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Author
Gaillard, M.K.

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Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

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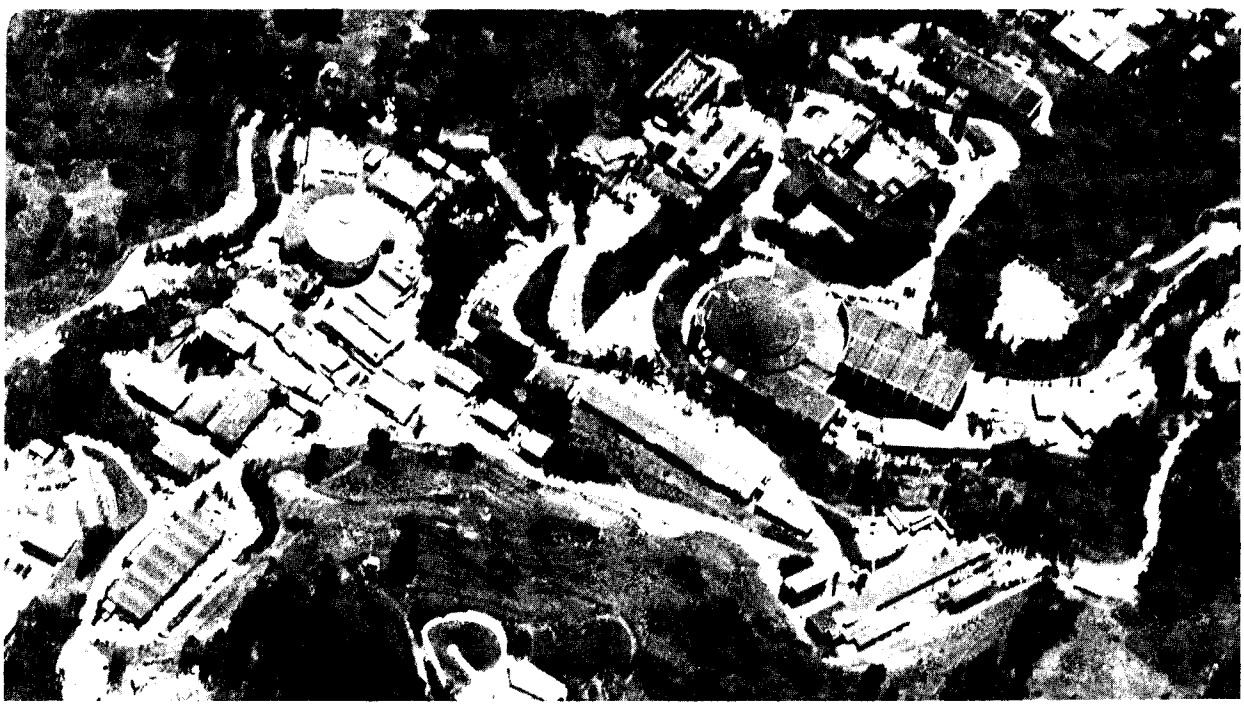
October 1984



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Mary K. Gaillard

Lawrence Berkeley Laboratory
and
Department of Physics
University of California
Berkeley, California 94720

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STRONGLY INTERACTING W's AND Z's

Mary K. Gaillard
(Representing the Strongly Interacting Higgs Subgroup)[23]

Lawrence Berkeley Laboratory and Department of Physics
University of California, Berkeley, California 94720

Introduction

The study focussed primarily on the dynamics of a strongly interacting W, Z (SIW) sector,[1] with the aim of sharpening predictions for total W, Z yield and W, Z multiplicities expected from WW fusion[1,2] for various scenarios. Specific issues raised in the context of the general problem of modeling SIW included the specificity of the technicolor (or, equivalently, QCD) model, whether or not a composite scalar model can be evaded, and whether the standard model necessarily implies an I = J = 0 state (≈ Higgs particle) that is relatively "light" (M ≲ hundreds of TeV). The consensus on the last issue was that existing arguments are inconclusive, and I shall not pursue it further in this report. While I shall briefly address compositeness and alternatives to the technicolor model, quantitative estimates will be of necessity based on technicolor or an extrapolation of pion data.

