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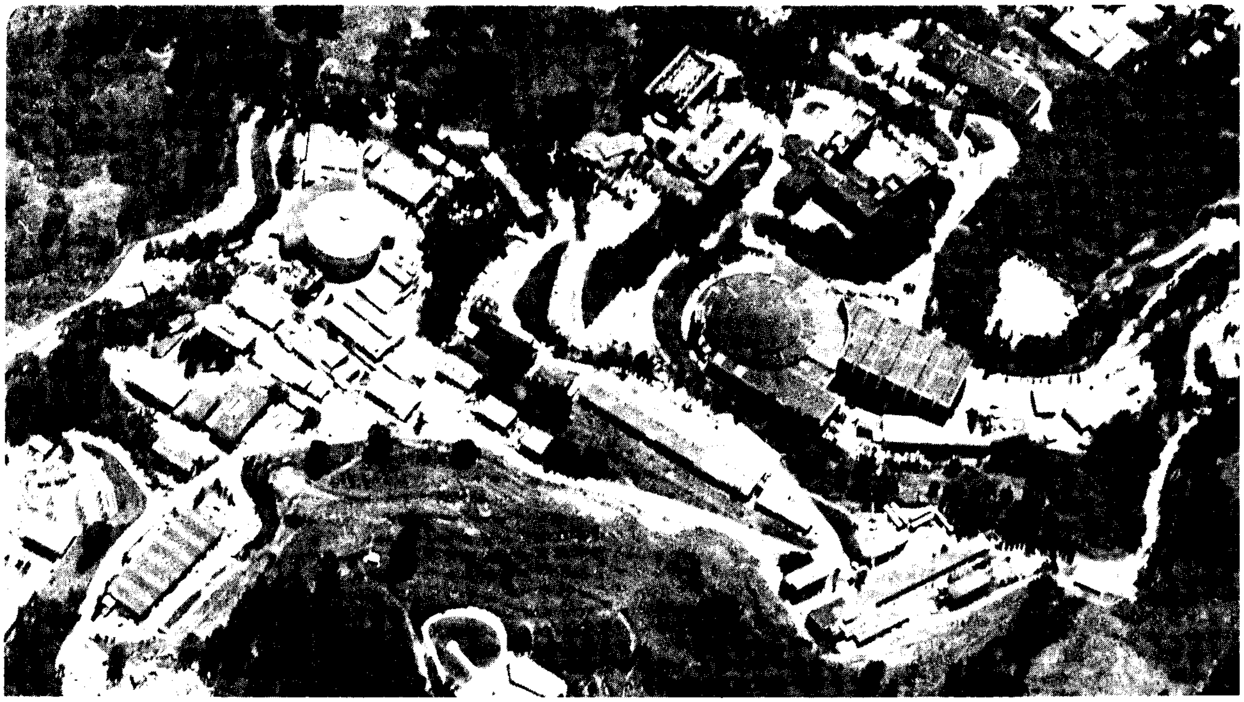

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Berkeley, California 94720

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INTRODUCTION TO THE WORKSHOP: ELECTROWEAK SYMMETRY BREAKING AT THE TeV SCALE

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Introduction

As viewed from today's perspective, electroweak symmetry breaking is both the central issue to be addressed by physics in the TeV region, and the most compelling argument for the need to explore that region. While the picture may change considerably over the next decade, it seems reasonable to focus theoretical attention on this issue which is in fact very broad in terms of its possible ramifications. Such a concerted effort can help to sharpen the scientific case for the SSC and provide fresh theoretical input to the ongoing series of workshops and studies aimed at forming a concensus on a choice of SSC design parameters.

To set the mood of the workshop I will review briefly the physics to be explored prior to the SSC as well as the motivations for exploration of the TeV region for hard collisions. I will follow with an example of a possible scenario for the first manifestation of electroweak symmetry breaking at the SSC.

