Theoretical Introduction to Physics with Linear Colliders

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The major open questions in particle physics are summarized, as are the abilities of linear colliders of different energies to add to the knowledge obtainable from the LHC in various scenarios for physics beyond the Standard Model. A TeV linear collider would provide much additional insight into electroweak symmetry breaking, in particular, and a multi-TeV linear collider would add even more value in all the scenarios studied, for example in models with supersymmetry or extra dimensions.

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1 Open Questions beyond the Standard Model

The primary justification for any new accelerator must be its capability to explore and understand new physics beyond the Standard Model. Motivating the searches for such new physics, there is a long list of fundamental questions raised but left unanswered by the Standard Model, including: What is the origin of particle masses? Are they due to a Higgs boson, and is this accompanied by other new physics? Why are there so many different types of matter particles? Are the fundamental forces unified? What is the true quantum theory of gravity? There are plenty of topics where LCs of different energies can contribute!

2 The Physics Case for a LC

The LHC will make the first exploration of the TeV energy range, and is confidently expected to discover the Higgs boson, if it exists. It is also likely to provide some evidence of whatever replaces it, if the Higgs boson does not exist. The LHC has also been shown to have excellent capabilities to search for other new physics that might accompany a Higgs boson around the TeV
scale, such as supersymmetry and/or extra dimensions.

Many studies have also shown that a LC can add significant value to this initial exploration of the TeV scale, notably in detailed studies of the Higgs boson, assuming it is light enough, and of any accessible new physics appearing at the electroweak scale, such as supersymmetry. A LC could also provide important and distinctive indirect tests of unification ideas, and also explore physics in extra dimensions, if they open up at a low enough energy scale.

These are strong arguments, which need to be developed at several different levels. Beyond the community assembled here, are they strong enough to convince the world-wide particle-physics community that it should unite around a consensus that the next major global project after the LHC should be a LC? And are they strong enough to convince circles in the world outside particle physics, notably other physicists, other scientists, funding agencies and politicians?

They may be easier to persuade once (if) the Higgs boson is discovered. The Higgs mass probability distribution obtained by combining direct and indirect information suggests that the Higgs boson may lie quite close to the present experimental lower limit of 114.4 GeV, with a 95% confidence-level upper limit in the Standard Model of about 260 GeV. Unfortunately, LEP was not able to discover the Higgs boson, and the hint found at the end of 2000 has finally diminished to below two standard deviations. CDF and D0 may be able to find some evidence before the start-up of the LHC, but the LHC should be able to make a 5-σ discovery with 10 fb$^{-1}$ of data, which should be obtainable in 2008.

3 Theorists are Getting Cold Feet

With make-or-break time for discovery of the Higgs boson at the LHC looming closer on the horizon - and supersymmetry, if it exists at the electroweak scale - at least some theorists are getting cold feet, exploring various avenues for avoiding a light Higgs boson and/or supersymmetry.

Some used to question whether the Higgs boson might be composite, but this possibility seems to be inconsistent with precision electroweak data, and is not discussed further here. However, questions have been raised about the interpretation of the electroweak data: are the different measurements consistent, or should some be discarded? If so, what would happen to the upper
Figure 1: (a) If the Standard Model Higgs boson weighs around 200 GeV, the top-quark loop contribution to its physical mass (calculated here with a loop momentum cutoff of 10 TeV) must cancel delicately against the tree-level contribution. (b) In ‘Little Higgs’ models, the top-quark loop is cancelled by loops containing a heavier charge-2/3 quark.

limit on $m_h$ and would there be other signatures of new physics? Even if one accepts the electroweak data at face value, is the renormalizable Lagrangian of the Standard Model adequate for describing them, or should one supplement the Lagrangian with higher-dimensional operators? If one includes such higher-dimensional operators, are credible corridors to higher Higgs masses opened up? Even if this is not the case, and the Higgs is relatively light, is supersymmetry the only mechanism for avoiding the fine-tuning problem? New alternatives are provided by ‘Little Higgs’ models, in which there are one-loop cancellations with an extra top-like quark, gauge bosons and additional Higgs fields. Finally, is it really established that a Higgs boson must exist? This question has been asked again within a new wave of Higgsless models, which must deal with strong $WW$ scattering and the ensuing implications for precision electroweak observables.

We now discuss some more aspects of these scenarios for avoiding the conventional light Higgs/supersymmetry scenario.

