BNL-45782

W_LW_L SCATTERING AT THE SSC*

Jonathan Bagger,[(a)] Sally Dawson[(b)] and German Valencia[(c)]

[(a)] Department of Physics & Astronomy, The Johns Hopkins University
Baltimore, Maryland 02138

[(b)] Physics Department, Brookhaven National Laboratory
Upton, New York 11973

[(c)] Theory Division, CERN
CH-1211 Geneva 23

ABSTRACT

We use higher-order chiral Lagrangians to study W_LW_L scattering at the SSC. We analyze a model that is consistent with crossing, unitarity and chiral symmetry, with no resonant behavior at SSC energies. The only signal is a slightly enhanced rate for W_LW_L scattering. Our results indicate the level of sensitivity that must be reached before the SSC can be assured of discovering the mechanism for electroweak symmetry breaking.

I. INTRODUCTION

Despite the great success of the standard model, not much is known about the mechanism by which the electroweak symmetry is broken from $SU(2) \times U(1)$ to the $U(1)$ of electromagnetism. There are many options, ranging from a standard Higgs scenario with elementary scalars, to some sort of dynamical scheme such as technicolor, walking technicolor, ultracolor, or even BCS theory. In the absence of experiment, there is no compelling reason to believe any particular model.

The task of the SSC is to address this question. Experiments at the SSC must be prepared to find an ordinary Higgs particle, or to find something else indicative of the weak symmetry breaking. One particularly important investigation is the study of W_LW_L scattering at high energies, which should reveal any s-channel resonances associated with the symmetry breaking, such as a scalar Higgs particle or a vector techni-rho. Alternatively, if there are no resonances, one would hope that W_LW_L scattering would be sensitive to the mechanism of symmetry breaking [1,2].

*Work supported by the National Science Foundation, grant PHY-90-96198, by the Department of Energy, contract DE-AC02-76CH00016, and by the Alfred P. Sloan Foundation.

In this paper we examine W_LW_L scattering at the SSC. Our study is based on chiral Lagrangians, which describe longitudinal W scattering in a model-independent way. Initial studies, carried out by Chanowitz and Gaillard [1] and by Chanowitz and Golden [3], used the lowest-order chiral Lagrangian and a crude unitarization procedure to predict that the cross-section for W_LW_L scattering should exhibit a slight enhancement in the absence of light resonances. More recently, Dobado, Herrero and Terron [4] have used higher-order chiral Lagrangians together with a Padé unitarization prescription to mimic the signals from very heavy Higgs-like and rho-like resonances. Each group concluded that the signals are marginal at best for the SSC.

Our approach is to use higher-order chiral Lagrangians to survey the physics associated with W_LW_L scattering. We start by constructing the leading higher-order Lagrangian. This Lagrangian contains two free parameters; it describes the effective interactions of longitudinal W's in the absence of light resonances. By varying these parameters, scan the full range of W_L physics (requiring all amplitudes to be consistent with crossing, unitarity and chiral symmetry). Our theories represent a set of worst-case scenarios for the SSC, in which there are no light resonances, and only a small enhancement in the rate of W_LW_L scattering. The results presented here indicate the level of sensitivity that must be reached before SSC experiments can be assured of discovering evidence related to the electroweak symmetry-breaking scheme.

II. CHIRAL LAGRANGIANS

Our analysis in this report relies on the electroweak equivalence theorem, which states that at energies $s \gg M_W$, longitudinal W scattering can be described by the scattering of Goldstone bosons, up to corrections of order M_W^2/s [5]. This has the important consequence that longitudinal W particles must obey the same low-energy theorems as Goldstone bosons.

On quite general grounds, it is known that the effective interactions of Goldstone bosons are determined by symmetry principles [6]. One only needs to know the full group G and the unbroken subgroup H. For the case at hand, the fact that $M_W = M_Z \cos\theta$ (together with the assumption that there are just three Goldstone bosons) implies that $G = \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$, and that H is the diagonal SU(2) subgroup [7], often called "weak isospin." This tells us that the Goldstone bosons parametrize the coset $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R/\mathrm{SU}(2)$, just like the pions of QCD.