State of the Standard Model

In a sense we are reaching the end of an era in the study of electroweak interactions, which are by now well understood as being described by the Lagrangian of a renormalizable, spontaneously broken gauge theory. The list of successes and precise, quantitative predictions is impressive. The attempt to understand the four-fermion charged current interactions in terms of a renormalizable theory culminated in the prediction and subsequent observation of neutral current phenomena as well as of the W and Z bosons, with precise predictions for their masses and other properties. Within the same context, the presence of strangeness changing charged currents, together with the observed strong suppression of their neutral current counterparts, led to the prediction and subsequent observation of charmed particles with precisely defined weak couplings and approximate estimates of their masses and other properties. The discovery of the τ-lepton implied, again within the context of a renormalizable theory, the existence of the (t,b) quark doublet; indeed, the entire third family of quarks and leptons had been anticipated in attempts to incorporate CP violation into the theory. Of this family, the t quark still awaits confirmation, as does direct evidence for the ν_τ.

There are hints from CERN that we may already be embarking on a new era. Possible interpretations of the zoo of intriguing $Sp\bar{p}S$ events were the focus of one of the workshop study groups. Whether any of these events really reflects new physics, as opposed to the traditional hiccups which tend to accompany the opening up of a new domain of experimentation, should be settled by the coming generation of facilities: an upgraded $Sp\bar{p}S$, TeV I, SLC, LEP and HERA.

In any event these facilities will provide a thorough testing of the standard model, including precision measurements of the W and Z masses and widths. In particular, the parameter $\rho = m_W/m_Z$ is sensitive to some high mass phenomena through radiative corrections. The high yield of Z's at SLC and LEP will permit searches for rare decays. About 5000 W → tb events should be produced at TeV I for an integrated luminosity of $10^{37}\mathrm{cm}^{-2}$, which should allow a rough check of GIM-KM unitarity.

An important aspect of the standard electroweak theory which has not yet been tested is the complex of trilinear and quadrilinear self-couplings of gauge bosons. Measurements of $e^+e^- \to W^+W^-$ at LEP II and of $qq \to WW$, WZ and $W\gamma$ at pp colliders will provide rough checks of the three vector boson coupling strengths. For LEP running somewhat below the two-W threshold, the process $e^+e^- \to eW\nu$ should allow a similar rough check[1] of the magnetic moment of the W.

It is possible that the "observed" electroweak gauge group $SU(2)_L \times U(1)$ is embedded in a larger group: TeV I should be able to probe for additional heavy Z's with masses up to 500 GeV if they have couplings to quarks of standard strength. LEP can search for very heavy Z's through propagator effects, while HERA will be sensitive to heavy W's as well, and also to the presence of right handed couplings for charged current reactions.

At lower energies, the copious sources of kaons and/or B mesons to be provided by CESR, TeV II and the AGS will help to pin down the parameters of the KM matrix, and in particular those governing CP violation. Searches for rare decays will also provide probes of higher mass scales.

Shelly's Plumber

There is still, of course, an important missing link in our present picture: the Higgs particle(s) or some other manifestation of electroweak symmetry breaking.

If the standard Higgs has a mass $m_H < 2\,m_W$ its decay will probably be too indistinctive to allow detection at a hadron collider. A possible exception is the case in which the decay $H \to t\bar{t}$ is kinematically forbidden; then there is a small window of possible Higgs masses for which the decay $H \to W + f\bar{f}'$ may have a substantial branching ratio[2]: $B(H \to W + f\bar{f}') = (6 \text{ to } 60)\%$ for $m_H = (120 \text{ to } 150)$ GeV. Generally, a Higgs with mass below the two-W threshold can most easily be detected using missing mass techniques in e^+e^- annihilation. For
$m_H \leq 40$ GeV, a standard Higgs could be found at SLC or LEP in Z^0 decay, or, depending on the top quark mass (and possibly at TRISTAN), via the decay of toponium into $H + \gamma$. LEP II can probe for a Higgs with mass $m_H \leq (2E_{beam} - m_Z)$ via the process $e^+e^- \to Z^0 + H$.

