

PHYSICS MOTIVATIONS FOR FUTURE CERN ACCELERATORS *

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ABSTRACT

We summarize the physics motivations for future accelerators at CERN. We argue that (a) a luminosity upgrade for the LHC could provide good physics return for a relatively modest capital investment, (b) CLIC would provide excellent long-term perspectives within many speculative scenarios for physics beyond the Standard Model, (c) a Very Large Hadron Collider could provide the first opportunity to explore the energy range up to about 30 TeV, (d) a neutrino factory based on a muon storage ring would provide an exciting and complementary scientific programme and a muon collider could be an interesting later option.

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1 Introduction

The central motivation for any CERN accelerator beyond the LHC must be provided by physics beyond the present Standard Model. LEP has tested the Standard Model very precisely, but has provided no direct evidence for physics beyond it. Atmospheric and solar neutrino oscillation experiments have provided the first experimental evidence for physics beyond the Standard Model, and long-baseline experiments using accelerator neutrino beams are underway to verify and explore this new physics. Recently, the Brookhaven experiment on the anomalous magnetic moment of the muon has reported a hint of a possible discrepancy with the Standard Model. Nevertheless, the possible direction of experimental physics beyond the Standard Model remains uncertain, and any prediction which experiments will be interesting for CERN after the LHC and the CERN-Gran Sasso neutrino project must be largely speculative.

The most prominent areas where the Standard Model leaves unsolved problems include the origins of the particle masses, the variety of particle types (flavours), the unification of the particle interactions, and a consistent quantum theory of gravity. All of these problems should ultimately be resolved in a ‘Theory of Everything’, and the long-term goal of particle physics is to discover and establish such a theory. Resolutions of the more immediate problems will provide some of its ingredients.

Particle masses are believed to be due to a Higgs boson, and LEP provided last year a hint that it might weigh about 115 GeV. The masses generated by the Higgs mechanism are, however, destabilized by quantum effects, unless new physics is invoked. Favoured theoretical scenarios for stabilizing particle masses have been the idea that the Higgs boson might be composite, or that it might be accompanied by supersymmetric particles, which have identical quantum numbers to the known particles, but have spins differing by half units. More recently, inspired by string theory, it has been suggested that there might be additional spatial dimensions beyond the three we know, and that these might remove the need for a large hierarchy between the intrinsic scale of gravity and the observed particle masses [1].

These scenarios all predict new physics at the TeV energy scale, which will initially be explored by the LHC. If confirmed, the Brookhaven measurement of a possible discrepancy in the anomalous magnetic moment of the muon would also hint at new physics at the TeV energy scale, and interpretations based on supersymmetry and lepton compositeness have been proposed. On the other hand, there is no clear hint of the energy scale where new flavour physics might be revealed, and the natural scales of grand unification and quantum gravity are beyond direct reach at foreseeable colliders, unless there are large extra dimensions. However, these might be tested indirectly, e.g., by the relations they predict between low-energy parameters, or by novel phenomena such as neutrino oscillations.

Despite the lack of direct accelerator evidence for physics beyond the Standard Model, LEP has provided some indirect indications which future directions might prove fruitful, and disfavoured some others. For instance, the precision electroweak data suggest the existence of a relatively light Higgs boson, favouring some weakly-coupled model of electroweak symmetry breaking, such as supersymmetry or a theory with large extra spatial dimensions. On the other

Process	LHC	LC	SLHC	VLHC	CLIC	
	14 TeV	0.8 TeV	14 TeV	200 TeV	3 TeV	5 TeV
squarks	2.5	0.4	3	15	1.5	2.5
sleptons	0.34	0.4			1.5	2.5
Z'	5.4	8	6.5	30	20	30
q^*	6.5	0.8	7.5	70	3	5
l^*	3.4	0.8			3	5
Extra two dimensions	9	5 – 8.5	12	65	20 – 33	30 – 55
$W_L W_L$	3.4σ		$> 3.4\sigma$	30σ	70σ	90σ
TGC (95%)	0.0014	0.0004	0.0006	0.0003	0.00013	0.00008
Λ compos.	35	100	50	130	300	400

