In this talk we survey the SSC signals and backgrounds for the physics of electroweak symmetry breaking. We study the process \( pp \to W W X \) and compute the rate for the “gold-plated” signals \( W^\pm \to \ell^\pm \nu \) and \( Z \to \ell^+ \ell^- \) \((\ell = e, \mu)\) for a wide variety of models. We use a forward jet tag and central jet veto to suppress the standard-model backgrounds. In this way we estimate the SSC sensitivity to the physics of electroweak symmetry breaking.

INTRODUCTION

During the past decade, particle physics passed from triumph to triumph. The discovery of the \( W \) and the \( Z \) demonstrated that the gauge structure of the standard model is correct. Precision measurements from LEP now indicate that the top-quark mass is about 150 GeV, and when top is discovered, the picture will be complete.

Or will it? Consider a theory with the known particles: quarks, leptons, gluons, the photon and the \( W \) and \( Z \). Then compute the scattering amplitude for two longitudinally-polarized \( W \) particles. As shown by Lee, Quigg and Thacker, the amplitude diverges with energy, and (perturbative) unitarity is violated below 2 TeV in the center of mass. Clearly, something must happen before then, and the SSC must be ready to find it.

On general grounds, we know that whatever unitarizes the \( W_L W_L \) scattering amplitude must also be responsible for giving mass to the \( W \) and \( Z \). Present experimental results shed little light on the issue. The fact that \( M_W \sim M_Z \cos \theta \) suggests that electroweak symmetry breaking respects a global symmetry \( G \supseteq SU(2)_L \times SU(2)_R \), spontaneously broken to \( H \supseteq SU(2)_V \). We will use this unbroken \( SU(2) \) “isospin” symmetry to organize our thinking about the physics of electroweak symmetry breaking.

THE STANDARD MODEL

In the standard model, the \( W_L W_L \) scattering amplitudes are unitarized by exchange of a spin-zero resonance, the Higgs particle \( H \). The Higgs is contained in a complex scalar doublet, \( \Phi = (v + H) \exp(2iw^a\tau^a/v) \), whose four components split into a triplet \( w^a \) and a singlet \( H \) under isospin. The \( w^a \) are the Goldstone bosons that give mass to the \( W \) and \( Z \), while the singlet is the Higgs particle \( H \).

The standard-model Higgs potential is invariant under an \( SU(2)_L \times SU(2)_R \) symmetry,

\[
\Phi \to L \Phi R^\dagger, \tag{1}
\]

with \( L, R \in SU(2) \). The vacuum expectation value \( \langle \Phi \rangle = v \) breaks the symmetry to the diagonal \( SU(2) \). In the perturbative limit, it also gives mass to the Higgs.
BEYOND THE STANDARD MODEL

There are many other alternatives that might describe the physics of electroweak symmetry breaking. In this talk we will study a variety of different models, each of which is completely consistent with all the data to date (including that from the Z). The models give an idea of the range of physics that might be seen at the SSC.

The first major distinction between the models is whether or not they are resonant in the $W_L W_L$ channel. If they are resonant, the models are classified by the spin and isospin of the resonance. If they are not, the analysis is more subtle, and we shall see that all possibilities can be described in terms of two parameters. In what follows, we will restrict our attention to nonresonant models, and to models with spin-zero, isospin-zero resonances (like the Higgs), and spin-one, isospin-one resonances (like the techni-rho).

Spin-zero, Isospin-zero Resonances

1) $O(2N)$. The first model we discuss represents an attempt to describe the standard-model Higgs in the nonperturbative domain. In the perturbatively-coupled standard model, the mass of the Higgs is proportional to the square root of the scalar self-coupling $\lambda$. Heavy Higgs particles correspond to large values of $\lambda$. For $M_H \gtrsim 1$ TeV, naive perturbation theory breaks down.

