In this talk we survey the SSC and LHC signals and backgrounds for the physics of electroweak symmetry breaking. We study the process $pp \to WWX$ 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 and LHC sensitivities to the physics of electroweak symmetry breaking.

1. Introduction

In the standard model of particle physics, electroweak symmetry is broken by a the vacuum expectation value of a Higgs particle $H$, whose mass is expected to be less than a TeV. To date, however, there is still no experimental evidence – either direct or indirect – in favor of the Higgs.

One fact is certain: New physics is needed to break the electroweak symmetry. If one uses the known particles and computes the scattering amplitude for longitudinally-polarized $W$'s, one finds that rate the diverges with energy, and that (perturbative) unitarity is violated below 2 TeV. New physics is necessary to unitarize the scattering amplitude.\(^1\) In the standard model, the new physics is just the Higgs particle $H$.

In this talk we will look beyond the Higgs to study the SSC and LHC signals and backgrounds for a wide variety of models that break electroweak symmetry and unitarize the $W_LW_L$ scattering amplitude. Each of the models is completely consistent with all the data to date (including that from the $Z$). Together, they indicate the range of new physics that might be seen at the SSC or LHC.

2. The Models

At present, all we know about electroweak symmetry breaking is that $M_W \simeq M_Z \cos \theta$, which suggests that the underlying physics respects a global symmetry $G \supseteq SU(2)_L \times SU(2)_R$, spontaneously broken to $H \supseteq SU(2)_V$. In this talk we will examine a wide variety of models consistent with this "isospin" symmetry. The first major distinction is whether or not a given model is resonant in the $W_LW_L$ channel. If it is resonant, the model can be classified by the spin and isospin of the resonance. If it is not, the analysis is more subtle, and we shall see that all possibilities can be
described in terms of two parameters.

2.1. Spin-zero, Isospin-zero Resonances

1) Standard Model. The standard model is the prototype of a theory with a spin-zero, isospin-zero resonance. The $W_L W_L$ scattering amplitudes are unitarized by exchange of the Higgs particle $H$. The Higgs is contained in a complex scalar doublet, $\Phi = (v + H) \exp(2i w^a \tau^a/v)$, whose four components split into a triplet $w^a$ and a singlet $H$ under isospin.

The standard-model Higgs potential is invariant under an $SU(2)_L \times SU(2)_R$ symmetry. 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. For the purposes of this talk, we will take $M_H = 1$ TeV.

2) $O(2N)$. This model attempts 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 way to explore 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.

2.2. 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. One can use the time-honored techniques of chiral Lagrangians to construct the coupling between the techni-rho and the Goldstone bosons. The basic fields are $\xi = \exp(i w^a \tau^a/v)$ and a vector $\rho_\mu$, which transform nonlinearly under $SU(2)_L \times SU(2)_R$.

For the processes of interest, the effective Lagrangian depends on just two couplings, which we can take to be the mass and the width of the resonance. In what follows we will choose $M_\rho = 2.0$ TeV, $\Gamma_\rho = 700$ GeV and $M_\rho = 2.5$ TeV, $\Gamma_\rho = 1300$ GeV. These values preserves unitarity up to 3 TeV.

2.3. Nonresonant models

The final models we consider are nonresonant at SSC energies. In this case the new physics contributes to the effective Lagrangian in the form of higher-dimensional operators built from the Goldstone fields. To order $p^4$ in the energy expansion, there are only three operators that contribute to $W_L W_L$ scattering. They are

$$L = \frac{v^2}{4} Tr \partial_\mu \Sigma \partial_\mu \Sigma^+ + \frac{L_1}{16\pi^2} \left( Tr \partial_\mu \Sigma \partial_\mu \Sigma^+ \right)^2 + \frac{L_2}{16\pi^2} \left( Tr \partial_\mu \Sigma \partial_\mu \Sigma^+ \right)^2. \quad (1)$$
Table 1. SSC cuts, tags and vetoes, by mode.

| $W^+W^-$ Basic cuts | Tag and Veto | $ZZ$ Basic cuts | Tag only |
|----------------------|-------------|-----------------|---------|
| $|y_ℓ| < 2.0$           | $E_{tag} > 3.0$ TeV | $|y_ℓ| < 2.5$ | $E_{tag} > 1.0$ TeV |
| $P_{T,ℓ} > 100$ GeV   | $3.0 < η_{tag} < 5.0$ | $P_{T,ℓ} > 40$ GeV | $3.0 < η_{tag} < 5.0$ |
| $ΔP_{T,ℓℓ} > 200$ GeV | $P_{T,tag} > 40$ GeV | $P_{T,Z} > \frac{1}{7} \sqrt{M_{ZZ}^2 - 4M_{Z}^2}$ | $P_{T,tag} > 40$ GeV |
| $\cos φ_{ℓℓ} < -0.8$  | $P_{T,veto} > 60$ GeV | $M_{ZZ} > 500$ GeV |
| $M_{ℓℓ} > 250$ GeV    | $|η_{veto}| < 3.0$ |

| $W^+Z$ Basic cuts | Tag and Veto | $W^+W^+$ Basic cuts | Veto only |
|-------------------|-------------|---------------------|---------|
| $|y_ℓ| < 2.5$      | $E_{tag} > 2.0$ TeV | $|y_ℓ| < 2.0$ | $P_{T,veto} > 60$ GeV |
| $P_{T,ℓ} > 40$ GeV | $3.0 < η_{tag} < 5.0$ | $P_{T,ℓ} > 100$ GeV | $|η_{veto}| < 3.0$ |
| $P_{T,miss} > 75$ GeV | $P_{T,tag} > 40$ GeV | $ΔP_{T,ℓℓ} > 200$ GeV |
| $P_{T,Z} > \frac{1}{2} M_T^*$ | $P_{T,veto} > 60$ GeV | $\cos φ_{ℓℓ} < -0.8$ |
| $M_T > 500$ GeV  | $|η_{veto}| < 3.0$ | $M_{ℓℓ} > 250$ GeV |

$^*$ $M_T$ is the cluster transverse mass.