In the event that such a "light" standard Higgs turns up at the next generation of facilities, will the final chapter of weak interactions come to a close? There is strong reason to suspect that the Higgs phenomenon represents only the tip of the iceberg, and that qualitatively new physics must be involved. The deeper issue, commonly known as the gauge hierarchy problem, is the puzzle as to why the W and Z masses are so small in the presence of large scale parameters such as the hypothesized grand unification scale or the Planck scale. In the context of a weakly coupled renormalizable theory, such "light" gauge bosons require similarly "light" scalar bosons, but scalar masses are highly unstable against radiative corrections.

There are of course, other hierarchy problems, in particular large ratios among fermion masses, which by rights should all be of the same order as the W and Z masses since they are governed by the same symmetry breaking scale parameter. This issue has received less attention, probably because we haven't yet understood how to sensibly formulate the question. In the case of the usual gauge hierarchy we know how to ask the question and even how to answer it. The three most popular answers are listed below.

Technicolor. A scalar particle may be kept light by a global chiral symmetry which is broken spontaneously by a condensate of massless technifermions, characteried by a scale parameter Λ_T

$$<\bar{\psi}_T\psi_T> \sim \Lambda_T^3,$$

which is the scale at which the presumed asymptotically free technicolor interactions become strong. If ψ_T is an electroweak gauge non-singlet, the condensate also breaks the electroweak symmetry, giving the observed W and Z masses for $\Lambda_T \sim (\sqrt{2}\,G_F)^{-\frac{1}{2}} \approx 250$ GeV. The exactly massless goldstone bosons of spontaneously broken chiral SU(2) are eaten by the $W^\pm$ and Z to become their longitudinal components. This hypothesis predicts a rich spectrum of technihadrons with masses in the TeV region. For ordinary fermions to acquire masses, the theory must be extended in a way which generally leads to the prediction of additional pseudo-goldstone bosons that are considerably lighter. At present no phenomenologically viable (nor grand unifiable) model for technicolor exists, but the idea is sufficiently attractive to warrant attention.

Supersymmetry. Since chiral symmetries control fermion masses, scalar masses can be controlled if they are superpartners of chiral fermions. In practice, the gauge hierarchy is usually implemented in supersymmetric models by exploiting instead the "non-renormalization" property of supersymmetry which protects scalar masses against large radiative corrections. The electroweak breaking scale is related to the supersymmetry breaking scale which is generally adjusted by hand. Supersymmetry is motivated by other arguments as well, and may play a vital role in the ultimate connection between gravity and the observed gauge interactions. In this case, it may or may not also provide the mechanism for stabilizing the Higgs mass. If it does, as in most popular models, one expects to discover lots of superpartners of quarks and gauge bosons with masses below a TeV-except in the perhaps perverse but logically possible event that the Higgs mass is greater than a TeV and/or that the Higgs sector "sees" supersymmetry breaking only through radiative corrections, in which case many squarks, sleptons and gauginos could have masses larger than the Higgs mass by an order of magnitude or more.

Compositeness. A third possibility is that the standard model is in fact an effective theory for describing composite quark and lepton (and gauge?) fields which appear point-like at energies well below the inverse radius of compositeness. Perturbative calculations break down for virtual momenta higher than this inverse radius which provides an effective cut-off that stabilizes the Higgs mass, or, equivalently, its vacuum expectation value. Present data already suggest that the scale of compositeness exceeds a TeV; if it is indeed the Higgs mass stabilizer, it must not exceed a few TeV. Just as for supersymmetry, it is possible that ordinary particles are composite on a scale which is unrelated to the weak interactions. Signals of compositeness include new interactions: effective four fermion couplings with strength characterized by the squared radius of compositeness, and new particles: excited states of quarks and leptons, in particular color non-singlet quarks that may be quasi-stable.

Since none of the above models is sufficiently well constrained and/or well formulated to allow quantitative mass predictions, searches in any available mass range are of interest. The Sp$\bar{p}$S, TeV I, SLC, LEP and HERA complex of facilities should allow probes for supersymmetric particles up to mass scales of about 100 GeV, and for compositeness up to a scale of about 6 TeV. The SSC will be able to push these scales up considerably,[3] and should be able to weed out technicolor if that is the mechanism which sets the electroweak breaking scale.

