The Phenomenology of a Hidden Symmetry Breaking Sector

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ABSTRACT

We calculate the production rate of gauge-boson pairs at the SSC in a model with a “hidden” electroweak symmetry breaking sector. We show that the signal of electroweak symmetry breaking is lower than the background and that we cannot necessarily rely on gauge boson pairs as a signal of the dynamics of symmetry breaking.

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It is generally assumed that in the elastic scattering of longitudinally polarized \( W \)s and \( Z \)s either there will be resonances with masses of less than 1 TeV (as in the weakly coupled one-doublet Higgs model) or the scattering amplitudes will become large, indicating the presence of new strong interactions at or above 1 TeV (see, for example [1]). In a recent paper [2], two of us argued that there is another possibility: If the electroweak symmetry breaking sector has a large numbers of particles other than the longitudinal components of the \( W \) and \( Z \), then the elastic \( W \) and \( Z \) scattering amplitudes can be small and structureless, i.e. lacking any discernible resonances, at all energies. It was further argued that in such a model it may not be possible to rely on the two-gauge-boson events as a signal of the symmetry breaking sector. A toy model with these properties, based on an \( O(N) \) scalar field theory solved in the limit of large \( N \), was discussed.

These arguments have been recently been disputed by Kane, Naculich, and Yuan [3] who argue that, independent of \( N \), the total number of \( W_L W_L, Z_L Z_L \rightarrow Z_L Z_L \) scattering events in the \( O(N) \) model is comparable to the number of events due to a standard-model “TeV Higgs” boson, and may therefore be large enough to be observed. However, for large \( N \) the would-be Higgs resonance is both light and very broad. In this note, we compute both the gauge boson pair signal and background for the toy model presented in ref. [2]. We show that, while the number of gauge boson scattering events is approximately independent of \( N \), the background is much larger for a light resonance and this signal is not observable.

We also estimate the \( Z_L Z_L \) signal which arises from gluon fusion through a top quark loop [4]. Because the would-be Higgs of this model is light and broad, even this contribution to the signal is smaller than the background by a factor of four or more making detection problematic, at best.

We begin by reviewing the toy model of the electroweak symmetry sector constructed in [2]. This model has both exact Goldstone bosons (which will represent the longitudinal components of the \( W \) and \( Z \) [5]) and pseudo-Goldstone bosons. The Lagrangian density is

\[
\mathcal{L} = \frac{1}{2} (\partial \vec{\phi})^2 + \frac{1}{2} (\partial \vec{\psi})^2 - \frac{1}{2} \mu_{0,\phi}^2 \phi^2 - \frac{1}{2} \mu_{0,\psi}^2 \psi^2 - \frac{\lambda_0}{8N} (\phi^2 + \psi^2)^2 ,
\]

where \( \vec{\phi} \) and \( \vec{\psi} \) are \( j \)- and \( n \)-component real vector fields. This theory has an approximate \( O(j + n) \) symmetry (i.e. \( N = j + n \)) which is softly broken to \( O(j) \times O(n) \) so long as \( \mu_{0,\phi}^2 \neq \mu_{0,\psi}^2 \). If \( \mu_{0,\phi}^2 \) is negative and less than \( \mu_{0,\psi}^2 \), one of the components of \( \vec{\phi} \) gets a vacuum expectation value (VEV), breaking the approximate \( O(N) \) symmetry to \( O(N - 1) \).
With this choice of parameters, the exact $O(j)$ symmetry is broken to $O(j - 1)$ and the theory has $j - 1$ massless Goldstone bosons and one massive Higgs boson. The $O(n)$ symmetry is unbroken, and there are $n$ degenerate pseudo-Goldstone bosons of mass $m_\psi (m_\psi^2 = \mu_0^2 - \mu_0^2)$. This model is particularly interesting since it can be solved (even for strong coupling) in the limit of large $N$ \cite{3}. We will consider this model in the limit that $j, n \to \infty$ with $j/n$ held fixed.