As discussed previously,[1] up to mass dependent effects, S-matrix elements with external longitudinally polarized W's and Z's (W_L, Z_L) are the same as S-matrix elements for their respective unphysical, or "eaten", spinless counterparts (w, z). In the strongly interacting limit where scalar self-couplings are much stronger than gauge couplings, the w, z system possesses an approximate chiral SU(2) symmetry analogous to that of pion chiral dynamics. Modeling the w, z system by scaling the pion system by the ratio

$$v/f_\pi = 250\,\text{GeV}/93\,\text{MeV}, \qquad (1)$$

of the parameters that characterize spontaneous chiral symmetry breaking in each case is, by definition, equivalent to a technicolor model for electroweak symmetry breaking with an SU(3) technicolor group.

Another possible source of multi-W, Z production was suggested,[3] namely a strongly coupled Yukawa interaction that would arise in the context of the standard electroweak model if there were very heavy fermions. This might then provide multi-W, Z events via gluon fusion (Fig. 1). Calculations of these processes are in progress,[4,5] in this report I will discuss only the ideas involved.

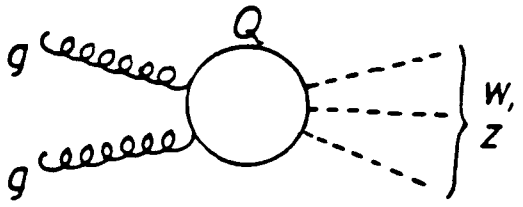

Fig 1 Possible gluon fusion mechanism for multi-W_L, Z_L production.

Technirho Production

Modeling the SIW sector on the pion sector would suggest a J = I = 1 (W, W), (W, Z) resonant analogue of the ρ(770): this is none other than the technirho for an SU(N) technicolor gauge interaction with N = 3. In addition to production[6] via resonance dominated $q\bar{q}$ annihilation, the ρ_T can be produced by the WW fusion process of Fig. 7, Ref. 1. The resulting differential cross section for $pp \to W^+W^- + X$ with a total c.m. energy of 40 TeV as a function of the W-pair invariant mass is shown in Fig. 2 for several values of N. The technirho parameters scale according to[7]

$$m_{\rho_T}(N) = (3/N)^{1/2}\, v\, m_\rho/f_\pi = 2\,\text{TeV}\,(3/N)^{1/2},$$
$$\Gamma_{\rho_T}(N) = (3/N)^{3/2}\, v\, \Gamma_\rho/f_\pi = 0.5\,\text{TeV}\,(3/N)^{3/2}. \qquad (2)$$

As N increases the resonance peak moves into a region of higher quark luminosity, but this advantage is eventually compensated for by a more rapidly decreasing width. Whether such scaling behavior, suggested by the large N limit of SU(N) gauge interactions, would be characteristic of a more general class of SIW models remains an open question.