Table 1: *Comparison of physics reaches with different colliders. The integrated luminosities assumed are 100 fb^{-1} for the LHC and VLHC, 500 fb^{-1} for the 800 GeV LC, and 1000 fb^{-1} for the SLHC and CLIC, corresponding in each case to one full year of running at nominal luminosity. Most of the numbers quoted are in TeV, but for strong $W_L W_L$ scattering the numbers of standard deviations are listed, and in Triple Gauge Coupling (TGC) case a pure number is given for λ_γ . In some cases, the sensitivities of hadron colliders to electroweak physics have not yet been evaluated accurately, and the corresponding entries are left blank. Many of the numbers given for the SLHC, VLHC and CLIC are still provisional.*

hand, these data disfavour strongly-interacting models with composite Higgs bosons, though we do not ignore such a possibility in the following. If there is indeed a light Higgs boson with mass close to the experimental lower limit set by LEP, the Standard Model cannot survive unchanged until the Planck or unification scale, and, more specifically, new physics would be *required* below about 10^5 to 10^6 GeV if the LEP hint of a 115 GeV Higgs boson were to be confirmed [2].

Even if the existence of supersymmetry or large extra dimensions were to be discovered by the LHC, full understanding of the theory behind would require additional measurements with a complementary collider. For example, what breaks supersymmetry, or what fixes the sizes of the extra dimensions? Plans for future CERN accelerators beyond the LHC should bear such questions in mind.

The principal options [3] for possible CERN accelerators beyond the LHC that we have considered include (i) an upgraded LHC with $E_{cm} = 14$ TeV and a luminosity of $10^{35} \text{ cm}^{-2}\text{s}^{-1}$ that we call the SLHC, (ii) a higher-energy hadron-hadron collider with $E_{cm} = 100$ to 200 TeV (the Very Large Hadron Collider - VLHC) [4], (iii) a linear e^+e^- collider with $E_{cm} = 3$ to 5 TeV, such as the CLIC collider that is being studied actively at CERN [5], and (iv) a muon collider (MC) with $E_{cm} < 4$ TeV. We couple the latter with other physics opportunities offered by muon storage rings, such as a neutrino factory and Higgs factories [6, 7].

2 Physics Reach of the LHC

We consider in the following a variety of possible physics topics beyond the Standard Model, including a range of benchmark scenarios for supersymmetric models consistent with the present experimental limits from LEP and elsewhere. We list in the Table the estimated physics reach of the LHC [8, 9] for these various types of physics beyond the Standard Model, including the accessible ranges for the masses of the possible supersymmetric partners for some known particles, of a new neutral weak boson Z' analogous to the well-known Z , of excited quark and lepton states q^* and l^* , the accessible size R_D of a pair of extra dimensions (which we parametrize by the energy scale M_D equivalent to $1/R_D$), the sensitivities to strong interactions between pairs of W bosons parametrized by a 1 TeV Higgs boson and to deviations from the Standard Model value for the Triple Gauge Coupling (TGC) λ_γ , and the reach for a compositeness scale L at which elementary particles might reveal internal structure.

As is well known, the LHC has a large reach for the strongly-interacting partners of quarks and gluons (the squarks and gluinos), and would be capable of reconstructing many of their intricate cascade decay modes. However, its reach for non-strongly-interacting supersymmetric particles such as the supersymmetric partners of leptons (sleptons) is more limited. The set of simplified benchmark supersymmetric models we have established [10] have universal supersymmetric mass parameters that are chosen to be compatible with the various Higgs boson and sparticle limits from LEP [1, 10, 11]. The universality we assume is just one of many specific variants of supersymmetry, and one of the primary tasks of future accelerators may be to probe its assumptions. The first panel of the Figure illustrates crudely the fractions of the rich sparticle spectra in these benchmark models that we estimate to be accessible to the LHC experiments. We see that the LHC discovers some supersymmetric particles in all these scenarios, but never discovers them all. For this reason, the LHC alone will not be able to pin down all the details of supersymmetry breaking.

Likewise, in models with large extra dimensions, the new physics may well show up within the range shown in the Table, although mass scales up to 100 TeV are also possible. Also, if the LHC were to discover a Higgs boson weighing about 115 GeV, but found no supersymmetric particles, the LHC would not cover the energy range up to 10^5 to 10^6 GeV where new physics should appear.

We infer from the Table and the Figure that, although the LHC has excellent prospects of making fundamental discoveries beyond the Standard Model, with mass reach well into the TeV range, it is unlikely to provide complete answers to all the ensuing questions.

