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Aspects of e^+e^- Physics at 1 TeV*

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ABSTRACT

A summary of several recent studies of electroweak e^+e^- physics is provided. The significance of upcoming SLC/LEP measurements of Z and W properties is discussed, with special emphasis placed on radiative corrections and polarization. New electroweak physics at a proposed TeV e^+e^- collider is presented as a natural outgrowth of the SLC/LEP programs. Precise tests of the trilinear gauge boson vertex through W pair production, searching for the disturbance of perturbative unitarity by radiative corrections, and of the gauge structure of a Z', through polarized e^- beams, are presented.

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1. ELECTROWEAK PHYSICS WITH e^+e^- COLLIDERS [1,2,3]

The technique of electron-positron annihilation has acquired a special significance over the past two decades in the study of electroweak physics. The electroweak interactions enjoy the property of being perturbative and thus, in principle, calculable to arbitrary accuracy. e^+e^- collisions (as well as lepton-hadron scattering) are tailor-made for detailed, precision tests of electroweak phenomena. They are "clean," with a well-understood initial state and computable backgrounds, producing both standard and "exotic" final states democratically. The use of polarized electron beams enhances the allure of e^+e^- colliders further, extending our understanding of the parity-violating weak interactions considerably.

The state of the art of e^+e^- annihilation will soon be provided by the new colliders at SLAC (SLC) and at CERN (LEP) [1]. Both of these machines will begin their careers with detailed studies of the Z neutral-current resonance, measuring the Z mass and width. Polarization at the SLC and at LEP will allow measurement of the Z couplings to fermions to unprecedented accuracy [4]. The charged-current W mass will be measured with W pair production at LEP2.

Although the SLC/LEP physics programs will greatly extend our understanding of the *gauge* interactions of the standard model, they will probably at best shed only indirect light on the profound mystery of the standard model, the *Higgs* sector, the source of electroweak symmetry breaking and presumably thus of the masses of all known particles [5]. Although such a sector appears absolutely necessary, little is known about it. Furthermore, the standard Higgs mechanism suffers from the well-known gauge hierarchy problem and the apparent unnaturalness of fundamental scalars. A variety of new physics has been proposed to replace, explain, or at least stabilize the scalar Higgs: supersymmetry, technicolor, composite models, extended Higgs sectors, and so on. Colliders with much higher interaction energies than currently available are necessary to explore the Higgs question thoroughly. An e^+e^- linear collider with a TeV center-of-mass energy (TLC) would be an ideal machine for such explorations, as the advantages of e^+e^- collisions outlined above become all the more important in uncharted regions. The major challenge facing such a project is achieving the necessary beam luminosity and event rates for worthwhile physics. A SLAC study group has worked over the past several years on this idea, exploring its theoretical, experimental and machine design aspects. Its basic work was summarized in the 1987 SLAC Summer School lectures, *Looking Beyond the Z*, and in the group's final report, issued this year [2,3]. Research on the TeV e^+e^- collider continues unabated.

The precise determination of the W mass and of the fermion-Z couplings [through the polarization asymmetry, $A_{LR}(Z)$], however, will already place important constraints on this new TeV physics, through the effect of radiative corrections. As shown by Appelquist and Carazzone, in an unbroken gauge theory, the effects of heavy particles in radiative corrections decouple at energies below the masses of those particles [6]. Nevertheless, this result is evaded in a theory with broken symmetries, if the heavy masses in question are connected in some way with the symmetry-breaking [7]. Then the effect of heavy particles in radiative corrections to low-energy processes is not suppressed and may even be enhanced. M_W and $A_{LR}(Z)$ are both directly sensitive to such corrections [8–11]. They can both be predicted, once M_Z is measured, on the basis of known standard model physics. Deviations from these predictions measure the effect of new particles from their radiative corrections. Within the standard model itself, the mass of the top quark and the mass and couplings of the Higgs are unknown, although constrained by direct searches and low-energy measurements sensitive to radiative corrections. The standard electroweak theory contains two general broken global symmetries: the custodial (or isospin) SU(2) symmetry (broken by mass splittings in isomultiplets, such as the W-Z or top-bottom splitting); and the chiral symmetry of the fermions (broken by the non-zero fermion masses). A combination of M_W and $A_{LR}(Z)$ can isolate these two effects in a general way, without further specifying the source of the symmetry-breaking [9–11]. Such knowledge bears directly on the mysterious Higgs sector, however, since all symmetry-breaking in the standard model seems to arise from it; and on the new physics postulated to accompany the Higgs mechanism. New generations of fermions will contribute as well. Physics involving gauge structure beyond the minimal SU(2)×U(1) can also be tested using $A_{LR}(Z)$; for example, searching for the presence of a Z' [12] and testing the predictions of grand unification [13]. The polarization asymmetry is almost completely independent of "hard-to-calculate" final-state effects, such as hadronization, yet exquisitely sensitive to the initial-state electron-Z couplings and the radiative corrections that modify those couplings. Its potential as a precise test electroweak gauge theory is not only far superior to current low-energy measurements (such as neutrino-hadron scattering), but superior as well to alternative SLC/LEP observables, such as the forward-backward asymmetry to muons, which are subject to bremsstrahlung and strong interaction effects or to poor statistics [8,14].