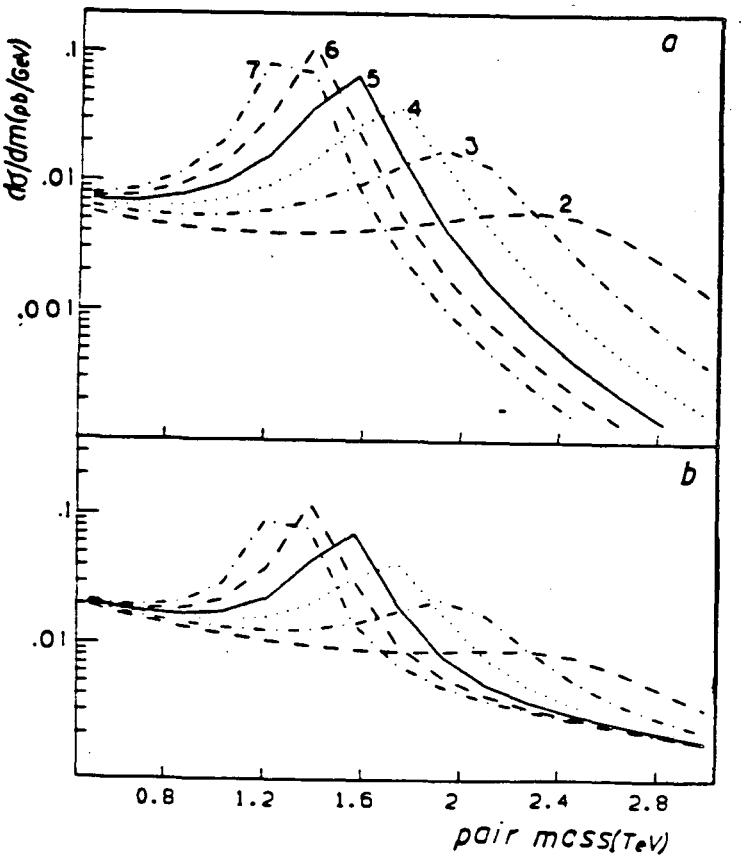

Fig. 2 Cross section for $pp \to W^+W^- + X$ through the W-fusion subprocess $q_1q_2 \to q_1'q_2' + W^+W^-$ via (a) technirho formation and (b) technirho formation plus continuum scattering in the Born approximation. The curves are labeled by the N of SU(N).

The results of Fig 2 are without rapidity cuts. Since qq interactions are as effective as $q\bar{q}$ collisions in WW fusion, and since for high invariant mass and a single partial wave the WW production is rather central, the effects of rapidity cuts should be fairly mild, reducing the signal by a factor of about 3 or less for $y < 1.5$. Comparison of Fig. 2 with Fig. 6-1 of EHLQ[6] suggests that the WW fusion process gives a contribution comparable to that of $q\bar{q}$ annihilation to production of the neutral technirho which EHLQ evaluated for $N = 4$. They found a higher yield for charged technirho production, while WZ fusion to $\rho_T^{\pm}$ should be less than WW fusion to ρ_T° because of the smaller Z-couplings to quarks. Aside from enhancement of a possibly detectable resonance peak in the WW channel, what one is getting is an appreciable excess (as compared with gauge interactions) of multi W, Z events in the high mass region. The contribution of Fig. 2(b) alone, which includes non resonant WW scattering, should give about 1500 W^+W^- events for an integrated luminosity of 10^{40} cm^{-2} in the W^+W^- invariant mass region above 500 GeV. Even without the resolution of a resonance peak, such an excess of W-pair events, if measurable, would signal new strong interactions.

S-Wave Scattering

It was suggested[8] that the s-wave amplitudes for W^+W^- scattering could be modeled by scaling up the measured s-wave $\pi^+\pi^-$ scattering amplitudes. Scaling with Eq. (1) is not entirely unambiguous near threshold, because threshold behavior involves two parameters: f_π or v which measures spontaneous chiral symmetry breaking, and m_π or $m_{W,Z}$ which measures its explicit breaking. Note that the ratios

$$m_\pi^2/f_\pi^2 = 2.27, \tag{3a}$$

$$m_W^2/v^2 = 0.11, \tag{3b}$$

are rather different. The masses are relevant for our purposes only as kinematic quantities that can play a role near threshold and also, for example, in governing phase space available for multi-particle production to be discussed below. In studying threshold behavior, scaling in momentum rather than energy may be the most reliable procedure.[8]

In the limit of a large Higgs mass, $m_H >> \sqrt{s}$, the s-wave born amplitude for $w^+w^- \to zz$ is

$$A_0(w^+w^- \to zz) = \sqrt{2}(A_{00} - A_{02})/3, \tag{4}$$

where A_{JI} is the partial wave amplitude for fixed spin J and "isospin" I:

$$A_{00} = -(8k^2 + 7m^2)/2v^2,$$
$$A_{02} = (2k^2 + m^2)/v^2, \tag{5}$$

where $k = (s - 4m^2)^{1/2}/2$ is the scattering c.m. momentum. With the substitutions $v \to f_\pi$ and $m \to m_\pi$ in Eq. (5), the A_{0J} are just the pion s-wave scattering amplitudes obtained[9] from PCAC and current algebra. In that case the terms linear in m_π^2 determine the scattering lengths[9] In the w, z case m^2 is in fact a meaningless parameter since the substitution $W_L, Z_L \to w, z$ is valid only to order $m_{W,Z}/E_{W,Z}$, and the masses of the w and z are gauge dependent quantities ($m_w = m_W/\xi$). The ratio (3b) assures us that $m_{W,Z}^2$ corrections are negligible in the region $\sqrt{s} \gtrsim 500$ GeV $\approx 2v$ in which we are interested.