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 not necessarily within the reach of the SSC. We choose to treat the uncertainties of unitarization in two ways:

1) LET CG. We take $L_1 = L_2 = 0$, and cut off the partial wave amplitudes when they saturate the unitarity bound.\(^1\)

2) 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.

3. Signal and Backgrounds

In the rest of this talk we will focus on SSC and LHC signals and backgrounds for the process $pp \rightarrow WWX$. We will concentrate on the “gold-plated” decays $W^\pm \rightarrow ℓ^±ν$ and $Z \rightarrow ℓ^+ℓ^-$, for $ℓ = e, μ$, in each of the final states $W^+W^-$, $W^+Z$, $ZZ$ and $W^+W^+$. We will take the signal to be the process $pp \rightarrow W_LW_LX$ because the longitudinal $W$’s couple most strongly to the new physics. We will take $pp \rightarrow W_LW_TX$ and $pp \rightarrow W_TW_TX$ 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 equivalence theorem, which lets us replace the longitudinal vector bosons by their corresponding would-be Goldstone bosons. We will also use the effective $W$ approximation to connect the $W_LW_L$
Table 2. Event rates per SSC/LHC-year, assuming $m_t = 140$ GeV, $\sqrt{s} = 40/16$ TeV, and an annual luminosity of $10^4/10^5$ pb$^{-1}$.

| Subprocess | Bkgd. | SM 1.0 | $O(2N)$ | Vec 2.0 | Vec 2.5 | LET | CG | Delay K |
|------------|-------|--------|---------|---------|---------|-----|----|---------|
| $W^+W^-$  |       |        |         |         |         |     |    |         |
| $M_{\ell\ell} > 0.25$ | 9.1/13 | 59/74  | 26/30  | 12/9.7  | 10/8.9  | 12/11 | 9.7/8.9 |
| $M_{\ell\ell} > 0.5$  | 5.0/5.6 | 31/32  | 16/16  | 9.3/6.4 | 7.4/5.3 | 9.3/7.0 | 6.9/5.0 |
| $M_{\ell\ell} > 1.0$  | 0.9/0.7 | 2.0/1.2 | 1.5/0.8 | 3.6/1.8 | 2.6/1.2 | 2.9/1.3 | 2.5/0.9 |
| $W^+Z$     |       |        |         |         |         |     |    |         |
| $M_T > 0.5$ | 2.5/2.3 | 1.3/1.0 | 1.5/1.1 | 9.6/4.8 | 6.2/3.2 | 5.4/3.1 | 5.5/2.9 |
| $M_T > 1.0$ | 0.9/0.4 | 0.6/0.3 | 0.8/0.4 | 8.2/3.4 | 4.8/1.9 | 4.0/1.7 | 4.3/1.7 |
| $M_T > 1.5$ | 0.3/0.1 | 0.2/0.1 | 0.3/0.1 | 5.9/2.1 | 3.4/1.1 | 2.5/0.8 | 2.9/0.9 |
| $ZZ$       |       |        |         |         |         |     |    |         |
| $M_{ZZ} > 0.5$ | 1.0/1.0 | 11/14 | 5.2/6.4 | 1.1/1.4 | 1.5/1.7 | 2.5/2.5 | 1.5/1.8 |
| $M_{ZZ} > 1.0$ | 0.3/0.2 | 4.8/4.8 | 2.3/2.2 | 0.5/0.4 | 0.8/0.6 | 1.7/1.2 | 0.8/0.6 |
| $M_{ZZ} > 1.5$ | 0.1/0.0 | 0.6/0.4 | 0.5/0.3 | 0.1/0.1 | 0.3/0.2 | 0.9/0.5 | 0.3/0.2 |
| $W^+W^+$   |       |        |         |         |         |     |    |         |
| $M_{\ell\ell} > 0.25$ | 3.5/6.0 | 6.4/9.6 | 7.1/10 | 7.8/12 | 11/16 | 25/27 | 15/16 |
| $M_{\ell\ell} > 0.5$ | 1.9/2.1 | 3.8/4.6 | 4.5/5.2 | 4.5/6.0 | 7.2/8.8 | 20/18 | 11/9.6 |
| $M_{\ell\ell} > 1.0$ | 0.3/0.3 | 0.7/0.5 | 1.1/0.7 | 0.6/0.5 | 1.5/1.2 | 8.3/4.9 | 5.3/2.6 |

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. We suppress these contributions by requiring a tag on the forward jet$^6$ 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.$^7$ The combination of a forward jet tag and central jet veto is very effective in reducing the background in all charge channels.

The precise SSC cuts we use are summarized in Table 1. (The LHC cuts are the same except for the jet tags, which are $E_{jet} > 2.0$, 1.5, and 0.8 TeV in the $W^+W^-$, $W^+Z$, and $ZZ$ channels, respectively.) 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.
4. 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 prepared for a high-luminosity program at the SSC and LHC.

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.\(^1\)

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 $W, Z \to jets$. 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 electroweak symmetry is dynamically broken, SSC and LHC studies of electroweak symmetry breaking might need a mature and long-term program before they give rise to fruitful results.

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6. References

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