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THE NEED FOR THE NEXT LINEAR COLLIDER*

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ABSTRACT

The need for the next generation electron-positron collider is discussed within the context of the Standard Model and the physics that must lie beyond it.

INTRODUCTION

High energy physics is beset by the problem of too much success. The Standard Model of strong and electroweak interactions between quark and lepton constituents of matter is in excellent agreement with experiment up to the highest explored energies and at the highest precision.

Along with the Standard Model comes 18 or so parameters (masses, couplings, mixing angles) which are not fixed *a priori* by present theory. The known quarks and leptons seem to know about each other, as they can be neatly grouped into three generations or families. Why are there generations? Why are there three of them? How are the 18 parameters fixed or at least related to each other? Are the quarks and leptons composed of common constituents? Are they grouped together by some larger symmetry? To these and many other questions we can only answer: We don't know. It is paradoxical that with all the success of the Standard Model comes its main problem: It can't be the whole story, but its very success means that we have precious little evidence on what larger theory encompasses it.

THE FRONTIER

With this background, where do we go? What is the frontier?

- We need to pin down the parameters of the Standard Model. This is not necessarily just a process of making things neat and tidy, for we might find with all the parameters known precisely that even some presently known phenomenon, like CP violation, would not agree with Standard Model expectations. The exquisite experiments in progress or planned on rare and/or CP-violating K and B decays are prime examples of this work.

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- We need to check the Standard Model up to quantum corrections. With the mass of the Z known with high precision, the parameters associated with the electroweak gauge boson part of the Standard Model are fixed to a sufficient degree that one can now compare with M_W or with coupling strengths, e.g., using the polarization asymmetry at the SLC, and check the quantum corrections that enter in graphical terms at one-loop order. Depending on how one views it, this is either a check on the consistency and correctness of the theory or a telescope to get a first glimpse of particles at still higher mass which affect the results through their presence as virtual states at one-loop.
- We need to find the top quark. It already appears that its mass is greater -than about M_W. It could well be out of the range of LEP II. Then, of present or near-term accelerators, only the Tevatron collider has a chance of finding it. Here is a place where the next linear collider could play a key role. While top might be discovered at the Tevatron and produced in abundance (or even discovered?) at the SSC, detailed studies of the properties and decays of a very heavy top quark are likely the province of an electron-positron machine. One is in a regime of masses where Quantum Chromodynamics (QCD) is truly capable of perturbative application, and incisive tests of the theory of strong interactions become possible as well in the top-antitop system produced (near threshold and in a well-defined state) in e^+e^- annihilation.
- We need to search for extensions and additions to the Standard Model in the "modest" form, for example, of new quarks and new leptons, but also in the dramatic form of whole new classes of particles such as occur in theories with supersymmetry. Such searches have turned up nothing up to now; the torch will be passed to the next generation of electron-positron and hadron colliders.
- We need to check on the gauge structure of the electroweak theory. This entails especially checking the correctness of the $W^+W^-Z^0$ triple gauge boson vertex. This can be done especially cleanly at an e^+e^- collider, and will be a prime focus of LEP II. Further, more sensitive probes of the $W^+W^-Z^0$ and $W^+W^-\gamma$ vertices await the still higher energies available at the next linear collider.

However, barring total surprises, the prime task facing high energy physicists over the next decade or so is that of uncovering the nature of electroweak symmetry breaking, the mechanism by which mass is given to the IV and Z, as well as quarks and leptons.

The massless gauge theory is beautiful and well behaved. At first glance, it appears that masses can be inserted in the crudest way by simply writing mass terms into the Lagrangian. However, with such a "hard" mass term the theory becomes sick-infinities arise and cross sections become divergent at high energy. A particularly salient example is provided by considering the scattering of two W bosons with longitudinal polarization, i.e., $W_L W_L \rightarrow W_L W_L$. This sounds like a theorist's gedanken experiment at best; it is not. In electron-positron or hadron–hadron collisions the leptons or quarks (in the hadrons) can emit (virtual) W's, which then collide with each other. Such would be the case at a linear collider operating in the TeV range. Calculations of this process with just gauge bosons alone gives answers that blow up as $E \rightarrow \infty$.

The Standard Model solves this by a "soft" mechanism for giving masses to particles. In picturesque terms, the originally massless W and Z bosons of the weak interactions "eat" spinless bosons put in the theory to be available for just this purpose, and acquire mass. In addition to the three (2 charged and 1 neutral) spinless bosons which disappear into the stomachs of the $W^{\pm}$ and Z, a fourth, neutral, spinless boson is left behind as a physical particle and witness to what has happened; this is the Higgs boson. With this particle present cross sections no longer blow up, the worst infinities disappear, and the theory is altogether much better behaved.

There are many variants on the same basic theme of breaking electroweak symmetry — "soft" ways of introducing mass into the theory so as to keep it well behaved. There could be many Higgs particles, composite Higgs bosons, technicolor theories, or even no extra particle(s) at all, and the nature of the symmetry breaking found in W's and Z's undergoing strong interactions at high energies, with a rich dynamics at energies in the TeV region.

Where is the Higgs, or more generally at what mass scale does the electroweak symmetry breaking mechanism become manifest physically? The Higgs boson could in principle be found at masses anywhere from a few GeV up to of order a few TeV. We cannot presently pinpoint the scale of symmetry breaking better than to say that very, very roughly, one expects it to be of the order of the W and Z boson masses or a few times that, i.e., several hundred GeV.

This can be studied in electron-positron collisions in a number of ways. Most important, there is the process already noted above:

$$e^+ e^- \rightarrow \bar{\nu}\nu \, W^+ W^- \, ,$$

with the W^+ and W^- scattering off each other. The prime issue is the nature of the interaction of the longitudinal bosons. In the simplest case, if a resonance (Higgs or other) is present, it will form a bump in the WW cross section. More generally, one wants to study this scattering process up to energies of a few TeV, if necessary, to be sure of being able to understand the nature of electroweak symmetry breaking. To do this will require pushing the frontier of accelerator physics and detector capabilities at both hadron–hadron colliders such as the SSC and at the next electron-positron linear collider