One possibility for exploring the nonperturbative regime is to exploit the isomorphism between $SU(2)_L \times SU(2)_R$ and $O(4)$. Using a large-$N$ approximation, one can solve the $O(2N)$ model for all values of $\lambda$, to leading order in $1/N$. The resulting scattering amplitudes can be parametrized by the scale $\Lambda$ of the Landau pole. Large values of $\Lambda$ correspond to small couplings $\lambda$ and relatively light Higgs particles. In contrast, small values of $\Lambda$ correspond to large $\lambda$ and describe the nonperturbative regime. In this talk we will take $\Lambda = 3$ TeV as a caricature of the strongly-coupled standard model.

2) Scalar. The second model describes the low-energy regime of a technicolor-like model whose lowest resonance is a techni-sigma. The effective Lagrangian for such a resonance can be constructed using the techniques of Callan, Coleman, Wess and Zumino.\(^4\) The resulting Lagrangian is consistent with the chiral symmetry $SU(2)_L \times SU(2)_R$, spontaneously broken to the diagonal $SU(2)$.

In this approach, the basic fields are $\Sigma = \exp(2iv^a \tau^a/v)$ and a scalar $S$. These fields transform as follows under $SU(2)_L \times SU(2)_R$,

$$\begin{align*}
\Sigma &\to L \Sigma R^\dagger, \\
S &\to S.
\end{align*}$$

To the order of interest, the Lagrangian contains just two parameters, which we can take to be the mass and the width of the $S$. In what follows, we will choose $M_S = 1.0$ TeV, $\Gamma_S = 350$ GeV. These values give unitary scattering amplitudes up to 2 TeV.

Spin-one, Isospin-one Resonances

1) Vector. This model provides a relatively model-independent description of the techni-rho resonance that arises in most technicolor theories.\(^5\) As above, one can use the techniques of CCWZ to construct the effective Lagrangian. The basic fields are $\xi = \exp(iw^a \tau^a/v)$ and a vector $\rho_\mu$, which transform as follows under $SU(2)_L \times SU(2)_R$,

$$\begin{align*}
\xi &\to L \xi U^\dagger = U \xi R^\dagger, \\
\rho_\mu &\to U \rho_\mu U^\dagger + ig''^{-1} U \partial_\mu U^\dagger,
\end{align*}$$

where $U(L, R, \xi) \in SU(2)$.

For the processes of interest, the effective Lagrangian again depends on just two couplings, the mass and the width of the resonance. In what follows we will choose $M_\rho = $
Table 1. Cuts, tags and vetos, by mode.

| Mode | Cuts | Details |
|------|------|---------|
| $W^+W^-$ Basic cuts | | Tag and Veto |
| $|y_\ell| < 2.0$ | $E_{tag} > 3.0$ TeV |
| $P_{T,\ell} > 100$ GeV | $3.0 < \eta_{tag} < 5.0$ |
| $\Delta P_{T,\ell \ell} > 200$ GeV | $P_{T,tag} > 40$ GeV |
| $\cos \phi_{\ell \ell} < -0.8$ | $P_{T,veto} > 60$ GeV |
| $M_{\ell \ell} > 250$ GeV | $|\eta_{veto}| < 3.0$ |
| ZZ Basic cuts | | Tag only |
| $|y_\ell| < 2.5$ | $E_{tag} > 1.0$ TeV |
| $P_{T,\ell} > 40$ GeV | $3.0 < \eta_{tag} < 5.0$ |
| $P_{T,Z} > \frac{1}{4}\sqrt{M_{ZZ}^2 - 4M_Z^2}$ | $P_{T,tag} > 40$ GeV |
| $M_{ZZ} > 500$ GeV | |
| $W^+Z$ Basic cuts | | Tag and Veto |
| $|y_\ell| < 2.5$ | $E_{tag} > 2.0$ TeV |
| $P_{T,\ell} > 40$ GeV | $3.0 < \eta_{tag} < 5.0$ |
| $P_{T,miss} > 75$ GeV | $P_{T,tag} > 40$ GeV |
| $P_{T,Z} > \frac{1}{4}M_T^*$ | $P_{T,veto} > 60$ GeV |
| $M_T > 500$ GeV | $|\eta_{veto}| < 3.0$ |
| $W^+W^+$ Basic cuts | | Veto only |
| $|y_\ell| < 2.0$ | $P_{T,veto} > 60$ GeV |
| $P_{T,\ell} > 100$ GeV | $|\eta_{veto}| < 3.0$ |
| $\Delta P_{T,\ell \ell} > 200$ GeV | |
| $\cos \phi_{\ell \ell} < -0.8$ | |
| $M_{\ell \ell} > 250$ GeV | |