To complete the baseline for our subsequent discussion of future CERN colliders, we also include in the Table a column showing the physics reach of a linear e^+e^- collider (LC) with $E_{cm} = 800$ GeV, such as TESLA, the NLC or JLC. Such a LC would complement the LHC in several respects, e.g., in the search for new weakly-interacting physics. This point is made in the second panel of the Figure, where we see that such a LC would (in several supersymmetric scenarios) observe non-strongly-interacting supersymmetric particles that would not be visible at the LHC. Moreover, a LC would provide many detailed measurements of sparticle properties

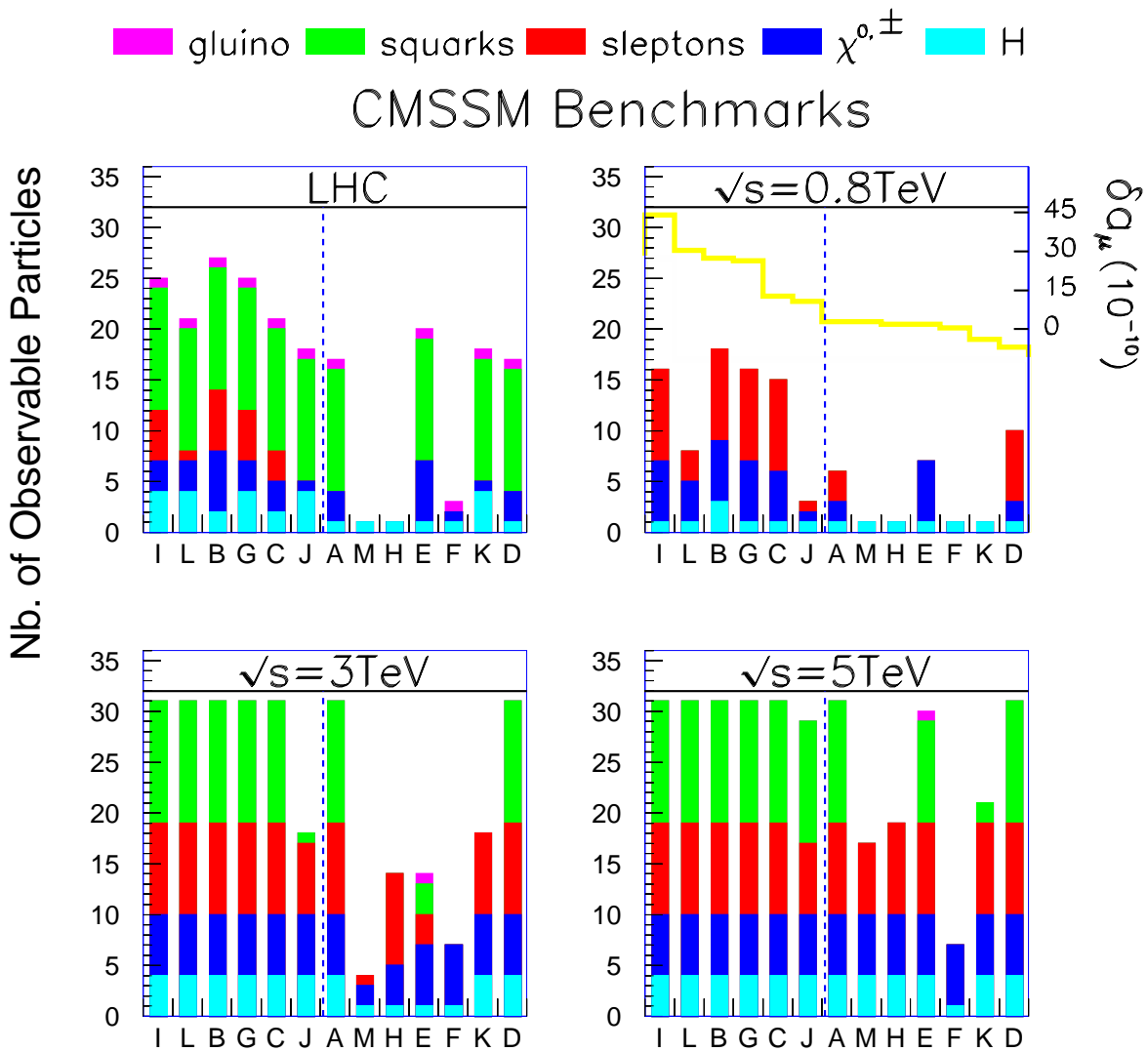


Figure 1: Comparison of the capabilities of various colliders to observe different species of supersymmetric particles, in a range of supersymmetric models whose parameters are chosen to be compatible with experimental constraints from LEP and elsewhere [10, 11]. The models are ordered by their degree of compatibility with the recent BNL measurement of the muon anomalous magnetic moment, as indicated by the line in the top right panel. We see that linear colliders complement the LHC via their abilities to observe weakly-interacting sparticles, in particular. In most of the restricted set of simplified models studied, CLIC (almost) completes the supersymmetric spectroscopy initiated by the LHC.

that would lie beyond the scope of a hadron-hadron collider.