The interactions of the pions in QCD are well-described in terms of a chiral Lagrangian. The chiral Lagrangian parametrizes the effective theory of pions that exists below the scale of the first resonances [8]. The lowest-order terms reproduce the famous low-energy theorems. The higher-order terms give corrections of order $\hat{s}/16\pi^2 f_\pi^2$, where $\hat{s}$ is the square of the CM energy, and $f_\pi = 93$ MeV is the pion decay constant. The higher-order corrections can be adjusted to describe the low-energy approach to the rho [9].

For the case of electroweak symmetry breaking, the Goldstone fields w^a play the role of the pions of QCD. To lowest order, the only difference is the strength of $F_\pi = v = 246$ GeV. To higher orders, the chiral Lagrangian can be adjusted to describe the dynamics associated with different symmetry breaking schemes [10]. In this sense the higher-order chiral Lagrangian provides a universal description of the weak interaction symmetry breaking, valid for subprocess energies $E \lesssim 4\pi v \simeq 3$ TeV.

The essential features of chiral dynamics are described by an SU(2) field Σ, given by

$$\Sigma \;=\; \exp(i2w^aT^a/v)\ . \qquad (1)$$

The SU(2) generators T^a are normalized so that $\mathrm{Tr}\,T^aT^b = \frac{1}{2}\delta^{ab}$. An arbitrary $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$ transformation acts on Σ as follows,

$$\Sigma \;\rightarrow\; L\Sigma R^\dagger\ . \qquad (2)$$

This induces a nonlinear transformation on the w^a. When $L = R$, the transformation linearizes and the w^a form a triplet of the unbroken SU(2).

Using these transformations, it is easy to write down the most general $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$ invariant chiral Lagrangian with at most four derivatives [11],

$$\begin{aligned}\mathcal{L} \;=\;& \frac{v^2}{4}\,\mathrm{Tr}\,\partial_\mu\Sigma\,\partial_\mu\Sigma^\dagger \;+\; \alpha_1\,\mathrm{Tr}\,[\,\partial_\mu\Sigma,\,\partial_\mu\Sigma^\dagger\,]^2 \\ &+ \alpha_2\,\mathrm{Tr}\,[\,\partial_\mu\Sigma,\,\partial_\nu\Sigma^\dagger\,]^2\ . \qquad (3)\end{aligned}$$

The leading-order term is unique; it gives rise to the low-energy theorems of chiral dynamics. The next-order terms are specified by two parameters, α_1 and α_2. They describe the first-order corrections in the energy expansion.

The Lagrangian (3) can be used to compute the Goldstone-Goldstone scattering amplitudes to order $\hat{s}^2$. There are two types of contributions to this order. The first is a direct coupling that follows from the tree-level Lagrangian. The second is a one-loop correction that must be included at order $\hat{s}^2$. The one-loop contribution renormalizes the parameters α_1 and α_2. It also gives finite logarithmic corrections that cannot be absorbed into a redefinition of the couplings [8].

The full range of low energy physics can be surveyed by scanning over α_1 and α_2, generating a set of models that are consistent for energies below the scale at which unitarity is violated. Since unitarity violation signals the onset of new physics (such as resonances), we shall search for models in which the violation is pushed to the highest possible energies. In this way we will free our work from the ambiguities that follow from a particular unitarization scheme [12].

The practical definition of unitarity is a matter of some controversy in the literature. However, for the case at hand, the correct condition is that each partial wave must respect elastic unitarity. For an isospin-I spin-J partial wave T_{IJ}, this implies

$$\mathrm{Im}\,T_{IJ} \;=\; |\,T_{IJ}\,|^2\ . \qquad (4)$$

Therefore our prescription will be to use the Lagrangian (3) to compute the real part of each partial wave (for $I, J \le 2$). We will then use (4) to find the imaginary part to order $\hat{s}^3$. With this prescription, our results will be fully unitary and crossing symmetric.