Physics at the TeV Scale

We saw that attempts to understand the relatively small scale of electroweak symmetry breaking tend to suggest the existence of new particles or new phenomena. There are various other hints from both particle physics and cosmology that new physics should appear at scales well below those associated with grand unification or gravity.

One is the non-observation of the decay $p \rightarrow \pi e$ with a partial life-time as estimated in the minimal SU(5) model. A possibility is that the unification idea is totally wrong, but then we must abandon our present understanding of the value of the weak mixing angle and the observed nucleon to photon density ratio. Furthermore, since the observed spectrum of fermions is indeed an SU(5) spectrum, it is difficult to imagine that the ultimate unification scheme does not embed SU(5) at some level. An alternative possibility is that the unification scale is much higher than standard model calculations predict. This has the possibly attractive feature that the unification scale and the Planck scale are essentially the same, and the danger that proton decay may be unobservable altogether, closing an important experimental window on unification. In any event the latter interpretation requires some new particles - if only extra generations of quarks and leptons - with masses above present laboratory sensitivity, but well below the unification scale.

Attempts to reconcile the density fluctuations required for galaxy formation with the observed degree of homogeneity in the microwave radiation background invoke particles which were thermally decoupled from photons by the time of galaxy formation; candidates have included massive neutrinos, gravitinos, axions, etc. Models for an inflationary scenario compatible with both astrophysical observation and particle phenomenology may require additional new fields. Finally, we are at present totally in the dark on the complex of issues including the spectrum of fermion masses, the Cabibbo-KM mixing angles and CP violation.

Whether any of the above issues is related to electroweak symmetry breaking is an open question, and it is not possible to pin down a mass scale at which their resolution should be revealed. However it seems likely that resolving the issue of electroweak symmetry breaking should point us in a clearer direction towards answers to some of the other questions.

Why is the TeV scale an immediate target? The mass of the $W^{\pm}$ was successfully predicted by a simple formula:

$$m_W = [\pi\alpha/\sqrt{2}\,G_F]^{1/2}, \qquad (1)$$

where α is the fine structure constant of QED and G_F is the Fermi constant. In the standard model the Higgs mass is predicted by a similarly simple formula:

$$m_H = [8\pi\alpha_H/\sqrt{2}\,G_F]^{1/2}, \qquad (2)$$

with the unfortunate difference that the "fine structure constant"

$$\alpha_H = \lambda^2/4\pi \qquad (3)$$

appearing in (2) is the expansion parameter for the perturbative theory of scalar interactions, and is itself unknown, except for the requirement that the observed vacuum be stable against radiative corrections, suggesting $m_H \geq 10$ GeV.

On the other hand, should the Higgs mass exceed a TeV, Eq. (2) implies that the parameter α_H exceeds unity and that perturbation theory is inapplicable to the scalar sector. One might worry that this would render fortuitous the successful predictions of the standard model, but it has been shown[4,5] that ordinary physics is highly screened from strong interaction effects in the scalar sector, just as, for example, anomalous magnetic moments of leptons are very insensitive to strong interactions in the hadron sector.

The relevance of all this to a supercollider is that a strongly interacting scalar sector cannot remain screened at very high energies. The reason is that α_H also governs the strength of the self couplings of the $W^{\pm}$ and Z through their longitudinal components, acquired by absorbing three of the scalars that together with the physical Higgs particle form a complex doublet of the weak SU(2) gauge group.

In the 1960's it was argued correctly, on the basis of unitarity of the S-marix and the observed fermi couplings, that exploration of energy scales up to 600 GeV would necessarily reveal either strong parity violation or qualitatively new physics associated with the underlying structure of the weak interactions. The latter we now recognize as the W and Z of the standard model, and the upcoming generation of experimental facilities is well adapted to study their properties as discussed above.

