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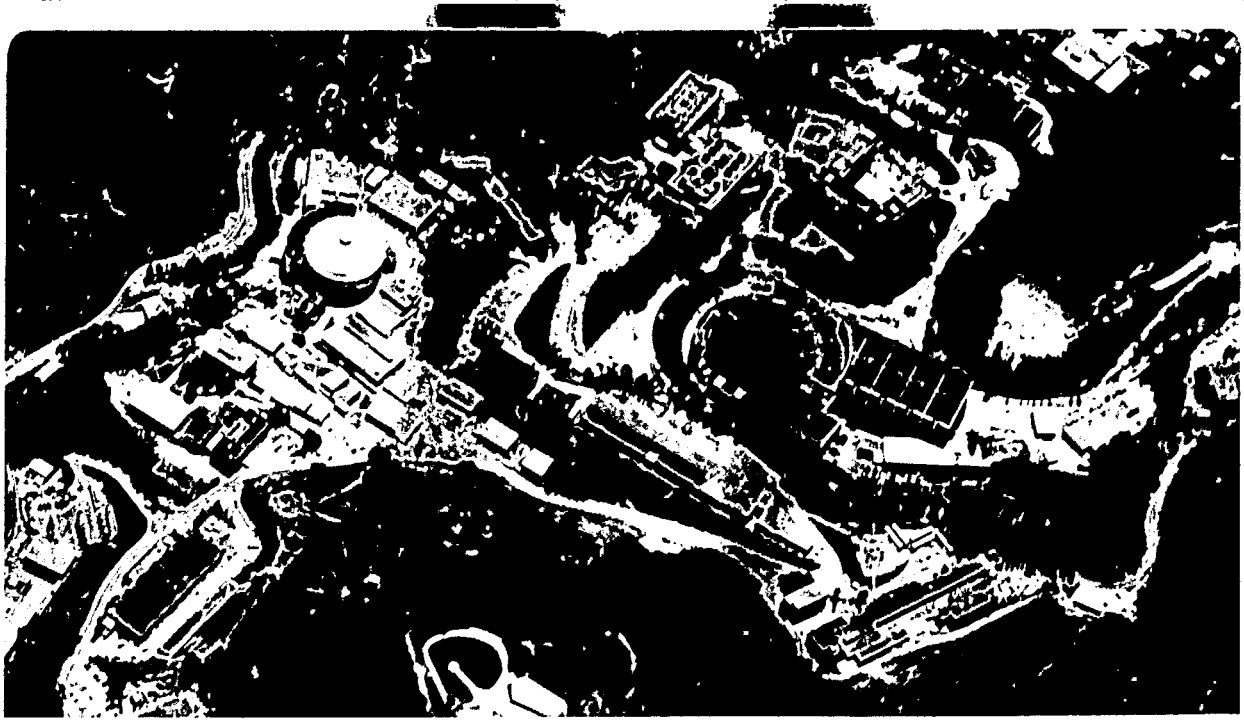
Presented at the Conference on Tests of Electroweak Theories: Polarized Processes and Other Phenomena, Miramare-Trieste, Italy, June 10-12, 1985

ELECTROWEAK INTERACTIONS AT THE SSC

R.N. Cahn

August 1985



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August 1985 LBL-20052

ELECTROWEAK INTERACTIONS AT THE SSC*

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Talk given at the meeting
Tests of Electroweak Theories: Polarized Processes and other Phenomena
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*This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of High Energy Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098.

The proposed Superconducting Super Collider, SSC, will produce elementary collisions at the TeV energy scale. It is anticipated to produce a luminosity of 10^{33} cm^{-2} sec^{-1} for pp collisions with $\sqrt{s} = 40$ TeV.[1] This might be accomplished with a 90 km ring of 6.5 T superconducting magnets, or alternatively with 2 T magnets and a larger ring. The SSC could be in operation in 1993. The estimated cost in 1984 dollars is $\$3 \cdot 10^9$ for the machine and laboratory, plus $\$1 \cdot 10^9$ for pre-construction research and development, computers, and detectors. Although we shall present specific arguments that suggest that the design luminosity and energy are well suited for exploring electroweak phenomena, the fundamental basis for their choice is that they are as big as present technology and foreseeable financing can provide. They thus offer the best hope of finding new clues to the fundamental nature of matter.