3 Physics Opportunities with Possible Future Accelerators

In this section we discuss the physics accessible to the possible accelerator options introduced above, namely the SLHC, VLHC, CLIC and muon storage rings.

3.1 SLHC

Preliminary estimates by the LHC project team [12] indicate that it should be possible to increase the peak luminosity from the design value of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ up to about $10^{35} \text{ cm}^{-2}\text{s}^{-1}$ by increasing the bunch intensity up to the beam-beam limit, replacing the inner quadrupole triplets with larger aperture magnets to reduce the β -value at the interaction points, and by halving the bunch spacing to 12.5 ns in order to preserve the luminosity lifetime.

On the other hand, more than a modest LHC energy upgrade looks much more difficult. The present dipoles may ultimately sustain a 9 Tesla field, which would correspond to a maximum $E_{cm} = 15.2 \text{ TeV}$. Even if advances in magnet technology made a substantially larger field possible, other problems such as the extraction of the increased synchrotron radiation power would present difficulties for fitting a significantly higher energy machine into the LHC tunnel.

Although the ultimate LHC centre-of-mass energy with the present magnets could be up to 15.2 TeV, the SLHC studies [13, 14] presented here [15] have conservatively assumed $L = 10^{35} \text{ cm}^{-2}\text{s}^{-1}$ and $E_{cm}=14 \text{ TeV}$. Running the LHC detectors at ten times the nominal LHC luminosity would cause non-negligible radiation and occupancy problems, but solutions appear feasible [16]. Here we only mention that one of the main consequences of the luminosity upgrade would be that a large part of the inner detectors of both experiments, e.g., the innermost layers of both trackers and the ATLAS Transition Radiation Tracker, would need to be replaced, in order to maintain the required performance for bottom-quark tagging, electron and tau measurements. On the other hand, calorimeters and the external muon spectrometers should be less affected by the luminosity increase, and should remain fully functional with upgrades of smaller scope.

The estimated physics reaches of the SLHC for supersymmetry, Z', q^*, l^*, M_D , strong WW scattering, TGC and Λ are shown in the third column of the Table. In the discovery channels, we see that the SLHC reaches somewhat further than the LHC, typically by about 20%. The order-of-magnitude increase in statistics should also make possible significant improvements in precision measurements, as indicated by the increased sensitivity to the TGC shown in the Table. Although these improvements are not dramatic, this relatively modest upgrade of the LHC might be very interesting if the LHC finds hints of some phenomena that need to be pinned down. For example, in some of our benchmark supersymmetric models, we expect gluinos to

weigh between 2.5 and 3 TeV, which is most likely in the range covered by the SLHC but not the LHC. Alternatively, in some supersymmetric models some flavours of squarks might be heavier than others, and the SLHC could complete the squark spectrum revealed by the LHC.

The results shown in the Table were obtained for final states containing objects with very large transverse energy, such as jets, leptons, photons or missing transverse energy. Since the pile-up noise in the calorimeter increases only by a factor of about 3 for a factor of 10 increase in luminosity, and gives a negligible contribution to the measurements of particles in the TeV range, calorimetric measurements of jets, electrons, photons and missing transverse energy at the SLHC should not suffer from the higher luminosity. However, electron identification requires a combination of calorimeter and tracker information, and the latter will only be available if the LHC inner detectors are largely replaced. Therefore, in order to be conservative, and not knowing a priori what level of detector upgrade will be technically and financially possible, for the studies presented here we have ignored electrons and considered only final states containing muons, jets, photons and missing transverse energy. It is clear, however, that full detector functionality, including the possibility of detecting and identifying all three lepton species, would be essential to profit fully from the increased luminosity of the SLHC, and to obtain more convincing results in the event of a discovery.