The scalar sector of the standard one-doublet Higgs model has a global $O(4) \approx SU(2) \times SU(2)$ symmetry, where the 4 of $O(4)$ transforms as one complex scalar doublet of the $SU(2)_W \times U(1)_Y$ electroweak gauge interactions. It is this symmetry which is enlarged in the $O(N)$ model: we will model the scattering amplitudes of longitudinal gauge bosons by the corresponding $O(j)$ Goldstone boson scattering amplitudes in the $O(j + n)$ model solved in the large $j$ and $n$ limit. Of course, $j = 4$ is not particularly large. Nonetheless, the resulting model will have all of the correct qualitative features, the Goldstone boson scattering amplitudes will be unitary (to the appropriate order in $1/j$ and $1/n$), and we can investigate the theory at moderate to strong coupling \cite{7}. We make no assumptions about the embedding of $SU(2)_W \times U(1)_Y$ in $O(n)$, i.e. no assumptions about the electroweak quantum numbers of the pseudo-Goldstone bosons: we will assume, however, that the pseudo-Goldstone bosons are $SU(3)$ color singlets\footnote{Gauge boson pair production in models with colored pseudo-Goldstone bosons is discussed in detail in \cite{8}.}

One may compute Goldstone boson scattering to leading order in $1/N$. The details of the calculation may be found in \cite{2}. The amplitude $a^{ij:kl}(s, t, u)$ for the process $\phi^i \phi^j \rightarrow \phi^k \phi^l$ is

$$a^{ij:kl}(s, t, u) = A(s)\delta^{ij}\delta^{kl} + A(t)\delta^{ik}\delta^{jl} + A(u)\delta^{il}\delta^{jk}$$  \hspace{1cm} (2)

where

$$A(s) = \frac{s}{v^2 - Ns \left(\frac{1}{\lambda(M)} + \bar{B}(s; m_\psi, M)\right)},$$  \hspace{1cm} (3)

and

$$\bar{B}(s; m_\psi, M) = \frac{n}{32N\pi^2} \left\{ \frac{1}{\sqrt{s/(4m_\psi^2 - s)}} \left\{ \log \frac{i - \sqrt{s/(4m_\psi^2 - s)}}{i + \sqrt{s/(4m_\psi^2 - s)}} - \log \frac{m_\psi^2}{M^2} \right\} \right\}$$  \hspace{1cm} (4)

1. Gauge boson pair production in models with colored pseudo-Goldstone bosons is discussed in detail in \cite{8}.
Here $s, t,$ and $u$ are the usual Mandelstam variables, $v$ is the weak scale (approximately 250 GeV), and $M$ is a renormalization point which we chose below such that the renormalized coupling, $\lambda(M)$, satisfies $1/\lambda(M) = 0$.

The amplitude $a^{ij:kl}$ of eqn. (2) may be used to derive partonic cross sections for $W_LW_L$, $Z_LZ_L \rightarrow Z_LZ_L$ which can then be folded with the appropriate gauge boson structure functions (using the “effective-W approximation” and the EHLQ set II structure functions) to yield the contribution of gauge boson scattering to the process $pp \rightarrow ZZ + X$. This contribution to the differential cross section for $ZZ$ production as a function of $ZZ$ invariant mass is shown in the dot-dash lines of fig. [1] for $n = 32$ and $M = 1500$ GeV.

As in the standard model, gluon fusion through a top quark loop provides a signal for gauge boson pairs comparable to the signal from gauge boson scattering. The correct computation in this model is somewhat nontrivial. We wish to work to lowest nonvanishing order in $\alpha_s$ (the QCD coupling constant) and the top quark Yukawa coupling. To this order, there are three diagrams that contribute to the $Z_LZ_L$ final state. The first is the simple top quark triangle diagram, the analogue of the Higgs production diagram in the standard model. Next there is the top-quark box, which produces final state longitudinal $Z$’s exactly as in the standard model. Lastly, there is a two-loop diagram, in which a box of quarks (not all four sides of which are top) produces a pair of Goldstone bosons which rescatter through the Higgs boson into $Z_LZ_L$. This last diagram must also be computed to get a correct, gauge invariant answer, since it is leading in $1/N$.