Unitarity of the S-matrix requires that in the region of negligible inelasticity, the partial wave scattering amplitudes are of the form:

$$A_{JI} = -16\pi E a_{JI}/k, \tag{6}$$

with

$$a_{JI} = \sin\delta_{JI}\exp(i\delta_{JI}), \quad E = \sqrt{s}/2. \tag{7}$$

Since A_{JI} does not diverge for $k \to 0$, we have

$$a_{JI} \underset{k\to 0}{\to} \delta_{JI} \propto k, \tag{8}$$

and the threshold behavior required by chiral symmetry is reproduced for any parameterization of δ_{JI} such that

$$\delta_{JI} \underset{k\to 0}{\to} (a_{JI})_{Born} = -k(A_{JI})_{Born}/16\pi E, \tag{9}$$

where the $(A_{JI})_{Born}$ for $J = 0$ are given in Eq. (5).

A standard unitarization procedure is the K-matrix formalism (we take $J = 0$) which defines the phase shift by:

$$\exp(2i\delta_K^I) = [1 + i(a_{0I})_{Born}]/[1 - i(a_{0I})_{Born}]. \tag{10}$$

Both unitarity and chiral symmetry will also be satisfied if we take instead the phase shifts

$$\delta_b^I = (a_{0I})_{Born}. \tag{11}$$

The s-wave intensity I for $\pi^+\pi^- \to \pi^\circ\pi^\circ$, defined as

$$I = |a_{00} - a_{02}|^2 = 9k^2\sigma(+- \to 00)/8\pi \quad , \tag{12}$$

has been measured by Cason et al[10] (Fig. 3(b)). From this they extracted values of the $I = 0$ s-wave phase shift using as input a parameterization of the $I = 2$ s-wave phase shift:

$$\delta_{02} = -(k/1.1\ \text{GeV})/[1 + (k/1.12\ \text{GeV})^2]. \tag{13}$$

The resulting data points for δ_{00} are shown in Fig 3(a) along with the parameterizations (10) and (11) of the phase shifts. For comparison we also show a simple linear extrapolation from the current algebra values[9] of the scattering lengths:

$$\delta_L^I = -k[A_{0I}(k=0)]_{Born}/16\pi m_\pi. \tag{14}$$

That the data is better reproduced (see especially Fig. 3(b)) by the parameterizations (10) and/or (11) indicates that the k^2 terms in (5), that are the only ones relevant to the w, z system, are indeed accurately reproduced by the data.

We note from Fig. 3(a) that the "input" parameterization for δ_{02} is close to the K-matrix parameterization (10), while the extracted $I = 0$ phase shift agrees better with the simple Born parameterization of Eq. (11). We therefore include in the intensity parameterizations, Figs. 3(b) and 3(c), one using (11) for δ_{00} and (10) for δ_{02}. This appears to give a reasonable fit to the pion intensity, although the K-matrix prescription (10) may be better for relatively low k.

The relevant lesson is for the $ww \to zz$ intensity, shown in Fig. 3(c), where the Born amplitude and the intensity expected for a Higgs of mass 1 TeV are shown for comparison. Total rates for multi-W, Z production via the WW fusion process have been estimated[11] by interpolating between the Born approximation in the limit $m_H >> \sqrt{s}$ and a 1 TeV Higgs, giving 3,000 to 10,000 events for an integrated luminosity of 10^{40} cm^{-2}. The unitarized s-wave amplitudes shown in Fig. 3(c) suggest only a slightly reduced yield with respect to the Born approximation in the region $\sqrt{s} \sim$ TeV where quark luminosities are most significant. Taking into account contributions from other partial waves (e.g. $J = 1$ resonance production as discussed above), these estimates are probably not overly optimistic, but we have, unfortunately, found no reason to suspect that they are overly pessimistic.

