dark matter and a large host of models provide viable dark matter candidates. A particularly compelling candidate is the so-called Weakly Interacting Massive Particles (WIMP) that naturally emerge from the standard cosmological history of the Universe as possible thermal relics that stop being in equilibrium with the plasma of the early Universe at a temperature roughly one order of magnitude below their mass and from that moment onward remain as relics in the Universe, interacting with the SM particles only through gravity, ultimately shaping the formation of galaxies and other cosmic structures. Thermal production of WIMPs can yield the observed abundance of dark matter for masses $M_{\text{WIMP}} \simeq \text{TeV}$ \( \left( \frac{g_{\text{DM,SM}}}{g_{\text{weak}}} \right)^2 \) where $g_{\text{DM,SM}}$ roughly denotes the strength of the couplings of processes that keep the dark matter in equilibrium, e.g. $\text{DM} \leftrightarrow \text{SM}$, and $g_{\text{weak}}$ is the coupling strength of the SM weak interactions.

Despite these requirements on the particle nature of the Dark Matter a large set of possibilities exists even if one restricts to consider weakly interacting massive particles. In Sec. 5 of Ref. [4] a comprehensive strategy is outlined to test a wide range of possible situations in which the Standard Model is extended by a WIMP and by other states possibly members of the same weak interactions multiplet or as independent state.

The approach we follow to study Dark Matter phenomenology by simply specifying masses and quantum numbers of new states has been called “Minimal DM” [35, 36, 37]. This approach has shown that new particles that can live also in very large (up to the 7-plet) representations of the SM $SU(2)$ group can give

(a) 95% excluded masses for new electroweak $n$-plet states with hypercharge $Y$. The exclusion for each state denoted by (1,n,Y) at CLIC Stage2 and Stage3 is presented in green and yellow bar [34].

(b) 95% excluded region for a new physics signal from a pure Higgsino in the mass-lifetime plane. The black dashed line denotes the theory prediction for a the lifetime of a pure Higgsino doublet. Green, Yellow and Blue areas correspond to 3 TeV, 1.5 TeV and 380 GeV CLIC runs expected exclusions.

Figure 3: Reach of direct searches for Dark Matter.
viable Dark Matter candidates. All this variety of weakly charged states are a target for future colliders. CLIC can probe them in several ways. First, one can perform model-independent indirect searches for new EW states by studying their radiative effects on the EW pair-production of SM particles, obtaining the 95% CL sensitivities reported in Figure 3a taken from results of Ref. [34]. The sensitivity reaches the thermal mass (i.e., the one which is needed in order to produce the observed thermal abundance) in the case of the Dirac fermion triplet candidate \((1, 3, e)_{DF}\). Second, one can exploit the fact that the charged component of the Minimal DM multiplet is long-lived, with a macroscopic decay length. Its distinctive signature is thus a “stub” track, which can be long enough to be seen if the particle is light enough to be sufficiently boosted. Figure 3b shows that CLIC can discover the thermal Higgsino at 1.1 TeV with this strategy.

In addition, it should be noted that CLIC is also sensitive to DM models that fall outside the Minimal DM paradigm, such as co-annihilation scenarios, in which two almost degenerate states can scatter into Standard Model states with a much stronger interaction than each of them singly. Models that exploit the presence of multiple states, such as the Inert Doublet model [38, 39, 40], can also be thoroughly explored at CLIC, extending significantly the domain of the parameters space probed in comparison to the HL-LHC capabilities [41, 42]. Details on these and other models are presented in Ref. [4]. Here we content with stating that in general CLIC can effectively probe DM models with a sufficient mass-splitting to produce signals featuring prompt jets, leptons and photons plus missing momentum.