An analogous argument, based on unitarity and the observed electroweak couplings of the standard model, leads to the conclusion[4,6] that either W's and Z's will develop strong interactions at effective c.m. energies of a few TeV or qualitatively new physics, related to the mechanism for electroweak symmetry breaking, will emerge. The latter may or may not take the form of a standard model Higgs or one of the richer scenarios described above.

The questions addressed at the workshop included:

What form might the new physics take?
What might be its experimental signals?

The purpose of asking questions such as these is to sharpen the requirements on energy and luminosity, and suggest directions for detector development, with the aim of assuring maximum accessibility to the physics of the TeV region, whatever form it might take. The physics reach for various choices of machine parameters and for the standard "bellwether" scenarios has been extensively treated by EHLQ.[3] Our purpose here was not to rehash the bellwethers, but rather to generate new ideas and new perspectives on old ideas.

An Example: A Minimal Scenario

Suppose that the study of hard collisons up to the TeV scale for effective c.m. energies reveals neither a standard model Higgs nor any obvious variation thereof. Suppose further that experimental data continues to conform to the standard model, so that observed electroweak physics is described by the GWS Lagrangian which in a renormalizable gauge takes the form:

$$\pounds = \pounds_{\text{gauge, matter}}(g, G_{\text{Yuk}}, m_{W,Z}, m_f, \xi) - V(\phi,H), \qquad (4)$$

where the first term includes mass and kinetic energy terms and gauge and Yukawa couplings, and ξ is a gauge parameter. The second term is the scalar potential; in the standard model:

$$V(\phi,H) = {m_H}^2H^2/2 + {m_H}^2H(|\phi|^2+H^2)/2v + {m_H}^2(|\phi|^2+H^2)^2/8v^2 \qquad (5)$$

where H is the physical Higgs particle, $\phi = (w^+, z, w^-)$ are the unphysical scalars absorbed as longitudinal components of (W^+, Z, W^-) in the unitary gauge, and v = 250 GeV is the usual scalar vacuum expectation value. The relevance of the potential (5) to TeV physics is that S-matrix elements with external w's and z's calculated from the Lagrangian (4) are equivalent[6-8] to the S-matrix elements for external longitudinally polarized W's and Z's, up to corrections of order m_W/E.

The potential (5) is characterized by a single unknown parameter, the physical Higgs mass m_H. As discussed above, for a Higgs mass of a TeV or more, (5) describes a strongly interacting system. However, one can try to exploit[9] the property[5] that the potential V is invariant under non linear transformations among scalars, whose generators satisfy the algebra of chiral SU(2) × SU(2). The first term in (4) contains the weak couplings of $w^\pm$ and z to fermions through scalar and pseudoscalar densities and to transversely polarized W's and Z's through vector and axial currents that are conserved up to corrections of order of the weak couplings and the W, Z squared mass. The situation is analogous to that of low energy hadron physics where an (approximately) chiral SU(2) invariant strongly interacting system couples to leptons through (partially) conserved axial and vector currents. Here the longitudinal vector bosons $W_L, Z_L \simeq w,z$ play the role of the pions of hadron physics. These general features are moreover not specific to the standard model; the situation in a minimal technicolor scenario is identical, and any scenario where no symmetry breaking phenomenon is manifested below the TeV scale is expected to display similar properties.

Ideally, then, one would like to understand the dynamics of a strongly coupled σ-model, just as for pion chiral dynamics. The strongly interacting limit of the minimal Higgs model has been analyzed for the presence of bound states or resonances[6,10] Regge poles,[11] or skyrmions.[12] Recently Einhorn[13] found that the leading N behavior in a 1/N expansion (here N = 2!) for a chiral SU(N) scalar sector suggests that there must be a J = 0 scalar state (which might as well be called the Higgs particle) with a mass of at most a few hundred GeV.