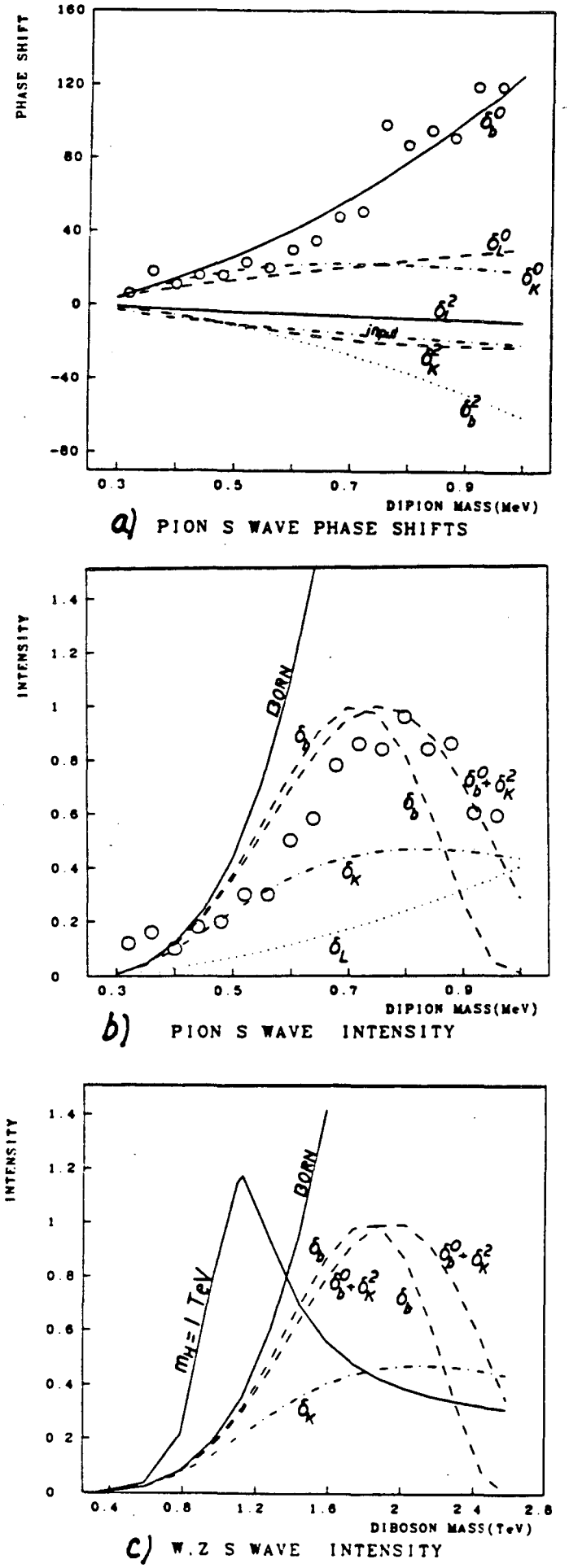

Fig. 3 Unitarized s-wave scattering intensities for $\pi^+\pi^- \to \pi^0\pi^0$ (b) and $W^+W^- \to ZZ$ (c) for various parameterizations of the phase shifts (a) consistant with low energy constraints. Circles are data points;[10] the I = 0 pion phase shift was obtained using an input parameterization for the I = 2 phase shift. Also shown are extrapolations of the Born, or soft pion, intensities.

Alternative Models of SIW

An alternative[12] to the QCD/technicolor model is the ultracolor of Georgi and collaborators: in the limit in which the scale where ultracolor becomes strong is close to the electroweak symmetry breaking scale (which, for viable models implies an additional strong, gauged axial U(1) coupling) ultracolor models resemble technicolor models, but with a richer spectrum of bosonic states. (An interesting feature of these models is that there are no baryonic states, so they are distinctly different from technicolor models.)