* $M_T$ is the cluster transverse mass.\(^5\)

They are

$$\mathcal{L}^{(4)} = \frac{L_1}{16\pi^2} (\text{Tr} \partial_\mu \Sigma \partial^\mu \Sigma^\dagger)^2 + \frac{L_2}{16\pi^2} (\text{Tr} \partial_\mu \Sigma \partial^\mu \Sigma^\dagger)^2. \quad (4)$$

The coefficients $L_1$ and $L_2$ contain all information about the new physics.

The difficulty with this approach is that at SSC energies, the scattering amplitudes violate unitarity between 1 and 2 TeV. This is an indication that new physics is near, but there is no guarantee that new resonances lie within the reach of the SSC. We choose to treat the uncertainties of unitarization in three ways:

1) \textit{LET CG}. We take $L_1 = L_2 = 0$, and cut off the partial wave amplitudes when they saturate the unitarity bound. This is the original model considered by Chanowitz and Gaillard.\(^7\)

2) \textit{LET K}. We take $L_1 = L_2 = 0$, and unitarize with a K-matrix.

3) \textit{Delay K}. We take $L_1 = -0.26$ and $L_2 = 0.23$, a choice that preserves unitarity up to 2 TeV. Beyond that scale, we unitarize the scattering amplitudes with a K-matrix.\(^8\)

These three models describe possible nonresonant new physics at the SSC.

**SIGNALS AND Backgrounds**

In the rest of this talk we will focus on SSC signals and backgrounds for the process $pp \to WWX$. We will concentrate on the “gold-plated” decays $W^\pm \to \ell^\pm \nu$ and $Z \to \ell^+ \ell^-$, for $\ell = e, \mu$, in each of the final states $W^+W^-, W^+Z$, $ZZ$ and $W^+W^+$. 

We will take the signal to be the process $pp \to W_LW_LX$ because the longitudinal $W$’s couple most strongly to the new physics. We will take $pp \to W_LW_TX$ and $pp \to W_TW_TX$ to be the background. These processes are dominated by diagrams that do not depend on the new physics, so we will represent the background by the standard model with a light
Higgs (of mass 100 GeV). The difference between this and the true background is negligible at the energies we consider.

We will simplify our calculations by using the electroweak equivalence theorem,\(^1\) which lets us replace the longitudinal vector bosons by their corresponding would-be Goldstone bosons. We will also use the effective \(W\) approximation\(^9\) to connect the \(W_L W_L\) subprocesses to the \(pp\) initial state.

In the \(W^+W^-, W^+Z\) and \(ZZ\) channels, the final states of interest are dominated by glue-glue and \(q\bar{q}\) scattering.\(^10\) We suppress these contributions by requiring a tag on the forward jet\(^11\) associated with an initial-state \(W\). In the \(W^+W^-, W^+Z\) and \(W^+W^+\) channels, there is a residual background from top decay that we suppress by requiring a central jet veto.\(^12\) The combination of a forward jet tag and central jet veto is very effective in reducing the background in all charge channels.

The precise cuts we use are summarized in Table 1. In all channels, the dominant residual background is transverse electroweak, followed by \(q\bar{q}\) annihilation and top decay.

Because we use the effective \(W\) approximation for our signal, we can only estimate the effects of the tag and veto. Therefore we have used the exact standard-model calculation with a 1 TeV Higgs to derive efficiencies for the tag and veto. These efficiencies are then applied to the effective \(W\) calculations to estimate the rate for each signal. The results for the signals and backgrounds are collected in Table 2.