The performance of a hadron collider with $E_{cm} = 28$ TeV and $L = 10^{34}$ cm⁻²s⁻¹ has also been looked at, in order to estimate the available physics as a function of energy as well as luminosity. Such a machine would extend the LHC physics reach by a factor between 1.5 and 2, depending on the channel studied. For example, a signal from strongly-interacting W pairs should be observable at the five-standard-deviation level with only 50 fb⁻¹ of integrated luminosity. However, it is not known currently how such a machine could be housed in the LHC tunnel, since it would require very high-field magnets and new ways to deal with synchrotron radiation.

3.2 VLHC

Studies have been made in the United States of the physics offered by a 100-200 TeV hadron collider, the VLHC [4]. Some estimates of the reach of this machine for $L = 10^{34}$ cm⁻²s⁻¹ are also presented in the Table, providing useful information about the physics interest of the energy regime beyond the LHC/SLHC.

Primarily for geographical reasons, we do not consider a VLHC to be the most likely option for CERN's future [3]. The most recent design study for a VLHC presents a machine with a circumference of 233 Km for $E_{cm} = 200$ TeV. The maximum size of ring that could be accommodated in the Geneva basin is guessed to have a circumference of about 80 Km, and the closest that a larger machine could be placed is probably beyond the Jura mountains in France. VLHC technical studies have been underway for several years in the United States. The main engineering issue is to find technically and economically viable solutions for the machine components, such as the magnets and cryogenics, and the tunnel.

Just as the LHC will be the first machine to enter and explore the TeV energy range, the VLHC will be able to explore the energy range up to about 30-40 TeV in the centre of mass for constituent collisions. In the absence of input from the LHC, it is not yet possible to make a compelling case for any particular scenario for new physics at the 10 TeV scale, in contrast to the TeV energy scale. However, we can envisage several possible scenarios emerging from the LHC data which would justify strongly the need for such a machine [15]. A few examples are:

- The LHC discovers supersymmetry, and supersymmetry is mediated by new gauge interactions. In this case, by measuring several sparticle masses and the lifetime of the next-to-lightest supersymmetric particle, the LHC experiments should be able to constrain, to within 30% or so, the scale at which supersymmetry breaking is communicated to the visible world. If this scale is in the energy range up to a few tens of TeV, then a VLHC could produce directly the corresponding new particles.
- The LHC discovers supersymmetry, and observes the squarks of the third generation, the supersymmetric partners of the top and bottom quarks, but not the squarks of the first two generations. This is possible in so-called inverted-hierarchy models, where the squarks of the first two generations can weigh several TeV without creating naturalness problems. We will then know that such squarks should exist, and a VLHC, which could produce squarks weighing up to about 15 TeV, is the only presently foreseen machine able to observe them.
- The LHC finds evidence for quark compositeness by observing a significant excess of centrally produced high- E_T di-jet events above the Standard Model expectation. It can be seen from the Table that the compositeness scale Λ would then be in the energy range up to a few tens of TeV. Then a VLHC could probe the production of new particles, such as excited quarks, giving more direct and conclusive evidence for compositeness.
- The LHC finds a hint for strong WW scattering, in which case a VLHC could study it with much higher statistics.
- The LHC finds evidence for large extra spatial dimensions, for instance by observing a significant signal in final states with jets and missing transverse energy. It can be seen from the Table that the fundamental scale of gravity would then be in the region of a few tens of TeV, and a VLHC should again be able to probe directly the scale of new physics.

3.3 CLIC

As already mentioned, linear electron-positron collider (LC) projects are being pursued actively in Germany [17], the U.S. [18] and Japan [19], as well as at CERN [5]. The first-generation LC projects being pursued elsewhere typically aim at centre-of-mass energies in the range 0.5 to 1 TeV, and we have chosen $E_{cm} = 800$ GeV as a standard [17] for comparison with the LHC and CERN's future options.

The physics reach for such a LC is inferior to the LHC for new strongly-interacting particles. On the other hand, as also seen in the Figure, such a first-generation LC would be largely complementary to the LHC, offering, for example, excellent opportunities to study in detail any light Higgs boson and make precise measurements of any supersymmetric particles within its reach, in particular the supersymmetric partners of weakly-interacting particles [17]. However, there is no guarantee that any supersymmetric particles would be accessible to a LC with $E_{cm} = 800$ GeV, and such a LC would not in general be able to complete the supersymmetric spectroscopy, as seen in the second panel of the Figure. We assume that some such sub-TeV LC will be built somewhere in the world, and that CERN should envisage constructing a higher-energy lepton-lepton collider, such as CLIC or a muon collider.