2. HEAVY PARTICLE EFFECTS IN W PAIR PRODUCTION — RADIATIVE CORRECTIONS AND UNITARITY DELAY [15]

Apart from examining the Higgs sector, a TLC can reveal new features of gauge interactions at energies above the masses of the W and Z bosons. A sensitive probe of new physics is provided by W pair production. At tree-level, three diagrams contribute to this process. One is the t channel neutrino exchange, the other the s channel Z and photon graphs. The latter contain the trilinear gauge boson vertex, which will be tested for the first time with W pair production. Even at tree level, this constitutes an important test of the standard model, as this vertex is a purely non-Abelian phenomenon. Loop corrections to this vertex give us qualitatively new information about the standard model unavailable in lower energy four-fermion experiments. Loop corrections are normally hard to see in particle experiments, unless they affect some quantity not sensitive to otherwise larger corrections (such as the polarization asymmetry) or they upset some delicate cancellation. In W pair production, the tree-level gauge symmetry enforces such a cancellation between the s and t channel graphs, ensuring that the W pair cross section obeys unitarity at high energies, well above the pair threshold, and falls like $(E_{\rm cm})^{-2}$. Any substructure affecting the trilinear vertex will destroy this cancellation and the cross section will behave in a non-trivial way as the energy rises. Such would occur, for example, if the W were composite.

Modifications of the couplings can arise from radiative corrections, without invoking anything so radical as a composite W. A new heavy generation of fermions, with a mass M, will upset unitarity if $M_W^2 \ll s \leq 4M^2$, with a term enhanced by s/M_W^2 relative to the tree-level cross section. Such an effect rises quadratically with energy and thus becomes easier to see at a TeV. The broken global chiral symmetry is responsible for this effect, with further enhancements if the fermions have mass splittings from the broken isospin symmetry. The non-unitary W production cross section gives a kind of preview of coming attractions even before we reach the production threshold for the new fermions. Heavy scalars have a similar effect, but not as dramatic, since they do not participate in chiral symmetry breaking. The effect for scalars relies only on isospin breaking. Part of the unitarity delay for either fermions or scalars arises from radiative corrections already present in four-fermion processes, but part is due to the new trilinear vertex. Once $s \geq 4M^2$, perturbative unitarity is restored.

The case of a heavy Higgs must be treated separately from heavy scalars having no vacuum expectation value, as the v.e.v. mixes in with the longitudinal components of the W and Z bosons. A large Higgs mass implies a large Higgs self-interaction and thus an interesting new sector of strong interactions among longitudinal gauge bosons. Work on the case of a heavy Higgs in vertex loop corrections is currently underway and will be presented elsewhere shortly [16].

3. GAUGE STRUCTURE OF A Z' WITH POLARIZED BEAMS [17]

Just as the polarization asymmetry at the Z allowed for precise determination of the fermion-Z couplings, the gauge structure of a Z' can be elucidated using a polarized e^- beam at a TLC. A Z' has a complication of mixing, in general, with the Z. The fermion-Z' couplings will depend on this mixing and thus on the pattern of symmetry-breaking responsible for the gauge boson masses. However, if $M_{Z'} \gg M_Z$, this mixing is suppressed, and the fermion-Z' couplings depend then only on the underlying gauge group alone and not on the symmetry-breaking.

The polarization asymmetry, $A_{LR}(Z')$, depends only on the electron-Z' coupling. One can also form a polarized forward-backward asymmetry, depending only on the final-state couplings, and the production cross section, both to a particular final-state species of fermion. (We consider only conventional final-state fermions, to simplify the problem.) The underlying gauge group imposes relationships among these three measureables. Comparing them can determine the extended electroweak gauge group containing the Z'

In the two cases worked out so far, we assume a fundamental E_6 group, with the fermions in the **27** representation. The two simplest breakings of the E_6 are to $SU(2)_L\times SU(2)_R\times U(1)_{B-L}$ and to $SU(2)_L\times U(1)''\times U(1)'''$. In the first case, the mixing of the electroweak groups with the new $SU(2)_R$ is fixed by the relation $Q = I_{L3} + I_{R3} + (B-L)/2$, where I refers to SU(2) isospin. Then the only free parameter not fixed by low-energy electroweak phenomenology is the right-handed coupling g_R. Any two of the three observables are fixed by a one-parameter relationship. Experimental comparison can then check if two observables fit such a relation, and if so, determine g_R. Another pair of observables then serves as a check on the first pair. In the second case, there are *two* new unknown parameters: the ratio of the U(1) couplings, g'''/g''; and the mixing angle between the two U(1)'s. [U(1) is Abelian, so its normalization is arbitrary.] Then we need *two* pairs to determine if the Z' falls into this group. This is possible, but we no longer have a remaining pair to serve as a check.

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APPENDIX [18,19]

For the purpose of simulating and computing the effect of initial-state radiation at the Z pole, a new Monte Carlo and Monte Carlo technique were developed at SLAC. The Monte Carlo, EXPOSTAR, can compute basic observables at the Z, such as cross sections and asymmetries [18]. The new technique circumvents several basic shortcomings of the traditional "importance sampling" Monte Carlo method [19]. The normal approach is to develop an approximant for an integrand and to sample this approximant. The approximant is usually some irregular shape in the sampling space. A box is usually drawn around this irregular shape that contains its largest dimension. The box is uniformly and randomly sampled and points ("events") not in the approximant space are thrown away ("rejected"). For a resonance, with a sharp, tall peak, this method is clearly inefficient, as most of the generated points will be thrown away. In the new method, one uses a discretized version of the original integrand as an approximant, so that no new function need to be developed. The space of the approximant is then a sliced-up copy of the original integrand ("noodles"). Sampling the approximant space then just involves sampling the noodles. The noodle method is fast and efficient, as no points are rejected. The noodle generator is approximately five to ten times faster than comparable name-brand Z Monte Carlos, such as BREMMUS. The general noodle method can be applied to any integrand; the implementation in EXPOSTAR is easily modified to simulate Z' physics at 1 TeV.

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