Note, however, that this prescription works only if $\mathrm{Re}\,T_{IJ} < 1/2$. This, therefore, will serve as our practical definition of unitarity. Using this condition, it is not hard to show that the leading contribution to the T_{00} partial wave violates unitarity at about 1.2 TeV. This bound, however, can be extended by a judicious choice of α_1 and α_2. Scanning the (α_1, α_2) parameter space, we find that the values

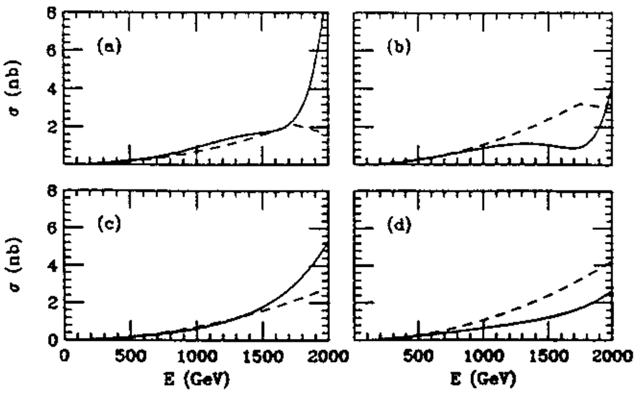

Fig. 1. Subprocess cross sections for the parameters of equation (5). The lowest-order amplitudes with the Chanowitz-Gaillard unitarization [1] are shown with dashed lines. (a) $W^+W^- \to W^+W^-$, (b) $W^+W^- \to ZZ$, (c) $W^+Z \to W^+Z$, (d) $W^+W^+ \to W^+W^+$.

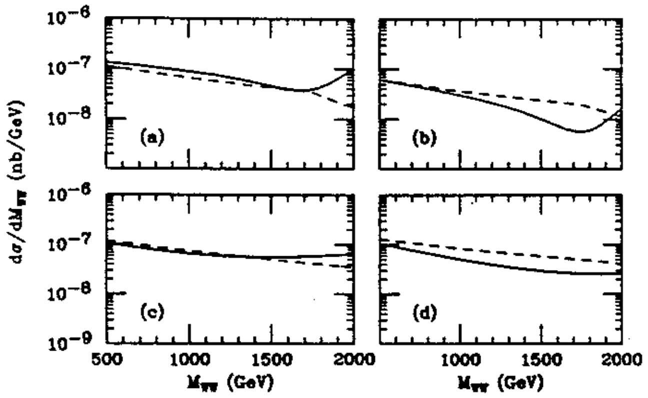

Fig. 2. Proton-proton cross sections for the parameters of equation (5). The lowest-order amplitudes with the Chanowitz-Gaillard unitarization [1] are shown with dashed lines.

$$
\begin{aligned}
\alpha_1 &= -0.00167 \\
\alpha_2 &= 0.00147\ , \qquad (5)
\end{aligned}
$$

measured at a renormalization scale $\mu = 1500$ GeV, delay the unitarity breakdown as much as possible, until 2.0 TeV. We shall use these values in the rest of this report.

III. THE SIGNAL AND BACKGROUND

In this section we will examine the signal that follows from the Lagrangian (3), with α_1 and α_2 chosen as in (5). This signal represents a potential worst-case scenario for the SSC, with no resonant behavior in any isospin channel. With these parameters, this

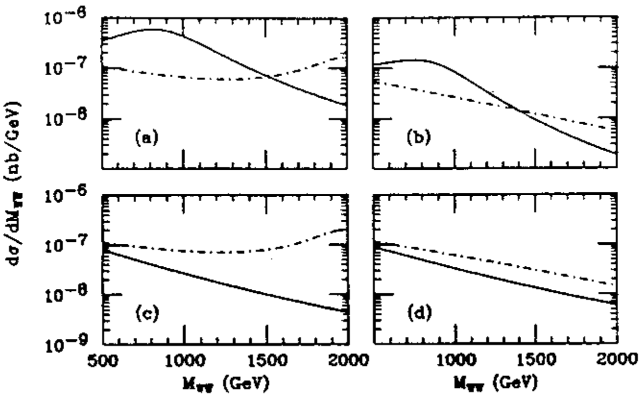

Fig. 3. Proton-proton cross sections for the O(2N) model (solid line) and for an $N = 3$ techni-rho (dot-dashed line).