The class of ultracolor models that might provide viable models for SIW are those in which ultrafermions fall into real representations of the ultracolor gauge group. In the minimal model of this class, left handed fermions form a (2, 2) and a (1, 1) of the SU(2) × SU(2) of the (here composite) scalar sector. These five left handed fermionic degrees of freedom define a 5-plet of "ultraflavor" U(5). The fermion condensates of the strongly coupled, gauged SO(N) spontaneously break this U(5) flavor symmetry to an SO(5) flavor symmetry, implying the existence of 15 Goldstone bosons that transform under SU(2) × SU(2) as:

$$0^-: (2,2) + (1,1) + (3,3) + (1,1). \tag{15}$$

The above fermionic condensate, in contradistinction to conventional technicolor models, does not break the electroweak $SU(2)_L \times U(1)$ gauge symmetry. To achieve electroweak symmetry breaking an axial U(1) gauge interaction is introduced that explicitely breaks flavor U(5) to flavor U(4). The fermion condensate arising from the strong SO(N) gauge interactions now breaks flavor U(4) to flavor SO(4), leaving only 10 Goldstone bosons, namely the (3, 3) + (1, 1) of Eq. (15) above. This means that the (2, 2) + (1, 1) are not decoupled in the zero-momentum limit. In particular,the (2, 2), which has the electroweak quantum numbers of the conventional complex Higgs doublet, can acquire a negative squared mass and trigger the breaking of the electroweak gauge symmetry. This scenario has a well defined set of "low lying" resonances which is richer than that of minimal technicolor models. In addition to the (3, 3) + (1, 1) in (15) that might be relatively "light" (m << TeV) because of their pseudogoldstone boson nature, there are 10 ground state spin one bosons:

$$1^-: (3,1) + (1,3) + (2,2), \tag{16}$$

that might have masses in the TeV region.

Since this scenario does not reduce simply to a v/f_π scaling of QCD, quantitative predictions of resonance parameters have not been attempted. The ultracolor alternative does however have in common with technicolor an underlying theory of fermions with strong gauge interactions, and it is anticipated that masses and widths should scale in a similar way with the number of gauged fermionic degrees of freedom.

Can we evade[13] fermions altogether as underlying constituents of a strongly interacting scalar sector? A pure scalar field theory is known to be inconsistant.[14] On the other hand no one would take seriously the notion that the scalars of SIW can be treated as an isolated system at arbitrary energies; the practical implications of difficulties of a pure scalar need not become manifest below the Planck scale.[15] Scalars can presumably be consistantly embedded within a supersymmetry/supergravity context, and pushing the scale of supersymmetry breaking up to the Planck mass poses no practical problem in this respect. Similarly scalars may be composite, but, again this could be relevant only at distances of the order of the

Planck length where perhaps fermions and even gauge bosons would also appear as composite. On the other hand, the results presented by Manton[16] may suggest that the elementary scalar sector of the standard electroweak model will cease to be a sensible description at a scale between 7 and 13 TeV.

The bottom line is that we have no real guidance. This makes experimental investigation of the TeV energy region all the more imperative and all the more exciting.

Multiplicity

For lack of a better guide we will proceed to further modeling with what we know how to do. Estimates[11] of multiplicities for an SIW sector have been made on the basis of massless phase space and assuming a factor $\sqrt{s}/v$ in amplitude, inspired by chiral symmetry, for each emitted W_L, Z_L. For processes involving couplings to "parity violating" weak external sources (W_T, Z_T, heavy quarks) this gives:

$$\sigma(n+1)/\sigma(n) = s/[16\pi^2 v^2 n(n-1)]. \qquad (17)$$

For purely "strong" effects that govern the WW fusion process, "parity" is conserved, and only an even number of W_L, Z_L can be produced; this gives

$$\sigma(n+1)/\sigma(n-1) = (s/16\pi v^2)^2/[n(n-1)(n-2)]. \qquad (18)$$

Ellis[17] has done a careful calculation of the "technirho" decay branching ratio using the constraints of current algebra and PCAC. The analogous calculation[18] for the ρ gave

$$\Gamma(\rho \to 4\pi^\pm)/\Gamma(\rho \to 2\pi^\pm) = 2 \times 10^{-5}. \qquad (19)$$

Scaling this result according to $f_\pi \to v$, $m_\pi \to m_W$ and $m_\rho = 700$ MeV $\to M_{\rho_T} = 1800$ GeV (900 GeV), gives

$$\Gamma(\rho_T \to 4w)/\Gamma(\rho_T \to 2w) = 3.7(1.9) \times 10^{-3}, \qquad (20)$$

to be compared with the prescription of Eq. (18) which gives 8.9 (0.6) $\times 10^{-3}$. Since the ρ_T decay involves p-waves, it is not surprising that phase space alone is inadequate, but the latter estimate is not off by an order of magnitude.