### 3.1 Heretical Interpretations of the Electroweak Data

It is notorious that the two most precise measurements at the $Z$ peak, namely the asymmetries measured with leptons and hadrons favour different values of $m_h$, around 50 and 400 GeV, respectively. Perhaps this discrepancy is just a
statistical fluctuation, or perhaps we do not understand hadronic systematics as well as we think\textsuperscript{8}? Another anomaly is exhibited by the NuTeV data on deep-inelastic $\nu - N$ scattering\textsuperscript{12}, which may be easier to explain away as due to our lack of understanding of hadronic effects. On the other hand, if either the lepton/hadron discrepancy or the $\nu - N$ anomaly is genuine, there may be new physics at the electroweak scale. In this case there would be no firm basis for the prediction of a light Higgs boson, which is based on a Standard Model fit\textsuperscript{8}. Unfortunately, it is unclear how the $Z$ peak discrepancy could be cleared up soon, whereas NOMAD may soon cast some light on the NuTeV anomaly.

3.2 Higher-Order Operators

If one regards the Standard Model simply as an effective low-energy theory, one should expect the renormalizable dimension-four interactions it contains to be supplemented by higher-dimensional operators of the general form\textsuperscript{9}:

$$L_{\text{eff}} = L_{\text{SM}} + \sum_i \frac{c_i}{\Lambda_i^{p_i}} O_{4+p_i}^{i}.$$  

A global fit to the precision electroweak data suggests that, if the Higgs is indeed light, the coefficients of these additional interactions are small: $\Lambda_i \sim 10$ TeV for $c_i = \pm 1$. The 'little hierarchy' problem is to understand why this should be the case\textsuperscript{11}.

However, conspiracies are in principle possible, enabling $m_H$ to be large, even if one takes the precision electroweak data at face value. Examples are shown in Fig. 2, where one sees corridors of the allowed parameter space extending up to a heavy Higgs mass\textsuperscript{9}. Any theory beyond the Standard Model must link the value of $m_H$ and the coefficients of these higher-dimensional effective operators in some way. A theory that predicts a heavy Higgs boson but remains consistent with the precision electroweak data should predict a correlation of the type seen in Fig. 2. At the moment, this may seem unnatural to us, but Nature may know better.

For the moment, we should not discard the possibility of a heavy Higgs boson. However, Fig. 2 suggests that, if this is the case, there would be observable effects due to higher-dimensional effective operators that could be measured at a LC\textsuperscript{2}.
Figure 2: If suitable non-renormalizable operators $O_{WB}$ or $O_H$ are included in the global electroweak fit with $c_i = -1$, corridors of parameter space leading to a large mass for the Higgs boson may be opened up.

3.3 Little Higgs Models

These models invoke a different mechanism for enforcing the loop cancellations needed to keep a light Higgs boson light. The strategy is to embed the Standard Model in a larger gauge group which is then broken spontaneously down to the Standard Model\(^5\). The Higgs boson appears as a pseudo-Goldstone boson, which guarantees that it is light before the loop effects kick in. Generally, the top-quark loop contribution to the Higgs mass-squared has the general form

$$\delta m_{H,\text{top}}^2(SM) \sim (115 \, \text{GeV})^2 \left( \frac{\Lambda}{400 \, \text{GeV}} \right)^2$$

As illustrated in Fig. 1, in Little Higgs models this is cancelled by the loop contribution due to a new heavy top-like quark $T$, leaving

$$\delta m_{H,\text{top}}^2(LH) \sim \frac{6G_Fm_T^2}{\sqrt{2\pi}} m_T^2 \log \frac{\Lambda}{m_T}.$$ 

Analogously, to cancel the loop divergences associated with the gauge bosons and the Higgs boson of the Standard Model, Little Higgs models contain new gauge bosons and Higgs bosons.
The net result is a spectrum containing a relatively light Higgs boson and other new particles that may be somewhat heavier:

\[ M_T < 2\text{TeV} \left( \frac{m_h}{200 \text{ GeV}} \right)^2, \quad M_W' < 6\text{TeV} \left( \frac{m_h}{200 \text{ GeV}} \right)^2, \quad M_{H^{++}} < 10\text{TeV}. \]  

(1)

In addition, there should be more physics at some energy scale above 10 TeV, for the ultra-violet completion of the theory. Some of these new particles should be accessible to the LHC\textsuperscript{13} and, if the new particles predicted in such models are within the reach for direct production at a LC, it will be able to explore them in detail. Even if not, a LC can probe such a model via careful studies of its light Higgs boson, e.g., by measuring accurately its decays into $\gamma\gamma$ and gluon pairs\textsuperscript{14}, as seen in Fig. 3.