**DISCUSSION**

The results in Table 2 summarize the outcome of our study. As expected, the signal rates are largest in the resonant channels. Note, however, that the rates are all rather low. The events are clean, but the low rates will make it difficult to isolate high-mass resonances. We must be ready for this worst-case scenario and leave the door open for a high-luminosity program at the SSC.

A second conclusion from Table 2 is that all channels are necessary. For example, isospin-zero resonances give the best signal in the \(W^+W^-\) and \(ZZ\) channels, while isospin-one resonances dominate the \(W^+Z\) channel. The nonresonant models tend to show up in the \(W^+W^+\) final state, so there is a complementarity between the different channels.\(^2\)

A third conclusion is that we cannot cut corners. Accurate background studies are crucial if we hope to separate signal from background by simply counting rates. We must also try to measure all decay modes the \(W\) and \(Z\), including \(Z \to \nu\bar{\nu}\) and \(W, Z \to \text{jets}\). Finally, we must work to optimize the cuts that are applied to each final state, with an eye to increasing the signal/background ratio without affecting the total rate. All these considerations indicate that if the Higgs is heavy, or if technicolor is correct, SSC studies of electroweak symmetry breaking might need a mature and long-term program before they give rise to fruitful results.

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Table 2. Event rates per SSC-year, assuming $m_t = 140$ GeV, $\sqrt{s} = 40$ TeV, and an annual luminosity of $10^4$ pb$^{-1}$.

|           | Bkgd. | SM  | Scalar | $O(2N)$ | Vec 2.0 | Vec 2.5 | LET CG | LET K | Delay K |
|-----------|-------|-----|--------|---------|---------|---------|--------|-------|---------|
| $W^+W^-$ |       |     |        |         |         |         |        |       |         |
| $M_{\ell\ell} > 0.25$ | 9.1   | 59  | 31     | 26      | 12      | 10      | 12     | 10    | 9.7     |
| $M_{\ell\ell} > 0.5$  | 5.0   | 31  | 20     | 16      | 9.3     | 7.4     | 9.3    | 7.0   | 6.9     |
| $M_{\ell\ell} > 1.0$  | 0.9   | 2.0 | 0.6    | 1.5     | 3.6     | 2.6     | 2.9    | 1.9   | 2.5     |
| $W^+Z$    |       |     |        |         |         |         |        |       |         |
| $M_T > 0.5$ | 2.5   | 1.3 | 1.8    | 1.5     | 9.6     | 6.2     | 5.4    | 4.7   | 5.5     |
| $M_T > 1.0$ | 0.9   | 0.6 | 0.9    | 0.8     | 8.2     | 4.8     | 4.0    | 3.3   | 4.3     |
| $M_T > 1.5$ | 0.3   | 0.2 | 0.3    | 0.3     | 5.9     | 3.4     | 2.5    | 1.8   | 2.9     |
| $ZZ$      |       |     |        |         |         |         |        |       |         |
| $M_{ZZ} > 0.5$ | 1.0   | 11  | 6.2    | 5.2     | 1.1     | 1.5     | 2.5    | 2.1   | 1.5     |
| $M_{ZZ} > 1.0$ | 0.3   | 4.8 | 3.4    | 2.3     | 0.5     | 0.8     | 1.7    | 1.3   | 0.8     |
| $M_{ZZ} > 1.5$ | 0.1   | 0.6 | 0.2    | 0.5     | 0.1     | 0.3     | 0.9    | 0.6   | 0.3     |
| $W^+W^+$  |       |     |        |         |         |         |        |       |         |
| $M_{\ell\ell} > 0.25$ | 3.5   | 6.4 | 8.2    | 7.1     | 7.8     | 11      | 25     | 21    | 15      |
| $M_{\ell\ell} > 0.5$  | 1.9   | 3.8 | 5.0    | 4.5     | 4.5     | 7.2     | 7.0    | 16    | 11      |
| $M_{\ell\ell} > 1.0$  | 0.3   | 0.7 | 0.7    | 1.1     | 0.6     | 1.5     | 8.3    | 5.8   | 5.3     |

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