The spectacular success of the electroweak theory culminating in the discovery of the W and Z bosons has made spontaneous symmetry breaking of $SU(2) \times U(1)$ a primary issue. In the simplest form of the standard model, spontaneous symmetry breaking is accomplished through a single complex Higgs doublet. Of the four degrees of freedom therein, three are taken up in the longitudinal components of the massive vector fields, leaving one neutral scalar particle, the Higgs boson.

This scenario is not unique. There may be more than one Higgs doublet, as required by supersymmetric models. Alternatively, the Higgs boson may not be fundamental, but instead a bound state of other fields as in technicolor models. The present discussion is restricted, however, to the simplest model, in which the Higgs boson is fundamental and arises from a single complex doublet.

This is an austere model. The electroweak sector includes only the Higgs boson in addition to the known particles. The supersymmetric and technicolor models include a plethora of new particles. Cross sections and signatures at the SSC for these particles have been reviewed by Eichten, Hinchliffe, Lane, and Quigg (EHLQ).[2] Lacking the multitude of new particles, the simplest model becomes the greatest challenge experimentally. Signs of the electroweak symmetry breaking are few and hard to identify.

Before evaluating the prospects for finding the Higgs boson at the SSC, we consider production of gauge bosons, W^+, W^-, and Z in various combinations. These processes are interesting in their own right and as backgrounds for more exotic processes.

1. The Basic Paradigm

With a design luminosity of 10^{33} cm^{-2} s^{-1}, a standard year can be taken to have an integrated luminosity of $\int \mathcal{L} dt = 10^{40}$cm^2 . Given a projected pp total cross section of 100 - 200 mb, this will produce about 10^{15} hadronic interactions. The bulk of these will involve low momentum transfer, albeit with large produced particle multiplicities. Those in which there are large momentum transfers are analyzed in terms of the partonic constituents (quark, anti-quark, gluon) of the proton. The probability of finding a parton of type j carrying a fraction between x and $x + dx$ of the proton's momentum is $F_j(x)dx$. In fact, F_j is also a function of Q^2, the momentum transfer squared with which the proton is probed. The evolution of F_j as a function of x and Q^2 is described by the Altarelli- Parisi equations. The most detailed consideration of the structure functions has been carried out by Eichten, Hinchliffe, Lane, and Quigg.[2] The cross section, $d\sigma$, for some process is simply the cross section for the elementary process, $d\hat{\sigma}_{ij}$ times the flux of partons of types i and j:

$$d\sigma = \sum_{ij} dx_1 F_i(x_1, Q^2) dx_2 F_j(x_2 Q^2) d\hat{\sigma}_{ij}. \tag{1}$$

Here $d\hat{\sigma}$ may describe a process like $qq \to qq, q\bar{q} \to W^+W^-$, etc. The incident partons can usually be assumed to have small transverse momentum. Thus the cm energy squared of the parton-parton system is $\hat{s} = x_1 x_2 s \equiv \tau s$. We can conveniently define a luminosity spectrum

$$\frac{d\mathcal{L}_{ij}}{d\tau} = \int dx_1 dx_2 F_i(x_1) F_j(x_2) \delta(\tau - x_1 x_2), \tag{2}$$

in terms of which

$$\sigma = \int d\tau \hat{\sigma}_{ij}(\tau s) \frac{d\mathcal{L}_{ij}}{d\tau}. \tag{3}$$

It is this partonic paradigm which underlies all subsequent discussions.

2. Single Production of W and Z

We can estimate the production of W using the above formulas. For the cross section for $u\bar{d} \to W^+$ we take the Breit-Wigner form

$$\sigma(E) = \frac{\pi}{p_{cm}^2} \frac{2J+1}{(2S_a+1)(2S_b+1)} \frac{\Gamma_{in}\Gamma_{out}}{(E-E_0)^2 + \frac{1}{4}\Gamma_{tot}^2} \tag{4}$$

In the narrow width approximation this becomes

$$\sigma(E) = \frac{\pi}{p_{cm}^2} \frac{2J+1}{(2S_a+1)(2S_b+1)} \frac{\Gamma_{in}\Gamma_{out}}{\Gamma_{tot}} 2\pi\delta(E - E_0). \tag{5}$$