Figure 4: CLIC reach for the Higgs plus a scalar singlet for electroweak baryogenesis.
Baryogenesis and electroweak phase transition  The mechanism responsible for the origin of the net baryons number of the Universe is currently unknown, and it might be discovered at CLIC if it is related with TeV-scale physics. A prominent example of such dynamical origin of the baryons in the Universe is the ElectroWeak BaryoGenesis (EWBG) scenario (see [44] for an introduction). This mechanism requires, among other things, a considerable modification of the SM thermal Higgs potential, that should give rise to an EW phase transition of strong first order, unlike the smooth crossover that is predicted by the SM. This is achieved through new scalar particles coupled with the Higgs, which can modify its potential at tree level or via loops. These particles, as they must have some interaction with the Higgs boson, can be probed at CLIC by precise measurements of the Higgs trilinear coupling and of single Higgs couplings to SM states, as well as by direct searches.

The most minimal of such models extends the Standard Model by just adding a new singlet scalar and allowing the most general scalar potential for a Higgs doublet and the new singlet scalar. This is a suitable illustrative benchmark because it contains the minimal amount of new physics (i.e., a scalar singlet $S$) that is needed to achieve a strong first-order phase transition. Several measurements can be used to constrain the model at CLIC, as is illustrated in Figure 4a, taken from [4, 43]. The figure displays a slice of the parameter space of the model for singlet mass $m_2 = 500$ GeV and singlet mixing with the SM Higgs boson $\sin \theta = 0.05$. The remaining parameters $a_2$ and $b_3$ are respectively the $|H|^2 S^2$ quadratic portal coupling and the $S^3$ trilinear vertex. The allowed points in the plane are marked as red circles, those for which the EW phase transition is strong enough are filled in green. All the green points can be probed both by the trilinear Higgs coupling measurement (black dashed) and by single $S$ production decaying to $HH \rightarrow 4b$ final state (blue dashed). For this choice of mixing, the entire plane is probed by single Higgs coupling measurements (gray region). Notice however that the effectiveness of single-Higgs couplings stems from the fact that the model at hand predicts sharp correlations between the modification of several Higgs vertices, but this correlations might be relaxed in other models. The CLIC capability of performing multiple competitive probes of the scenario instead allows to draw robust conclusions. Indeed the measurement of the Higgs trilinear couplings remains a powerful constraint even when $\sin \theta \rightarrow 0$, and it allows to exclude models with $m_S > 450$ GeV.

In addition it is possible to search at CLIC for pair production of the singlet $S$, which is mediated directly by the $a_2$ coupling, hence it is allowed even when $S$ and the Higgs boson doe not mix. In a scenario completely driven by the $a_2$ coupling it is possible to study loop effects on the Higgs potential and put constraints on the model using the same measurements mentioned above: single Higgs couplings and triple Higgs couplings. The limits in this scenario are reported in Figure 4b, where the $a_2$ coupling is renamed $\lambda_{HS}$ following the notation of Ref. [20]. This figures also report the regions of parameter space in which the $\lambda_{HS}$ coupling is large enough, or the singlet is light enough, that CLIC can produce ten or one hundred $S$ pairs. The number of events to be produced to put a bound or discover $S$ depends on the specific decay of the singlet $S$, but
these numbers are reasonable estimates for an $e^+e^-$ collider and experimental signatures with moderate level of background. From these considerations CLIC is expected to be sensitive to pair production of singlet scalars related to EWBG for a large region of the parameter space in which the phase transition can be first order.

CLIC can also probe TeV-scale Baryogenesis models of radically different nature. In particular it is possible to test the “WIMP baryogenesis” scenario [45], where the baryon asymmetry is generated via the baryon number violating decays of TeV-scale long-lived particles. The favorable experimental conditions of CLIC allow to probe unexplored regions of the mass-lifetime parameter space of this model [4]. As shown in Figure 6b CLIC can explore long decay lengths that are necessary to generate necessary out-of-equilibrium decays in the early Universe, significantly extending the reach of the HL-LHC [46, 47, 45, 48].