What I shall discuss here is a more modest approach adopted by Mike Chanowitz and myself:[9] given that the longitudinally polarized gauge bosons W_L, Z_L develop strong interactions, how can we experimentally study this strongly interacting system? First, we must produce a system of two or more W_L, Z_L, which is not entirely trivial, as W_L and Z_L couplings to quarks are suppressed up to corrections of order m_q/m_W or m_W/E_W. In addition we are working in a regime where perturbation theory is not applicable. However, the replacement $W_L, Z_L \rightarrow w, z + O(m_W/E)$ in S-matrix elements and the chiral symmetry of strong w, z interactions allow us to determine the W_L, Z_L couplings near threshold through soft pion theorems. The threshold behavior obtained in this way is given precisely[8] by the Born approximation to the GWS Lagrangrian (4), (5). The resulting amplitudes for multiple W_L and Z_L production are roughly characterized by a factor E/v for each emitted W, or Z, . In the limit $m_H \rightarrow \infty$, v is the only scale parameter of the system, so simple scaling arguments imply that the Born approximation must be valid for some energy range between multi-W production thresholds and that energy at which a damping scale (m_H?, Λ_T?) sets in to restore unitarity in the s-wave scattering channel, as it must. This scale will presumably be signaled by resonance production or similar phenomena. Whatever the dynamics of such a strongly coupled system should turn out to be, it should be characterized by events with a high multiplicity of W's and Z's.

We therefore considered various mechanisms for the production of a system of two or more W_L,Z_L and made multiplicity estimates based on the E/v scaling law, which is equivalent to the Born approximation that automatically satisfies the current algebra constraints. We considered two extreme cases: a) the Higgs mass sits at its "unitarity limit" value[6] of a TeV, where it becomes so broad that establishment of a resonance in the WW and ZZ systems may be problematic, and
b) 1 TeV $\le \sqrt{s_{WW}} << m_H$ (in this case tree unitarity breaks down in the s-wave channel for $\sqrt{s_{WW}} \simeq 1.8$ TeV).

The most copious source of longitudinally polarized W's and Z's turns out to be the analogue of the Cahn-Dawson mechanism[14] for Higgs production (Fig. 1). At first sight, this would appear to give a negligible contribution because the W_L coupling to light quarks is suppressed by a factor m_W/E_W in amplitude at each qq'W vertex. However this factor is exactly compensated for by the fact that, as opposed to the case for transversely polarized vector bosons, longitudinal W emission does not vanish in the forward direction.[9] We estimated the total yield from this mechanism using parameterizations of the total W_LW_L cross section adjusted to reproduce the correct threshold behavior, an asymptotic logarithmic energy dependence, with or without a broad (Higgs) resonance in the energy region accessible to the SSC. In all cases, the yield of events including a pair of Z_L's is expected to exceed[15] the Z-pair yield[3] from conventional gauge interactions for sufficiently high sub-energies for the vector boson system. In contrast, the light $q\bar{q}$ annihilation channel, which can produce a significant yield of pairs of longitudinally polarized bosons only in a pure J = 1 state, is dominated by pair production of transversely polarized vector mesons. In either case the Z/W production ratio will be enhanced in the presence of important strong interaction effects.

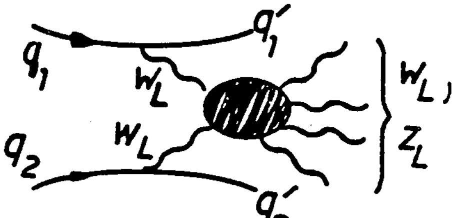

Figure 1

As the potential (5) conserves "parity", with w and z defined as parity-odd, the mechanism of Fig. 1 will produce only even numbers of vector bosons. To lowest order in the weak gauge coupling constant, the dominant mechanism for production of an odd number of w, z (or W_L, Z_L) is that of Fig. 2. For case a), $m_H \simeq 1$ TeV, the cross section is dominated by on-shell Higgs production and decay; for case b), 1 TeV $\le \sqrt{s} << m_H$, the Born approximation cross section is constant, and, if extrapolated to asymptotic energies, would exceed the cross section for three W, Z production via conventional gauge interactions which must (with appropriate cuts on angular separation) scale as 1/s. Unfortunately, for the energy range accessible to the SSC the gauge background apparently[16] dominates three body production, presumably because of multiple polarization degrees of freedom in the final state.