Here we want the total rate so $\Gamma_{out} = \Gamma_{tot}$. The incident quarks are essentially massless so $p_{cm}^2 = M_w^2/4$. For Γ_{in} we take the rate into a single color pair: $\Gamma_{in} = \Gamma_{tot}/12$. (Note that $\Gamma(W^+ \to u\bar{d}) \approx \Gamma(W^+ \to c\bar{s}) \approx 3\Gamma(W^+ \to \mu^+\nu)$), so

$$\sigma = \pi^2 \frac{\Gamma_{tot}}{M_W} \delta(\tau s - M_W^2). \tag{6}$$

For $d\mathcal{L}/d\tau$ we use a convenient parameterization[3] of the results of EHLQ

$$\frac{d\mathcal{L}}{d\tau} = \frac{A}{\tau^{\gamma/2}} e^{-\beta\sqrt{\tau}}, \tag{7}$$

with $A = 0.251$, $\beta = 12.81$, $\gamma = 2.67$. For our case, $\sqrt{\tau} = 0.082/40 = 2.05 \cdot 10^{-3}$ and $(d\mathcal{L}/d\tau) = 3.7 \cdot 10^6$. This must be divided by 3 to make sure that the quark and anti-quark have the same color. Altogether,

$$\sigma = \frac{1}{3} \int d\tau \frac{d\mathcal{L}}{d\tau} \pi^2 \frac{\Gamma_{tot}}{M_W} \delta(\tau s - M_W^2) = \frac{\pi^2}{3s} \frac{\Gamma_{tot}}{M_W} \frac{d\mathcal{L}}{d\tau} \approx 100 \text{ nb}. \tag{8}$$

Thus we expect about 10^9 W's per year and slightly fewer W's. These numbers are in good agreement with those of EHLQ. The Z production rate is expected to be about $6 \cdot 10^8$/yr. If only those Z's and W's whose rapidities satisfy $|y| < 1.5$ are accepted, the rates fall by a factor of about 4.

At present, it is not clear what one would do with 10^9 W's. When the SSC begins operation, SLC and LEP will have studied the Z at a level of 10^7 events. LEP II may be studying or about to study the W at a level of 10^3 - 10^4 events. The salient point is that we do not know how to identify the W's and Z's that decay hadronically. They are, as far as is known at present, buried in an overwhelming

background of hadronic events in which two jets simulate the decay jets of a W or Z.

3. Production of Pairs of Gauge Bosons.

Pair production W^+W^- is of interest because it involves the non-Abelian trilinear coupling W^+W^-Z. The elementary process involves the annihilation of a fermion-anti-fermion pair. The cross section has been calculated by Brown and Mikaelian.[4] It depends on the center of mass energy, s, and the quark type. Crudely, we can write

$$\sigma(f\bar{f} \to W^+W^-) = \frac{\pi\alpha^2}{24x_W^2}\frac{C}{\hat{s}}, \tag{9}$$

where $x_W = \sin^2\theta_W$, and C is a dimensionless constant, depending on the quark type, of order 8. For each quark flavor we get a contribution

$$\sigma(pp \to W^+W^-X) \approx \int d\tau \frac{d\mathcal{L}}{d\tau}\sigma(f\bar{f} \to W^+W^-) \approx \int d\tau \frac{A}{\tau^{\gamma/2}} e^{-\beta\sqrt{\tau}} \frac{\pi\alpha^2}{24x_W^2}\frac{C}{\tau s}. \tag{10}$$

The integration begins at $\sqrt{\tau} = 2M_W/\sqrt{s}$. Since this is small, we can ignore the factor $\exp(-\beta\sqrt{\tau})$ with the result:

$$\sigma(pp \to W^+W^-X) \approx \frac{\pi\alpha^2}{12x_W^2 s} AC\frac{1}{\gamma}\left(\frac{\sqrt{s}}{2M_W}\right)^{\gamma}. \tag{11}$$

Using $A = 0.251$, $\gamma = 2.67$, for the $u\bar{u}$ contribution we find

$$\sigma(pp \to W^+W^-X) \approx 1.7 \cdot 10^{-35}\mathrm{cm}^2 C\left(\frac{\sqrt{s}}{40\mathrm{TeV}}\right)^{0.67}. \tag{12}$$

For $C = 8$ and adding the $d\bar{d}$ contribution we estimate σ $(pp \to W^+W^-X)$ $= 2 \cdot 10^{-34}$cm at the SSC, i.e. $2 \cdot 10^6$ WW pairs, in rough agreement with EHLQ. The analogous results for W^+Z, W^-Z, and ZZ are about $4 \cdot 10^5$ in each mode.