Hidden Sector The possibility that sets of particles secluded from our view exist in “mirror world” is an open question. These particles may be secluded to us because of a tiny coupling between Standard Model states and the new physics states in question. Such feeble interactions may be useful in a number of contexts to address open issues of the Standard Model, see e.g. Ref. [49] for a discussion, hence their search is very motivated. These searches are very challenging because the properties of the new physics states can only be vaguely guessed, hence a broad program of searches needs to put in place to effectively explore this idea. In this context it is possible that new physics manifests itself with light new particles, which we have not yet seen because of their tiny couplings with SM particles. CLIC can make progress on the experimental exploration of this scenario in unique corners of its vast parameter space. For example, the clean environment and the absence of trigger allows CLIC to improve significantly over the HL-LHC in the search for Higgs or Higgs-like bosons decay to long-lived particles [50, 51], reaching exclusion of

$$BR(h \to \text{displaced vertexes}) \sim 10^{-4},$$

as shown in Figure 6a. This result can be recast for searches of heavier Higgs bosons, as detailed in Section 8 of Ref. [4]. These searches allow CLIC to probe models of electroweak symmetry breaking, emerged in the context of “Neutral Naturalness” scenario, such as the Fraternal Twin Higgs [52] and Folded Supersymmetry (see e.g [53]) solution of the Naturalness Problem.

CLIC can also search for relatively heavy Axion-Like Particles, that may be part of a feebly interacting sector that extends the Standard Model. These sectors may find their origin in several theoretical contexts, hence they are a useful simplified model to express the reach of CLIC in general parameter space ruled by the mass of the ALP and its decay constant. As a high energy collider CLIC can probe ALPs that are obviously outside the reach of dedicated low-energy experiments [54]. In Figure 5 we show results for the photo-phobic ALP [55] case, that are in any case representative for other couplings structures involving photons as well, and we can see about one order of magnitude of
improvement in the bound of the decay constant of the ALP. In particular it is remarkable that CLIC can improve on LHC bounds and is able to enter regions of parameters space for the model in which the ALP mass is less than or comparable with its decay constant, where the models are more motivated.

Last but not least it should be recalled that CLIC technology may already now enable new types of experiments with low energy electron beams that may discover new light gauge bosons of possible relevance for the Dark Matter puzzle [56, 57]. This might be a useful testing ground for CLIC technology with a very good chance to add new knowledge in the quest for Dark Matter. On a similar note it is worth to recall that a multi-TeV leptonic collider may allow parasitic use of the beam for fixed target experiments [58] sensitive to other types of light new particles, therefore attaching a bonus exploration of the so-called “intensity frontier” to the already very rich exploration of the high energy frontier that CLIC can deliver.

Neutrino Mass Evidence for flavor oscillations in neutrinos demands these particles to be massive. Mixing parameters of the neutrino flavors subject to weak interactions with the charged leptons are established in experiments. Still we lack a deep understanding of the origin of neutrino masses. These masses cannot be explained in the Standard Model and they require new physics either in the form of a chiral partner of the left-handed neutrinos, that is as a heavy right-handed neutrino, or in the form of new contact interactions between leptons and the Higgs boson. These interactions happen to be non-renormalizable, hence they require some new physics at higher mass scales to originate to them.

CLIC has sensitivity to a large set of models in which lepton number is an almost approximate symmetry, which makes very natural to have small neutrino masses in the form of a Majorana mass. Other presentations appeared at this workshop [61, 59, 62, 60] give in-depth discussions on the models and the search for these models at colliders. Here we recall some representative results. For example, see Figure 7, in the inverse-seesaw model it is possible to have large Yukawa couplings between the Higgs boson and the right-handed neutrinos,
(a) Excluded cross-section time Higgs branching ratio in the exotic mode $h \rightarrow \pi^+\pi^-$. The reference rate for CLIC 3 TeV is $\sigma_h \sim 0.4$ pb in this study [50, 51].

(b) LHC (blue) and CLIC (orange) exclusions for the particles responsible of the generation of the baryon number in the WIMP baryogenesis scenario. CLIC outermost (innermost) contour is for 30 events (3 events) produced in the detector acceptance for displaced vertices.