Figure 3: The rates for Higgs decays into $\gamma\gamma$ and gluon pairs are sensitive to the scale $f$ in little Higgs models, enabling precision measurements at a LC to distinguish them from a Standard Model Higgs boson at the same mass\textsuperscript{14}.

3.4 Higgsless Models

The most radical alternative to the Higgs sector in the Standard Model is offered by Higgsless models, which were originally formulated in the conventional four dimensions\textsuperscript{10}. Inverting the usual argument that $WW$ scattering would violate unitarity if there were no Higgs boson, one would expect such Higgsless models to exhibit strong $WW$ scattering at the TeV scale. This is likely, a priori, to be incompatible with the precision data. The second wave of Higgsless
models addressed this problem by adding an extra dimension, and postulating boundary conditions that break the electroweak symmetry. These extra-dimensional variants are able to delay the onset of strong $WW$ scattering to about 10 TeV, and the simplest variants exhibit a forest of Kaluza-Klein excitations with masses starting above 300 GeV. However, compatibility with the precision electroweak data is still an issue for such models, motivating epicyclic variants with a warped extra dimension and special brane kinetic terms.

Clearly, if the lightest Kaluza-Klein modes do have masses around 300 GeV, they would provide directly a cornucopia for a LC. Additionally, the sort of massive resonance predicted in models with strong $WW$ scattering might be detectable indirectly at a LC.

4 Measuring the Properties of a Light Higgs Boson

The capabilities of a sub-TeV LC for precision measurements of the branching ratios for a light Higgs boson into modes such as $\bar{b}b, \tau\tau, gg, \bar{c}c, WW$ and $\gamma\gamma$ are well documented, and some new studies have recently become available. For example, the capabilities of the LHC and a LC for measuring the top-Higgs coupling have recently been evaluated in the context of the joint LHC/LC study. It has also been realized recently that a higher-energy LC has certain advantages for precision measurements, even of a light Higgs boson, due mainly to the much larger cross sections for Higgs production at multi-TeV energies. For example, one can measure accurately rare decay modes, such as $H \rightarrow \mu\mu$ for $m_H = 120$ GeV and $H \rightarrow \bar{b}b$ for $m_H = 180$ GeV. Another topic where a higher-energy LC has an advantage is in measuring the Higgs self-couplings. It is well known that the trilinear Higgs coupling of a light Higgs boson can be measured at a low-energy LC, and it has recently been shown that this might be possible for a heavier Higgs boson at the luminosity upgrade of the LHC, the SLHC. A study has also been made of the measurement of the effective Higgs potential using a 3-TeV LC. This would have a much larger cross section for $HH$ pair production than a sub-TeV LC, enabling the accuracy in the measurement of the HHH coupling to be improved for all masses between 120 and 240 GeV, as seen in Fig. 4(a).

Strong $WW$ scattering may be parameterized by effective higher-order gauge-boson couplings that appear at the quartic level. These can be measured in $WW, WZ$ and $ZZ$ final states at the LHC, and (more accurately)
in $WW$ and $ZZ$ final states at a LC. Going beyond the effective ‘low-energy’ interactions, one or more $WW$ resonances may appear. The first hint of a $WW$ resonance may be given by form-factor measurements, and a 500-GeV LC would be able to probe the existence of a $\rho$-like resonance far beyond its direct energy reach. The parameters of such a resonance might be measured first at the LHC, but they could be measured more precisely at a 500-GeV LC, as seen in Fig. 4(b)\textsuperscript{14}.

Such a $WW$ resonance might be observable directly for the first time at a multi-TeV LC. The channel $ee \rightarrow Hee$ could be used to establish its existence beyond any doubt if it weighs $< 1$ TeV, as seen in Fig. 5(a), and one could find a resonance in strong $WW$ scattering via the $e^+e^- \rightarrow H\nu\bar{\nu}$ channel even if it weighs $> 1$ TeV, as seen in Fig. 5(b)\textsuperscript{17}.