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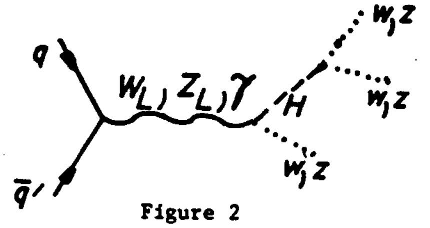

Figure 2

On the other hand, if the scalar system is indeed strongly interacting, events with four or more W's and Z's should significantly exceed the yield expected from gauge couplings alone. However, the multi-body event rates anticipated on the basis of the E/v rule are extremely small: for an integrated luminosity of 10^{40}cm^{-2} and a c.m. energy of 40 TeV, we found about 150 three body and 10-100 four body events using the prescriptions described above. In this case backgrounds present a major problem. While conventional gauge interactions[3] should not represent a prohibitive background for the total yield of multi W, Z events expected from the mechanism of Fig. 1, the anticipated two-jet QCD background is larger than the multi- W, Z signal by many orders of magnitude. Demanding one leptonic decay still leaves[15] an overwhelming background from W or Z plus high p_T jet. An important issue is thus whether the hadronic decays of W's and Z's can be distinguished from QCD jets. The wisdom which emerged from discussions at the $p\bar{p}$ workshop[15] is that a reduction factor of 1/7 in the background to signal ratio can be achieved by requiring a jet mass equal (within an appropriate definition) to the W,Z mass. This appears to be insufficient to extract two-body W and Z events for the yields estimated in Ref. 9. Demanding two leptonic decays (which excludes detection of two-W events) reduces the rates to a barely detectable level, even with a luminosity of 10^{33} cm^{-2}sec^{-1}. Therefore better methods for separating hadronic W and Z decays from QCD jets are highly desirable, not only for the scenario discussed here, but also if multi-W, Z events are to be used, for example, to test the standard model gauge couplings, or to search for a lighter ($2m_W < m_H <$ TeV) standard model Higgs, a technirho, etc. Sciulli[17] has considered the possibility of measuring the angular separation between individual particles in a jet. He concluded that the background reduction factor could be improved to about 1/25 in this way and suggested that a factor of 1/100 might be achievable. However this may be at the price of a severe reduction in solid angle: the total estimated[9] yield of multi W_L, Z_L events with invariant mass above 500 GeV is three to ten thousand for an integrated luminosity of 10^{40} cm^{-2}.

It might also be possible to extract a signal for strongly interacting vector bosons by less direct methods than identification of individual multi W_L, Z_L events, such as an anomalously high yield of W and Z leptonic decays and/or an anomalously high Z/W ratio in events with total transverse energy above, say, 500 GeV. If the muon angular distribution in $Z \rightarrow \mu\mu$ can be measured, it might further be possible to establish[15] an enhancement of longitudinally polarized Z's in this sample. These questions clearly require further study.

On the more theoretical side, a better understanding of the dynamics of a strongly interacting W_L, Z_L system, or plausible models of such a system, might give a better indication as to whether the low yield of events with multiplicity ≥ 3, estimated[9] by extrapolating the required threshold behavior (Adler zeros) is a fair guess or whether (hopefully?) it appreciably underestimates the multi-body event yield.

Conclusions

The questions raised above are intended to illustrate the way in which thinking about a specific scenario can raise further questions as part of an iterative process of providing not only input into the choice of SSC design parameters, but also directions for detector design, algorithms for data analysis, etc. Further study on the physics of strongly interacting W's and Z's did in fact go on at the workshop, as reported below along with the conclusions of other working groups. These included supersymmetry, compositeness, non standard Higgs particles, standard Higgs with mass $m_W < m_H < 2m_W$, mirror fermions and other exotics.

The physics to be revealed by exploring the TeV region at the SSC will undoubtedly bear little resemblance to anything discussed here, but hopefully exercises such as this and other workshops will leave us better prepared to exploit it.

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Note: For reasons of space, references to the standard (pre 1983) literature, not specifically addressing a strongly interacting scalar sector, have been omitted.

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