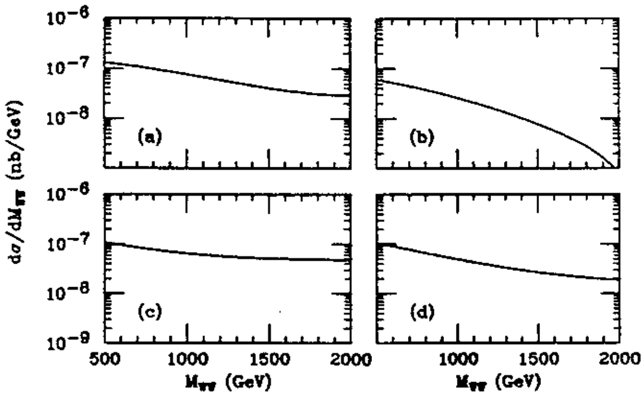

Fig. 4. Proton-proton cross sections for the parameters of equation (5), with K-matrix unitarization.

Lagrangian describes a world in which all new resonances are pushed well past 2 TeV.

The cross-sections that follow from the effective Lagrangian with the parameters (5) are shown in Figures 1 and 2. Figure 1 shows selected subprocess cross-sections as a function of the CM energy. At low energies, the full calculation agrees with the lowest-order results because both obey the appropriate low-energy theorems. At higher energies, the effects of the higher-order terms become important, and the curves differ significantly.

Figure 2 shows the subprocess cross sections after they are convoluted with the W_L luminosity in a proton [13]. The W_L luminosity is evaluated using the effective W approximation at SSC energies, assuming $\sqrt{s} = 40$ TeV. The plots are cut off at $M_{WW} = 500$ GeV because the equivalence theorem does not hold at low energies. Note that the differences between the

Table I
Signal Cross Sections, in Events per SSC-year

	$500 < M_{WW} < 2000$		$1000 < M_{WW} < 2000$		$1500 < M_{WW} < 2000$	
	$\|y\| < 1.5$	$\|y\| < 2.5$	$\|y\| < 1.5$	$\|y\| < 2.5$	$\|y\| < 1.5$	$\|y\| < 2.5$
W^+W^-	750	1,380	380	700	160	290
$W^\pm Z$	960	2,000	600	1,260	300	670
ZZ	350	650	160	260	50	90
W^+W^+	270	480	140	250	60	110

Table II
Background Cross Sections, in Events per SSC-year

	$500 < M_{WW} < 2000$		$1000 < M_{WW} < 2000$		$1500 < M_{WW} < 2000$	
	$\|y\| < 1.5$	$\|y\| < 2.5$	$\|y\| < 1.5$	$\|y\| < 2.5$	$\|y\| < 1.5$	$\|y\| < 2.5$
W^+W^-	12,000	56,000	1,200	4,600	230	790
$W^\pm Z$	5,900	36,000	610	3,100	120	560
ZZ	2,900	11,000	280	920	50	150

graphs is much less pronounced; this simply reflects the fact that the W_L luminosity falls sharply with energy. In the absence of resonances, the falling luminosity makes it very hard to distinguish between different models of strong-interaction physics [10].

For comparison, we show in Figure 3 the same plots for the O($2N$) model (with $\Lambda = 3$ TeV) and for $N = 3$ technicolor. The O($2N$) model is supposed to describe a strongly-interacting Higgs theory, and it indeed has an enhancement in the W^+W^- and ZZ channels [14]. The $N = 3$ techni-rho is described in Ref. [15]; it gives rise to an enhancement in the W^+W^- and $W^\pm Z$ final states. In comparison, the chiral model of Figure 2 has a small enhancement in all three channels, which can be interpreted as the approach to a set of high-energy resonances [16].

The model discussed here violates unitarity at 2.0 TeV, so the graphs presented here are not reliable for $M_{WW} \gtrsim 1.8$ TeV. To probe this region, one has to rely on some unitarization scheme. Different schemes have different virtues; we will content ourselves with the observation that a particular scheme can either increase or decrease the signal. For example, applying a K-matrix to the model presented here, we find the graphs shown in Figure 4. The signal is reduced compared to Figure 2.