Ellis[17] applied the same techniques to calculate the $\sigma(2w \to 4w)/\sigma(2w \to 2w)$ cross section ratio in the Born approximation for $m_H >> s$. In this case there is a large $J = 0$ contribution, and the estimate using the prescription (18) is fairly accurate, as can be seen in Fig. 4. This unfortunately lends confidence to the estimates of Chanowitz and myself[11] who found 10 - 75 four-body W_L, Z_L events for $\int dt\, L = 10^{40}$ cm^{-2} with $\hat{s} \geq 0.5$ TeV from the WW fusion process for various parameterizations of the WW total cross section for $m_H \geq 1$ TeV.

At sufficiently high energies one expects the scaling law (18), or the chiral symmetric Born amplitudes, to break down. Again one can model[8,17] the SIW sector by scaling up the pion sector in the resonance region. This could underestimate SIW multiplicities, because, as indicated by the ratios (3), if we scale according to $s_W = (v/f_\pi)^2 s_\pi$, the available phase space for multi-W, Z production at s_W exceeds that for multipion production at s_π, because of accidents of mass values. Jaffe[8] pointed out however that 4π production does not become significant below multi-resonance thresholds, where the pion mass is itself insignificant. In other words the principle source of high multiplicity pion production appears to be resonance decay, with the primary interactions always being $2 \to 2$ scattering, or $1 \to 2$ decays. This feature may be specific to the underlying QCD structure and duality diagram prescription that it implies. So again the question arises: can we evade[13] an elementary fermion model?

Table 1 shows the number of 4-body W_L, Z_L events for $\int dt\, L = 10^{40}$ cm^{-2} expected from resonance production by W^+W^- fusion for various resonance parameters, assuming a product of branching ratios in the range

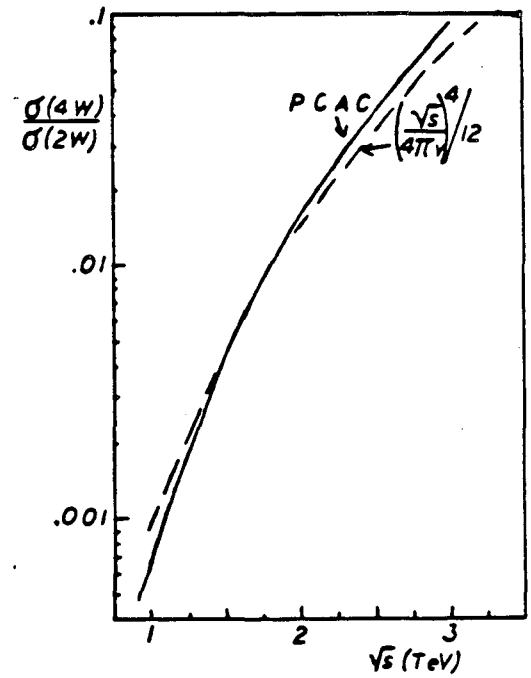

Fig. 4 Fraction of 4W production in W^+W^- scattering as predicted from chiral symmetry,[17] compared with estimates based on phase space and the $\sqrt{s}/v$ rule.[11]

$$0.1 \leq B(4w) \cdot B(2w) \leq 0.25. \qquad (21)$$

The resonance parameters are obtained by scaling pion resonance parameters using the prescription (2) for $N = 3$ (QCD) and $N = 7$. Only if the scaled up version of the $\rho(770)$ has a substantial branching ratio into 4-body final states (not the case for the pion system, nor anticipated by the chiral symmetry estimate, Eq. (20)) can we expect more than a handful of 4-body events from these processes. Hopefully the real SIW will not mimic QCD so closely.

Table 1 Expected number of 4-body W_L, Z_L events from resonance production by WW fusion in pp collisions with $\int dt\, L = 10^{40}$ cm^{-2} and $E_{cm} = 40$ TeV, assuming Eq. (21).