5 Other New Physics at the Electroweak Scale

If the Higgs boson is light, and in particular if it is very close to the direct search limit, the effective Higgs potential is in danger of being destabilized by the loop corrections due to the top quark. These tend to turn the effective...
Higgs potential negative far below the Planck scale, and the loop corrections due to a light Higgs boson would be insufficient to counteract them. These should be supplemented by new physics appearing at a relatively low energy scale, for which the best candidate may be supersymmetry. This argument is independent of the primary motivation for expecting supersymmetry at accessible energies below about a TeV, namely the hierarchy problem. Other reasons for liking supersymmetry include the fact that it enables the gauge couplings to unify (though there are other ad hoc fixes for this), the prediction of a low Higgs mass, and a natural candidate for the cold dark matter advocated by astrophysicists and cosmologists.

To my mind, none of the alternatives currently available on the market – extra dimensions, little Higgs models, Higgsless models, etc.– are as satisfactory as supersymmetry. This is not to say that supersymmetry is completely satisfactory itself - for example, the mechanism and scale of supersymmetry breaking are obscure and supersymmetry does not, by itself, explain the magnitude of the electroweak scale, it merely stabilizes it. However, supersymmetry often appears as a component in these alternative scenarios, for example to stabilize the scales of extra dimensions.
6 Studies of Supersymmetry

The minimal supersymmetric extension of the Standard Model (MSSM) contains over 100 parameters, mostly in the parameters that break supersymmetry via masses $m_0$ for the spin-0 supersymmetric partners of the Standard Model fermions, masses $m_{1/2}$ for the spin-1/2 supersymmetric partners of the Standard Model bosons and trilinear soft supersymmetry-breaking parameters $A$. In order to visualize the parameter space, one often makes simplifying assumptions about these parameters, and it is popular to assume that the parameters $m_0, m_{1/2}$ and $A$ are universal for the different sparticle types, in the so-called constrained MSSM (CMSSM).

The regions of CMSSM parameter space allowed by the accelerator and dark matter constraints, particularly in the latest version after the WMAP data, are typically narrow lines, as seen in Fig. 6(a)\textsuperscript{21,22}. One may then study the capabilities of different accelerators to make measurements as one varies the CMSSM parameters along one of these WMAP lines, as exemplified in Fig. 6(b), or one may choose to study in more detail benchmark points located at specific places along these lines, as indicated in Fig. 6(a). Fig. 6(b) displays the numbers of different sparticle species that would be detectable at the LHC and/or a 1-TeV LC as one varies parameters along the WMAP line for $\tan \beta = 10$ and $\mu > 0$\textsuperscript{21}. The LHC measurements would enable one to calculate the relic LSP density and check whether it falls within the WMAP range. Fig. 7(a) shows the result of one such calculation based on realistic errors in such LHC measurements, assuming the parameters of one specific benchmark point\textsuperscript{21}. The error is already comparable with the WMAP uncertainty, and could be refined significantly with the aid of LC measurements\textsuperscript{23}.

Fig. 7(b) compares the numbers of different sparticle species that could be detected at the LHC and linear colliders of different energies\textsuperscript{7,21}. We see that the LHC and LC have complementary capabilities, in that the LC can observe many types of weakly-interacting sparticle that would be invisible at the LHC - as long as the LC centre-of-mass energy is above its production threshold. In many cases, several sparticles would be seen at a 500-GeV LC, more would be seen at a 1000-GeV LC, and others would require an even higher centre-of-mass energy. High-precision sparticle measurements could be made via the positions of edges in dilepton spectra at the LHC, followed by threshold measurements and final-state lepton spectra at a LC. In this and other examples, the LC measurements would provide considerable added value for the determination of sparticle masses and the underlying CMSSM parameters\textsuperscript{14}, making possible
Figure 6: (a) The strips of CMSSM parameter space allowed by WMAP and other constraints for $\mu > 0$ and different choices of $\tan \beta$, with candidate benchmark points indicated, and (b) the numbers of types of supersymmetric particles detectable along the WMAP strip for $\tan \beta = 10$, combining the LHC and a 1-TeV LC.

crucial tests of our ideas about grand unification of sparticle masses as well as gauge couplings.