CERN and its partner laboratories have been developing for several years the CLIC double-beam technology for generating high accelerating gradients in the range 100 to 200 MV/m, enabling a higher-energy LC to be constructed in a tunnel of length similar to that proposed for a lower-energy LC with a lower accelerating gradient [5]. Preliminary geological studies indicate that a tunnel up to about 35 Km long could be accommodated in good rock between the Jura mountains and Lake Geneva, in the immediate neighbourhood of the present CERN site [3]. This would be sufficient to accommodate a CLIC machine with centre-of-mass energy up to 3 or 5 TeV. CLIC would be able to provide polarized beams, which are useful for several physics topics such as sparticle studies and searches for extra dimensions (see the second numbers in the last two columns of the sixth row of the Table), and would also have options for $e\gamma$ and $\gamma\gamma$ collisions, which have better reaches for some physics topics.

We see in the Table that CLIC with $E_{cm} = 3$ to 5 TeV has an impressive physics reach for all the physics topics studied [20, 10], with many capabilities beyond those of the LHC and a first-generation LC. Moreover, we see in the Figure that CLIC would be able to complete much of the sparticle spectroscopy opened up by the LHC, going significantly beyond the reach of a lower-energy LC. As an example, CLIC may be the first machine able to disentangle the different squark flavours and complete the spectra in most of our simplified benchmark models if it attains $E_{cm} = 5$ TeV. We think it is important not to lose sight of this ultimate goal for CLIC. CLIC also has excellent potential for many of the other physics topics in the Table, such as extra dimensions, strong WW scattering, measuring the TGC, and lepton compositeness. For example, CLIC would enable multi-TeV Kaluza-Klein resonances in extra dimension scenarios to be studied in great detail.

The experimental environment at CLIC offers several challenges, as compared to a lower-energy LC. For example, the colliding beams are expected to radiate energetic photons much more strongly, reducing and smearing the nominal centre-of-mass energy, and leading to an imbalance in the visible momentum in the final state. Also, photon-photon collisions are expected to be relatively more copious than at a lower-energy LC, and large incoherent creation of electron-positron pairs is also expected. Dealing with these problems requires close collaboration on the machine-detector interface, which has already started within the CLIC physics study group.

Initial analyses do not reveal any showstopping problems created by the relatively large

beam energy spread inherent to CLIC at high energy and luminosity. For example, direct studies of a heavy Z' boson analogous to the known Z would be very easy at CLIC, enabling many of its properties to be measured with per mille precision [21]. Studies have also been made of the production of pairs of supersymmetric particles [22]. Their missing-energy signatures would be quite distinctive, and the thresholds for their production could also be measured easily. In addition to discovering and measuring precisely new supersymmetric particles, CLIC would also be able to distinguish and measure more precisely sparticles discovered at the LHC.

There are several ways in which the extra information provided by CLIC could prove to be essential. A few examples are:

- The LHC discovers supersymmetry and measures the masses of a few supersymmetric particles, with the first-generation LC perhaps finding and measuring some more. As previously mentioned, in the simplified benchmark supersymmetric models we have studied, CLIC would complete the supersymmetric spectrum and enable detailed measurements to be made. Thus it might cast light on the mechanism of supersymmetry breaking, which might be a window into string physics.
- The LHC finds evidence for large extra dimensions. In this case, the combination of data at different CLIC energies will enable the number and size of the extra dimensions to be determined independently. The LHC finds evidence for quark compositeness. In this case, CLIC could reveal lepton compositeness, completing the revelation of a new layer of fundamental structure. It might well also be that excited leptons would appear at CLIC even if excited quarks have not appeared at the LHC, if CLIC attains 5 TeV.
- The Higgs boson weighs 115 GeV, as suggested by LEP, but the LHC finds no supersymmetry or evidence for quark compositeness. CLIC would be able to measure the Higgs self-coupling with better than 10% precision, enabling the effective potential to be mapped, would observe any charged Higgs bosons weighing up to 2 TeV or so, and would provide new opportunities to observe the heavier neutral Higgs bosons in supersymmetric models. Moreover, we see from the Table that CLIC is best placed to find compositeness over essentially all the energy range up to about 10^5 to 10^6 GeV, where new physics must appear if the Higgs boson weighs 115 GeV.
- The LHC finds a hint of strong WW scattering, in which case CLIC could study it with high statistics and precision [23].