To gain a rough idea of the magnitude of the signal, we have integrated the proton-proton cross-section, using the EHLQ set I structure functions (with $Q^2 = M^2_{WW}$) [17], subject to the cuts 2000 GeV $> M_{WW} >$ 500, 1000 and 1500 GeV, and rapidity $|y| < 1.5$ and 2.5. The results are presented in Table I, in events/SSC-year, assuming an annual luminosity of 10 fb^{-1}. All initial states that contribute to a given final state are included. Because we have used the equivalence theorem, the numbers are correct to leading order in M_W/M_{WW}. The results are not adjusted for efficiencies; nor do they include branching fractions for the W and Z decays. If only the e, μ final states are considered, the rate is very small.

A careful computation of the background is beyond the scope of this report. However, an under-estimate of the background can be obtained by considering lowest-order cross section for $\bar{q}q \to W^+W^-$, $W^\pm Z$, or ZZ [18], evaluated using the EHLQ set I structure functions, with $Q^2 = \hat{s}$ [17]. Such a computation was done for us by T. Han, who found the numbers quoted in Table II, subject to the same cuts as in Table I. (The numbers increase by a factor of about 1.3 if a QCD K-factor is included.)

The numbers presented in these tables are subject to significant uncertainties from the choice of proton structure functions. Nonetheless, they can be used to make general statements about what one might expect at the SSC. A glance at the tables indicates that in most cases, the signal is substantially below the background. The best signal/background ratio, about 2.5, is obtained in the $W^\pm Z$ channel, for $|y| < 1.5$ and $1500 < M_{WW} < 2000$ GeV. However, once the e, μ branching fraction is taken into account, and a 50% detection efficiency is assumed, the rate is reduced to just

1.8 signal events over 0.7 background events per SSC-year. The rate can be improved by loosening the cuts. If the rapidity cut is relaxed to $|y| < 2.5$, the event rate increases to about 4.1 e, μ events over 3.4 background per SSC-year. If the rapidity cut is left at $|y| < 1.5$ but the M_{WW} cut is reduced to $1000 < M_{WW} < 2000$ GeV, there are 3.6 signal events over 3.7 background. The low rates and structureless signal will make it very difficult to separate the signal from the background without W_L/W_T identification or increased luminosity. (Note that the signal rate would have been even lower if we had used a K-matrix to unitarize the region above 2 TeV.)

The channel with the smallest background is the W^+W^+ channel. The analysis, however, is complicated by significant contamination from $\bar{t}t$ decays. The signals and backgrounds for this channel have been carefully analyzed by Barger, Cheung, Han and Phillips [19], who looked at e and μ final states. They found 2.4 events over 3.5 background (with $m_t = 100$ GeV) for the O($2N$) model, and 3.9 events over 3.5 background for $N = 3$ technicolor, assuming a 50% detector efficiency, as well as a central jet veto. Using these figures as a guide, and comparing Figures 2 and 3, we estimate that we might expect approximately 4.6 leptonic signal events over 3.5 background per year at the SSC. This signal rate is consistent with what one might expect from Table I.

IV. CONCLUSION

In this paper we have analyzed a model, based on chiral perturbation theory, that describes the interactions of longitudinal W's and Z's up to 2 TeV. The model is unitary and crossing symmetric, and is also completely consistent with all low-energy phenomenology. Its only signal at the SSC is a slightly enhanced scattering rate into longitudinal vector bosons.

While we do not take this model too seriously as a realistic alternative to the standard model, we must point out that it is a logical possibility. It represents a potential worst-case scenario, where the signal has a small rate and a structureless spectrum. Such a signal would be exceedingly hard to detect, but it does indicate the sensitivity that might be required to detect the mechanism for weak symmetry breaking at the SSC.

V. REFERENCES

[1] M. S. Chanowitz and M. K. Gaillard, Nucl. Phys. **B261**, 379 (1985).

[2] M. S. Chanowitz, in *The Salt Lake City Meeting: Proceedings*, Salt Lake City, Utah, eds. C. DeTar and J. Ball (World Scientific, Singapore, 1987); Ann. Rev. of Nucl. Part. Phys. **38**, 323 (1988).

[3] M. Chanowitz, and M. Golden, Phys. Rev. Lett. **61**, 1053 (1988); (E) **63**, 466 (1989).