Our present theoretical ignorance means that we do not know the scale of supersymmetry breaking, and therefore does not yet permit us to fix the scale at which a LC could be certain of observing any supersymmetric particles. Fig. 8 displays a set of scatter plots of the masses of the lightest visible and next-to-lightest visible supersymmetric particles (LVSP and NVSP, respectively) that could be detected directly at a future LC, if $E_{CM} > 2m_{LVSP,NVSP}$. For comparison, the green points are accessible to the LHC, the blue points provide a suitable density of cold dark matter, and the yellow points are those where this dark matter might be detectable directly in scattering experiments. Arguments about the fine-tuning of the electroweak scale (and the magnitude of the relic dark matter LSP density) suggest that sparticles might be more ‘likely’ to appear near the lower ends of one of the ranges shown, but we cannot be sure how much fine-tuning is too much.

Panel (a) of Fig. 8 is for the CMSSM, whereas panel (b) relaxes universality for the masses-squared of the Higgs bosons and panel (c) allows all the scalar masses-squared to vary, requiring only that they remain positive when renormalized up to the GUT scale. These panels all assume the gravitino to
be sufficiently heavy that the LSP is the lightest neutralino, whereas panel (d) fixes $m_{3/2} = m_0$, in which case the LSP may be the gravitino and the next-to-lightest supersymmetric particle might be a neutralino or stau in some regions.

The general conclusion is that a sub-Tev LC would cover only portions of the allowed supersymmetric parameter spaces (though these portions might be favoured by fine-tuning arguments), whereas a 3-TeV LC would cover most of the allowed parameter spaces.

Returning to the CMSSM, Fig. 7(b) also displays the numbers of different species of supersymmetric particles that could be seen at a 3- or 5-TeV LC. Such a machine would stand a chance of observing ‘all’ the sparticles, and would also be able measure in detail the heavier sparticles – such as squarks and the heavier gauginos and Higgsinos – better than the LHC. Studies of heavy slepton production have confirmed that one could, for example, measure the smuon decay spectrum and infer the smuon and LSP mass (to ±2.5% and 3%, respectively), despite the greater amount of beamstrahlung inevitable at such a higher-energy LC. With such measurements, one could extend to higher masses the game of checking GUT and superstring predictions for the unification of sparticle masses.
Figure 8: Scatter plots of the masses of the lightest visible supersymmetric particle (LVSP) and next-to-lightest visible supersymmetric particle (NVSP) in (a) the CMSSM, (b) a model with non-universal Higgs scalar masses, (c) general scalar masses - all assuming a neutralino LSP - and (d) the CMSSM with $m_{3/2} = m_0$, in which case the LSP may be the gravitino.

One may safely conclude that any LC above the sparticle threshold would be very interesting, and that a multi-TeV LC would have considerable added value in many supersymmetric scenarios, even assuming the prior construction of a sub-TeV LC.

7 Extra Dimensions

If Nature is not wise enough to choose supersymmetry, what alternatives might she choose? Extra dimensions were first suggested by Kaluza and Klein in scenarios for the unification of gravity and electromagnetism. More recently, it
has been realized that they are required for the consistency of string theory, and it was observed that they could help unify the strong, weak and electromagnetic forces with gravity if at least one of the extra dimensions is somewhat larger than the Planck length. Larger extra dimensions, around an inverse TeV, could be the origin of supersymmetry breaking, and even larger extra dimensions have been postulated in attempts to reformulate the mass hierarchy problem.

Extra dimensions could be wrapped around in an $S_1$ geometry, as postulated by Kaluza and Klein (KK), or they could be warped, as postulated by Randall and Sundrum (RS). Such models may predict a very rich electron-positron annihilation spectrum due to RS recurrences. One of the most interesting possibilities is that there are universal extra dimensions. In this case, as seen in Fig. 9, the KK spectrum would look disconcertingly similar to a supersymmetric spectrum, except that the spins of its KK recurrences would differ from those of supersymmetric partners of the Standard Model particles. A sufficiently energetic LC would be ideally placed to measure their spins, which would be more challenging at the LHC. In such a scenario with universal extra dimensions, the lightest KK particle would be stable, and a possible candidate for the astrophysical dark matter.

Figure 9: The spectrum of Kaluza-Klein recurrences possible in a model with universal extra dimensions. There are qualitative resemblances to a supersymmetric spectrum, whose states have different spins.
8 Summary

As discussed above, there are (still) many good reasons to expect new physics in the TeV range. However, we shall not know what form this new physics takes, and what is its energy scale, before the LHC starts providing results. As emphasized repeatedly, LCs above thresholds for new physics will provide tremendous added value. At least until we know (presumably from the LHC) where the threshold(s) for new physics may be, it is surely advisable to maintain flexibility in the maximum energy which such LCs could reach.

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