While the total number of gauge boson pairs produced would be substantial, detecting them will not be easy. The anticipated branching fractions for $W^+ \to e^+\nu, \mu^+\nu, \tau^+\nu, u\bar{d}, c\bar{s}, t\bar{b}$ are 1/12, 1/12, 1/12, 1/4, 1/4, 1/4 ignoring phase space corrections for the $t\bar{b}$ mode. For the Z, the branching ratio for each charged lepton mode should be 3%, to each neutrino pair 6%, to charge 2/3 quarks 10% and to charge -1/3 quarks 13%. Thus insisting on two charged leptonic decays (and not τ)

costs a factor of $3.6 \cdot 10^{-3}$ for ZZ, 10^{-2} for WZ and $2.8 \cdot 10^{-2}$ for WW. The next most distinctive signature would be one leptonic and one hadronic decay. However, a careful analysis for Stirling, Kleiss and S. Ellis has shown that the background for W + jet + jet, where the two jets have the invariant mass of a W, overwhelms the putative signal.[5]

Another two gauge boson process is the production of $W\gamma$. A dramatic angular distribution is expected and in principle provides a means of measuring the magnetic moment of the W. Unfortunately, consideration of the realistic limitations of plausible SSC experiments indicates that only a very crude measurement of the anomalous moment of the W will be possible.[6]

4. Production of Three Gauge Bosons

The cross section for the production of three gauge bosons has been calculated recently by M. Golden and S. Sharpe.[7] There are contributions from a large class of diagrams involving various couplings of W's, Zs, and γ's. In addition, there are diagrams in which a (possibly virtual) Higgs boson is emitted from a W or Z line and decays into W^+W^- or ZZ. Such diagrams may be considered separately, and their contributions added incoherently with little loss in accuracy.

Ignoring the Higgs boson diagrams, Golden and Sharpe find that the standard SSC year should yield about 5000 $3W$ events, 4600 $2W + Z$ events, 1300 $W + 2Z$ events, and 450 $3Z$ events. For a Higgs mass of 200 GeV, the extra contribution from processes involving the Higgs is substantial. It would add 7100, 4100, 2400, and 1350 events respectively to those given above. Needless to say, the problems of identification discussed in connection with the two gauge boson production appear here as well.

5. Higgs Boson Production

The orthodox Higgs boson is hard to produce because its couplings to ordinary quarks are proportional to m_q/M_W. The two important production mechanisms are designed to circumvent this. In the gluon fusion mechanism, gluons couple to a heavy loop.[8] In the WW mechanism, two virtual W's (or Zs) combine to produce a Higgs boson.[9]

It is not enough to produce the Higgs boson: it must be detected as well. Schemes to find the Higgs boson in e^+e^- annihilation rely on signatures accompanying the Higgs boson, *e.g.* $Z \to H\mu^+\mu^-$. This is not directly applicable to hadron colliders. Thus an attempt must be made to identify the Higgs boson di-

rectly. For $M_H < 2M_W$, the dominant decay is $H \to b\bar{b}$ or $H \to t\bar{t}$ (if allowed). It is generally agreed that such decays will be hopelessly buried in the ordinary QCD background.[10,11] For a heavier Higgs, the dominant decay are to W^+W^- and ZZ with approximate widths

$$\Gamma(H \to W^+W^-) \approx 30\text{GeV}(\frac{M_H}{500\text{GeV}})^3$$
$$\Gamma(H \to ZZ) \approx 15\text{GeV}(\frac{M_H}{500\text{GeV}})^3. \tag{13}$$

It is not coincidental that for $M_H \approx 1$ TeV the width of the Higgs boson becomes comparable to its mass, for this is the region in which the Higgs-W-Z sector ceases to be perturbative. Above $M_H = 600$ or 700 GeV, the large width of the Higgs boson may preclude its discovery. We are left with a region between 170 GeV and 700 GeV where the W^+W^- or ZZ signature may permit the discovery of the Higgs.