3.4 Muon Storage Rings and Colliders

Another possible option for CERN's future is to develop a complex of muon storage rings. The first component would be a high-intensity proton driver, for example a superconducting proton linac (SPL) that would reuse LEP radiofrequency cavities [24]. This could also make possible interesting upgrades for other CERN facilities, ranging from ISOLDE to the CERN-Gran Sasso

neutrino beam and the LHC. The SPL would also offer interesting possibilities in short-baseline neutrino physics and studies with stopped muons.

The next steps in a programme of physics with muons would be to capture them, cool them, and accelerate them in recirculating linacs. The first physics option offered would be simply to store the energetic muons, allowing them to decay producing intense and well-understood beams of electron and muon neutrinos – a neutrino factory [6, 7, 25]. This would offer interesting physics opportunities in the search for long-baseline oscillations between electron and muon neutrinos and matter effects on neutrino oscillations. The most exciting opportunity may be the search for CP violation [25]. A neutrino factory would be the logical next step after the current generation of long-baseline neutrino experiments, and might provide a unique window on grand unification via the lepton sector.

If the technique of muon cooling could be refined, the next options might be to collide muons in one or more Higgs factories, exploiting the direct-channel $\mu^+\mu^- \rightarrow H$ production mechanism. Such a MC would be a unique machine for measuring the Higgs line shape, as LEP did for the Z . It would also offer ideal opportunities to study CP violation in the Higgs sector, as expected in some supersymmetric models. In the longer run, one could also envisage building a high-energy MC, which would probably be limited to $E_{cm} < 4$ TeV by the neutrino radiation hazard. Its physics reach would be equivalent to that of CLIC for the same E_{cm} and luminosity, and the smaller beam-energy spread and better energy calibration would confer some advantages on a MC, though the absence of $\mu\gamma$ and $\gamma\gamma$ collisions might be a handicap. There are some physics scenarios in which colliding muons may be preferable to colliding electrons, for example in Higgs physics or in certain supersymmetric models that violate R parity. On the other hand, muon decays will provide important challenges to detector builders, and large controlled beam polarization will not be available, unlike at CLIC.

Since there are many technical hurdles on the route to a MC, which surely has a longer development time-scale than CLIC, we do not discuss it further, except to comment that a muon storage ring complex, including a high-energy MC, could fit comfortably within the area of the existing CERN accelerators.

4 Summary

We have discussed briefly possible future high-energy accelerator options for CERN, and note the following preliminary impressions.

- (a) The SLHC presents interesting possibilities that may provide good physics return for the relatively modest capital investment required to upgrade the LHC luminosity and the LHC detectors.
- (b) CLIC provides excellent long-term perspectives within all the speculative scenarios for physics beyond the Standard Model that we have considered, and is therefore a very attractive option for CERN's long-term future beyond the LHC. CLIC would complement

and go beyond the LHC, being an ideal machine to study heavy new weakly-interacting particles, and could fit comfortably in the neighbourhood of the CERN site.

- c) A neutrino factory based on a muon storage ring would provide an exciting and complementary scientific programme, probing grand unified theories, but a high-energy muon collider is not a prospect for the near future.
- d) A decision on the construction of a VLHC, which is unlikely to fit in the neighbourhood of the CERN site, could only be taken after a few years of LHC running at the design luminosity. Should the LHC data give indications that the next energy scale, e.g., that of supersymmetry breaking, compositeness or extra dimensions, lies around 50 TeV or below, then a VLHC would be the ideal machine to produce directly the corresponding new particles and probe their interactions.

In conclusion, we comment that many open questions will be answered by the LHC, and possibly other experiments, before the decision about CERN's following high-energy accelerator needs to be finalized. The LHC will certainly provide many clues to the 'Theory of Everything', but further accelerator experiments will be needed to identify it. Quite possibly, some completely new phenomenon will be discovered at the LHC that will be more exciting than any of the theoretical speculations discussed here. This brief survey has indicated that there are already many strong options for new CERN accelerators beyond the LHC, suitable for addressing the questions it will leave open.

CERN has, in the LHC, a forefront project that will establish its leadership in high-energy physics. The organization should have similar ambition for its projects after the LHC.

Acknowledgements

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