To get a rough estimate of the rate, we concentrate on the top-quark triangle, ignoring the other two diagrams. The amplitude for this diagram is

$$
\frac{\alpha_s}{2\pi} \left[ v^2 - Ns \left( \frac{1}{\lambda(M)} + \tilde{B}(s; m_\psi, M) \right) \right] \left( g^{\mu\nu} - \frac{2p_2^\mu p_1^\nu}{s} \right) I(s, m_t^2) . \tag{5}
$$

Here $p_1$ and $p_2$ are the momenta of the two incoming gluons with polarization vectors associated with $\mu$ and $\nu$ and colors with the $a$ and $b$ respectively, and the function $I(s, m_t^2)$ is the Feynman parameter integral

$$
I(s, m_t^2) = m_t^2 \int_0^1 dx \int_0^{1-x} dy \frac{(1 - 4xy)}{m_t^2 - xys - i\epsilon} , \tag{6}
$$

and $m_t$ is the mass of the top quark. The contribution of this process to $ZZ$ production is shown as the solid curve in fig. [1].
The irreducible background to observing the Higgs boson in $Z$ pairs comes from the process $q\bar{q} \rightarrow ZZ$ and is shown as the dashed curves in fig. 1. We see that the background is more than an order of magnitude larger than the gauge boson scattering signal and that this signal is unobservable. Even the gluon fusion contribution to the $Z_L Z_L$ production cross section is lower than the background by a factor of four or more, making detection of such a broad resonance problematic.

In [3] it was shown that the numbers of final state gauge boson pairs from gauge boson scattering is roughly independent of $N$ if $\sqrt{NM}$ is held fixed. This is because as $N$ increases for fixed $\sqrt{NM}$, $M$ and the mass and width of the Higgs boson decrease like $1/\sqrt{N}$. The increased production of Higgs bosons due to their smaller mass is approximately cancelled by the Higgs boson’s smaller branching ratio into $W$s and $Z$s. The number of signal events, therefore, is approximately independent of $N$ and is the same as the number which would be present in the model with $n = 0$ described in ref. [7]. Since the signal for gauge boson scattering in that model is (marginally) observable [3] and since the number of $ZZ$ events is roughly independent of $n$, the authors of ref. [3] argue that the signal may be observable for any $n$.

We have calculated the signal and background for the parameters chosen in [3], $n = 8$ and $M = 2500$ GeV (with a Higgs mass of approximately 485 GeV). The results are plotted in fig. 2 and the results for $n = 0$, $M = 4300$ GeV are plotted in fig. 3. It is true that the total number of gauge boson scattering events is comparable in figs. 2,3, and even in fig. 1. However, the background is much greater when $n = 8$ or 32 since the corresponding Higgs is much lighter. The gauge boson scattering signal with $n = 8$ or 32 is “hidden” because the Higgs boson is both light and broad. In both cases, the gluon fusion signal is substantially larger than the gauge boson scattering signal. The signal, however, is still significantly below the background, making detection of a broad resonance difficult, at best.

By way of comparison, the signal for a 485 GeV standard model Higgs is shown in fig. 4. In this case, because the Higgs is relatively narrow, on the peak the gauge boson scattering Higgs signal is comparable to the background and the gluon fusion signal is well above the background.