The gluon-gluon fusion mechanism has a cross section[12]

$$\sigma = \frac{\sqrt{2}G_F}{64}(\frac{\alpha_s^2}{\pi})\frac{|N|^2}{9}(\tau\frac{d\mathcal{L}}{d\tau})_{gg}, \tag{14}$$

where N is a complex function of $\lambda = m_\tau^2/m_H^2$ which for small λ is

$$N \approx 3\lambda[2 - \frac{1}{2}(\ln\lambda^{-1} + i\pi)^2]. \tag{15}$$

For $m_\tau = 40$ GeV and $m_H = 200$, 400, 600 GeV we find $|N|^2 = 1.5$, 0.2, 0.007 respectively.

We can use these numbers to obtain a crude estimate of the cross section. A fit to the EHLQ[2] luminosities is given[3] by

$$(\tau\frac{d\mathcal{L}}{d\tau})_{gg} \approx 2 \cdot 10^4 \exp(-24.8\tau^{0.2}). \tag{16}$$

For the three values of m_H, $\sqrt{\tau} = 0.2/40$, 0.4/40, 0.6/40, we find $(\tau d\mathcal{L}/d\tau) = 1 \cdot 10^3, 4 \cdot 10^2, 2 \cdot 10^2$ respectively. If we take $\alpha_s = 0.1$, we find cross sections $\sigma(m_H = 0.2 \text{ TeV}) = 45$ pb, $\sigma(m_H = 0.4 \text{ TeV}) = 2.4$ pb, $\sigma(m_H = 0.6 \text{ TeV}) = 0.04$ pb. Thus the cross section falls rapidly with increasing m_H. This is the consequence, primarily, of the function $N(\lambda)$.

The WW mechanism relies on the large coupling of longitudinal Ws and Z's to the Higgs boson. If the quarks that radiate the W's and Zs are assumed to

continue forward, one finds the approximation of Chanowitz and Gaillard,[13] and of Dawson:[14]

$$\sigma(\hat{s}) = \frac{1}{16M_W^2}\left(\frac{\alpha}{x_W}\right)^3\left[(1+\frac{M_H^2}{\hat{s}})\log\frac{\hat{s}}{M_H^2} - 2 + 2\frac{M_H^2}{\hat{s}}\right], \tag{17}$$

for the WW process. Here $x_W = \sin^2\theta_W$. This overestimates the cross section by 20-50% for low s and a few percent at high s. While this is good enough for most calculations, it is interesting that there are correction terms that do not vanish as $s \to \infty$. A quasi-analytical expression is good to 1-2% for $s > 1$ TeV and $M > 0.2$ TeV:

$$\sigma(\hat{s}) = \frac{1}{16M_W^2}\left(\frac{\alpha}{x_W}\right)^3\left[(1+\frac{M_H^2}{\hat{s}})\log\frac{\hat{s}}{M_H^2} - 2 + 2\frac{M_H^2}{\hat{s}} - 2(1-\frac{M_H}{\sqrt{\hat{s}}})^2\frac{M_W^2}{M_H^2}\log\frac{M_H^2}{M_W^2}\right]. \tag{18}$$

The important feature of the WW mechanism is that the cross section is proportional to $1/M_W^2$, not $1/M_H^2$. As a result, it is relatively insensitive to M_H and does not fall off rapidly in this variable as does the gluon fusion process. For $M_H > 0.3$ TeV, the WW mechanism dominates the cross section. For the SSC energy and $M = 0.3$ TeV, each mechanism gives $\sigma = 5$ pb, i.e. a total of 100,000 events before cuts. For $M = 0.5$ TeV, this has dropped to 40,000 events.

The conservative view is that only the leptonic decays of the gauge bosons are observable. In fact, only the ZZ decay of the Higgs leads to reconstruction of the mass. This costs a factor 1/3 for insisting on ZZ and $(0.06)^2$ for requiring either ee or $\mu\mu$ for each Z. This leaves just 120 events for $M = 0.3$ TeV and 50 events for $M = 0.5$ TeV. In addition, kinematic cuts will be necessary simply because of the finite acceptance of detectors.

Two conclusions are immediate:

1. A reduction of the luminosity by a factor of ten would make the experiment impossible with only these decay modes.

2. It would be invaluable to have a reliable means of detecting W's and Z's from their hadronic decays. The outlook here is not bright.