*Figure 6: Searches for Long Lived new physics states.*
which CLIC can exclude up to 10 TeV mass when the Yukawa coupling is of order 1 \cite{59, 60}. Even greater reach around tens of TeV is expected for models (e.g. these discussed in Refs. \cite{63, 64, 65}) featuring a doubly charged scalar lepton for Yukawa coupling of order 1 \cite{66}. Furthermore CLIC can easily exclude the presence of electroweak charged scalars and fermions, such as the heavy mediators of type-2 and type-3 see-saw models, with masses below 1.5 TeV over the entire parameters space of the models. In particular for type-2 sees-saw CLIC is able to probe the model for any value of the vacuum expectation of the triplet neutral scalar \cite{67}, dramatically improving on the situation of the HL-LHC which is hardly sensitive to the case of VEV greater than 100 KeV \cite{68}.

3 Summary of physics results, their impact and discussion

The above results make clear that a multi-TeV lepton collider emerges as a uniquely powerful and balanced option for future exploration of the high energy frontier. Multi-TeV lepton colliders can attain a thorough exploration of the TeV scale and deliver significant progress on the several open issues of the Standard Model. In fact, CLIC can thoroughly explore the existence of new Higgs bosons in the TeV mass ballpark observing them directly as new particles produced in the $e^+e^-$ collisions as well as measuring their subtle impact on the couplings of the 125 GeV Higgs boson. Furthermore CLIC can test TeV scale solutions of the baryon number and Dark Matter puzzles which involve TeV scale new states as well as test neutrino mass generation mechanisms featuring new dynamics at the TeV scale.

The strength of CLIC reach for new physics is built on two pillars: the possibility to carry out very precise measurements, that is typical of $e^+e^-$ machines, and the unprecedented large center of mass energy it can attain, 3 TeV, which makes it a discovery machine capable to observe a large set of the new particles that are predicted in motivated new physics models. In the discovery of new particles CLIC is remarkable because of its ability to explore directly the electroweak sector up to multi-TeV energy scales. This is a unique and defining feature of CLIC in the landscape of currently proposed $e^+e^-$ projects.

The interpretation of the new physics reach of CLIC in the context of new physics scenarios makes clear that CLIC competes very well with the reach of $pp$ colliders. In fact the possibility to search for new electroweak states enables to test new physics scenarios searching for their very core ingredients, i.e. CLIC is often sensitive to the electroweak states that are directly involved in the solutions to the open issues of the Standard Model. The interpretation of searches for colored particles, at any collider, is in general less sharp and less conclusive, as these states can relatively easily be avoided or made heavier in most models.
Therefore it appears fair to say that a multi-TeV $e^+e^-$ machine such as CLIC can teach us sharp and definitive lessons on the physics of the TeV.

The great advantage of CLIC in the search for new electroweak states comes from the relatively low levels of backgrounds that are expected. In such an environment it will be possible to test thoroughly new physics at the weak scale, including exotic kinds of new physics that show up in subtle signatures such as anomalous tracks, extra displaced vertexes in the events, other types of long lived states or exotic jet-like energy deposits recorded only in some of the layers of the detectors. Being sensitive to new electroweak charged states in the whole range of energies up to beyond TeV masses, including when they give rise to subtle and exotic signatures, CLIC will bring us to a vantage point from which we can draw definitive conclusions on many open issues of the Standard Model.

It should also be remarked that CLIC will deliver the full set of results in a relatively short time-scale, only 34 years from the first stone to the last recorded collision, which is a relatively short time in the landscape of the future colliders projects currently under discussion. This gives best chances to keep an active experimental community, constantly reinvigorated by young ones attracted by the challenge of working on intellectually stimulating projects at the technical forefront of the epoch. Furthermore it is possible to envisage a fruitful concurrency with other lines of experiments that attack the quest for fundamental interactions from a different angle, e.g. small and large dark matter detectors or highly-precise low energy experiments, which may otherwise preempt the scope of discovery of a future collider facility if this is coming on-line or delivering final results too late. On the flip side, the interplay with other experimental lines of research may be very synergetic as the CLIC energy and luminosity plans can be adjusted to follow hints from other searches for new physics.

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