[4] A. Dobado, M. Herrero, and J. Terron, CERN-TH.5670/90; CERN-TH.5813/90.

[5] J. M. Cornwall, D. N. Levin and G. Tiktopoulos, Phys. Rev. **D10**, 1145 (1974); **11**, 972 (E) (1975); B. W. Lee, C. Quigg and H. B. Thacker, Phys. Rev. **D16**, 1519 (1977); M. S. Chanowitz and M. K. Gaillard, Nucl. Phys. **B261**, 379 (1985); Y.-P. Yao and C. P. Yuan, Phys. Rev. **D38**, 2237 (1988); J. Bagger and C. Schmidt, Phys. Rev. **D41**, 264 (1990).

[6] S. Weinberg, Phys. Rev. **166**, 1568 (1968); S. Coleman, J. Wess and B. Zumino, Phys. Rev. **177**, 2239 (1969); C. Callan, S. Coleman, J. Wess and B. Zumino, Phys. Rev. **177**, 2247 (1969); S. Weinberg, Physica **96A**, 327 (1979).

[7] M. Chanowitz, H. Georgi, M. Golden, Phys. Rev. **D36**, 1490 (1987); Phys. Rev. Lett. **57**, 2344 (1986).

[8] J. Gasser and H. Leutwyler, Ann. Phys. **158**, 142 (1984); Nucl. Phys. **B250** 465 (1985).

[9] J. F. Donoghue, C. Ramirez and G. Valencia, Phys. Rev. **D39**, 1947 (1989); G. Ecker, J. Gasser, A. Pich and E. de Rafael, Nucl. Phys. **B321**, 311 (1989); G. Ecker, J. Gasser, H. Leutwyler, A. Pich and E. de Rafael, Phys. Lett. **223B**, 425 (1989).

[10] For example, at tree level, $-\alpha_1 = \alpha_2 > 0$ describes a rho-like resonance, while $\alpha_1 > 0$, $\alpha_2 = 0$ describes a Higgs. See J. F. Donoghue and C. Ramirez, Phys. Lett. **234B**, 361 (1990); S. Dawson and G. Valencia, preprint BNL 45194 (1990), to appear in Nucl. Phys. B.

[11] We have not written terms that vanish for on-shell external states.

[12] Amplitudes unitarized by different techniques have been studied by W. W. Repko and C. J. Suchyta III, Phys. Rev. Lett. **62**, 859 (1989); D. Dicus and W. W. Repko, Phys. Lett. **B228**, 503 (1989); A. Dobado, M. J. Herrero and T. N. Truong, Phys. Lett. **B235**, 129 (1990); R. Rosenfeld, Phys. Rev. **D42**, 126 (1990).

[13] M. Chanowitz and M.K. Gaillard, Phys. Lett. **B142**, 85 (1984); G. Kane, W. Repko, and W. Rolnick, Phys. Lett. **B148**, 367 (1984); S. Dawson, Nucl. Phys. **B249**, 42 (1985).

[14] M. Einhorn, Nucl. Phys. **B246**, 75 (1984).

[15] J. Bagger, T. Han, R. Rosenfeld, this volume. See also R. Casalbuoni, P. Chiappetta, S. De Curtis, F. Feruglio, R. Gatto, B. Mele and J. Terron, Phys. Lett. **B249**, 130 (1990); R. Casalbuoni, P. Chiappetta, M. C. Cousinou, S. De Curtis, F. Feruglio, R. Gatto, Marseilles preprint CPT-90/P.2429 (1990).

[16] If we had chosen to include the six-derivative terms in the chiral Lagrangian, even these enhancements could have been pushed to higher energies.

[17] E. Eichten, I. Hinchliffe, K. Lane and C. Quigg, Rev. Mod. Phys. **56**, 579 (1984); 1065(E) (1986).

[18] R. Brown, D. Sahdev, and K. Mikaelian, Phys. Rev. **D20**, 1164 (1979).

[19] V. Barger, K. Cheung, T. Han, and R. Phillips, Phys. Rev. **D42**, 3052 (1990). See also D. Dicus, J. Gunion and R. Vega, SLAC preprint SLAC-PUB-5407 (1990).