6. The Intermediate Mass Higgs Boson.

The problem of detecting a Higgs boson of mass less than $2M$ remains a disturbing one. The proposal to look for the sequence $pp \to W^* \to W + H$ made some years ago[15] was revived recently.[16] The idea is to use the final state W as a trigger and to detect the decay of the Higgs into $t\bar{t}$. Then the mass of the Higgs boson is to be reconstructed from the t-quark jets. In fact, it appears that this does effectively reduce many backgrounds. Unfortunately, a careful study of the limitations of detector capabilities indicate that the sought for peak in the invariant mass will be washed out. This is unavoidable because of losses of neutrinos, ambiguities of which tracks ought to be assigned to a jet and the energy resolution of calorimeters.[6]

7. Strongly Interacting W's and Z's

Shortly after the suggestion of the WW mechanism for Higgs production, Chanowitz and Gaillard pointed out that the colliding W's offered an excellent opportunity to study the interactions of longitudinal Ws and Zs.[13] Originally it was hoped that multiple $(> 2)W$ and Z production might indicate the presence of the strong interactions which are expected if the Higgs mass reaches 1 TeV or so. Unfortunately, the calculations of Golden and Sharpe showed that the production of ordinary (transverse) Ws and Zs would overwhelm the expected effects.[7] Still, there remains the possibility of seeing effects in the production of pairs of gauge bosons.

The idea is to look for pairs of gauge bosons with an invariant mass in the 1 to 2 TeV range. Chanowitz and Gaillard[17] consider two particular models. The first is simply the standard model, but with a Higgs mass of 1 TeV, so that the Higgs can barely be regarded as a particle since its width is 0.5 TeV. The second is based on a non-linear sigma model in which the longitudinal W's and Z's play the role of charged and neutral pions.

The predictions of the standard model with $M = 1$ TeV show the dominance of the Higgs particle. The W^+W^- and ZZ signals are 10 - 50 times the WZ or like-sign WW signals. If we insist on leptonic Z decays (one possibly to a neutrino pair), there are 28 events predicted above 1 TeV invariant mass, over a background of 9 events from $q\bar{q} \to ZZ$. Clearly the problems here are the low event number and the reliability of the background calculation. If the background is calculable only to a factor of three, a signal cannot be discerned.

The model based on the sigma model shows rather different results. All the WW, WZ and ZZ channels are comparable. While the standard model shows a peak in the WW invariant mass spectrum near 1 TeV, this model is structureless. The signal to noise in all channels is about one-to-one. For example, there are 84 W^+W^- pairs expected in leptonic channels over a background of 100 for pair masses greater than 1 TeV. Again, the uncertainty in the background calculation is a cause for concern.

An additional background to pair production of gauge bosons needs to be considered: production in two separate elementary partonic interactions in the same event.[18] A crude estimate is obtained by assuming that there is no correlation between the elementary events. As noted above, one SSC year should produce about 10^{15} hadronic events and 10^9 W's of each sign. Thus one event in 10^6 has a W, so perhaps one in 10^{12} will have two W's from independent sources. Requiring that the invariant mass of the pair is greater than 1 TeV might reduce the rate by a factor of 1/4 or so, leaving 250 events. This is not negligible on the scale at hand. However, the $W's$ produced in this fashion will have rather small transverse momentum relative to the beam, while the pairs of interest will have large transverse momentum. This should provide an effective discriminator. Indeed, most of the W's will go down the beam pipe.

8. CONCLUSIONS

The standard SSC year will provide roughly 10^9 single gauge boson events, 10^6 double gauge boson events and 10^4 triple gauge boson events. There is no known way to identify the hadronic decays of the W and Z so the number of identifiable gauge bosons will be much reduced. Within the simplest version of the orthodox electroweak model, the Higgs boson is an elusive target. If its mass is greater than twice the W mass, it decays into W^+W^- (or ZZ). A standard SSC year will produce about 100,000 Higgs bosons if $M_H = 300$ GeV. The only sure signature is from $H \to ZZ$ with both Z's decaying leptonically. This leaves 120 events before kinematical cuts. This is a pessimistic scenario but a feasible one. The greatest improvement would come from an effective means of identifying gauge bosons by their hadronic decays.

Acknowledgments

I would like to acknowledge the assistance and criticism of W.J. Stirling, M.S. Chanowitz, and M.K. Gaillard.

This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of High Energy Physics, of the U.S.

Department of Energy under contract DE-AC03-76SF00098.

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This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

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