There are two technical shortcomings in the calculation of the cross sections presented above. Firstly, in computing the gauge boson scattering signal, we have used both the

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2 And therefore higher gauge boson partonic luminosity [9].
equivalence theorem \[5\] and the effective-$W$ approximation \[7\]. Strictly speaking, both of these approximations hold only at energies above a few times the $W$ mass. Even at 200 GeV, however, the corrections should be of order one \[8][12\], whereas the background at these energies when $n = 32$ is more than an order of magnitude larger. While we cannot precisely determine the number of gauge boson scattering events, it is clear that they are swamped by the background. Second, in computing the gluon fusion signal, we have only computed the contribution from a top quark triangle diagram and have not included the contributions from the other two of the three leading diagrams, as discussed above. These will interfere with the contribution we have computed. However, we do not expect this to change any of our conclusions.

In general, the two-gauge-boson scattering signal of the symmetry breaking sector is not visible above the background unless the gauge boson elastic scattering amplitudes are big. This can happen either if the symmetry breaking sector is strongly coupled or at the peak of a narrow resonance. We can see this just by counting coupling constants: the background ($qq \to ZZ$) is order $g^2$ and is a two body final state, while the signal ($qq \to qqZZ$) is naively of order $g^4$ and is a four body final state. When the symmetry breaking sector is strongly interacting and the final state gauge bosons are longitudinal, this naive $g^4$ gets replaced by $g^2 a_{ijkl}$, and the signal may compete with the background. Since $a_{ijkl}$ in the $O(4 + 32)$ model is never large, the signal rate never approaches the background rate.

Moreover, while we have concentrated on the signal for the $ZZ$ final state, the arguments given here should apply equally to all other two-gauge-boson signals as well. In the $O(4 + 32)$ model it is likely that none of the two-gauge-boson signals of the symmetry breaking sector may be observed over the background. In this model even observing all two-gauge-boson modes will not be sufficient to detect the dynamics of electroweak symmetry breaking – one will need to observe the pseudo-Goldstone bosons, and identify them with symmetry breaking.

In conclusion, we see that in models of electroweak symmetry breaking with a large number of pseudo-Goldstone bosons the longitudinal gauge boson scattering amplitudes may be small and structureless at all energies. In this case we cannot necessarily rely on gauge boson pairs as a signal of the dynamics of symmetry breaking.

We would like to thank Kenneth Lane for useful conversations, Elizabeth Simmons for reading the manuscript, and Gordon Kane, Steven Naculich, and C.-P. Yuan for sending
us ref. prior to publication. R.S.C. acknowledges the support of an Alfred P. Sloan Foundation Fellowship, an NSF Presidential Young Investigator Award and DOE Outstanding Junior Investigator Award. This work was supported in part under NSF contract PHY-9057173 and DOE contracts DE-AC02-89ER40509 and DE-FG02-91ER40676, and by funds from the Texas National Research Laboratory Commission under grant RGFY91B6.
Figure Captions

Fig. 1. Differential production cross section for \( pp \rightarrow ZZ \) (at a \( pp \) center of mass energy of 40 TeV) as a function of invariant \( Z \)-pair mass for \( j = 4, n = 32, m_\psi = 125 \) GeV and the renormalization point \( M = 1500 \) GeV. A rapidity cut of \(|y| < 2.5\) has been imposed on the final state \( Z \)s. The gauge boson scattering signal is shown as the dot-dash curve and gluon fusion signal (with \( m_t = 120 \) GeV) as the solid curve. The background from \( q\bar{q} \) annihilation is shown as the dashed curve. In all contributions, the rapidities of the \( Z \)s must satisfy \(|y_Z| < 2.5\). All computations use the EHLQ set II [10] structure functions with \( Q^2 = M_W^2 \) in the gauge boson scattering curve, and \( Q^2 = \hat{s} \) in the other two cases.

Fig. 2. Same as fig. 1 with \( n = 8 \) and \( M = 2500 \) GeV, as in ref. [3].

Fig. 3. Same as fig. 1 with \( n = 0 \) (ref. [4]) and \( M = 4300 \) GeV.

Fig. 4. Same as fig. 1 for a standard model Higgs boson with mass 485 GeV.
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