Low energy model (MeV)	"Technicolor" extrapolation (GeV) N = 3	N = 7
$g\ 1^+(3^-)$	$g_T\ 1^+(3^-)$	$g_T\ 1^+(3^-)$
m = 1691	m = 4546	m = 2976
Γ = 200	Γ = 538	Γ = 201
$B_2 \cdot B_4 = 0.17$	< 0.3 event	5 - 12 events
$\rho'\ 1^+(1^-)$	$\rho_T'\ 1^+(1^-)$	$\rho_T'\ 1^+(1^-)$
m = 1600	m = 4301	2815
Γ = 300	Γ = 806	Γ = 301
$B_2 \cdot B_4 \leq 0.3$	1.5 to 4 events	8 to 20 events
$\rho\ 1^+(1^-)$	$\rho_T\ 1^+(1^-)$	$\rho_T\ 1^+(1^-)$
m = 770	m = 2070	m = 1355
Γ = 154	Γ = 414	Γ = 155
$B_2 \cdot B_4 = 0$	100 - 280 events	230 - 580 events

Strongly Interacting Yukawa Sector

If there are very heavy fermions that acquire masses via Yukawa couplings to the standard model Higgs doublet, then the physical Higgs and the longitudinally polarized vector bosons W_L, Z_L are strongly coupled to the heavy fermions. This has been suggested[3] as a possible source of multiple Higgs production, especially relevant to the case of an elusive "intermediate" mass ($40\ \mathrm{GeV} \lesssim m_H \lesssim 2m_W$) Higgs boson,[19] via gluon fusion through a heavy quark loop as in Fig. 1.

In the scenario considered here, $m_H \gtrsim 1$ TeV, the process of Fig. 1 could under certain circumstances provide an additional source of multi-W-Z events. Calculations of the general multi-boson loops are underway;[4,5] here I shall outline the physical principles involved. The strong sector of the theory is now defined by the scalar and heavy fermion sectors including Yukawa couplings. The scalar sector alone possesses as before a chiral SU(2) symmetry, and S-matrix elements for the "pseudo-scalars" $w^\pm$, z are equivalent to S-matrix elements for $W_L^\pm$, Z_L up to $O(m_W/E)$ corrections. To the extent that the heavy quarks are pair-wise degenerate, i.e. that their Yukawa couplings are invariant under suitably defined chiral SU(2) transformations, the full strongly interacting sector is chiral SU(2) invariant. As the Goldstone bosons of this spontaneously broken chiral symmetry, the $w^\pm$, z (or $W_L^\pm$, Z_L) must decouple at zero momentum. On the other hand, if there is substantial splitting for some quark doublet, this represents an explicit breaking of SU(2) × SU(2), and the Goldstone theorem need not apply.

To illustrate, consider gluon fusion to a single (real or virtual) z (or Z_L). Working in a renormalizable gauge the z couples to the heavy quark through a pure pseudoscala coupling proportional to the third component of the quark weak isospin. The calculation of the gluon fusion process reduces to the Steinberger[20] calculation of $\pi^\circ \to \gamma\gamma$, giving the well known result that the amplitude drops rapidly to zero for $m_Q^2 < p_t^2/2$, and takes a non-zero value essentially independent of m_Q for $m_Q^2 \gtrsim p_t^2$. Since the two components of a quark weak isodoublet contribute with opposite signs, there is no net contribution unless they satisfy a mass relation $m_{Q1}^2 \le p_t^2 \lesssim m_{Q2}^2$. Roughly, one obtains a contribution proportional to:

$$\Sigma_H I(Q_H) = \Sigma_H J(U_H) - \Sigma_H J(D_H). \qquad (22)$$

where U_H and D_H are "heavy" ($m_H^2 \gtrsim p_t^2$) quarks of charge 2/3 and − 1/3 respectively and $I(U) = J(U)$ ($I(D) = -J(D)$) is the contribution to the amplitude of Fig. 1 from an external quark Q = U or D.

Alternatively, one may transform the fields to obtain the non-linear σ-model formulation, in which case the w, z appear only with derivative couplings and couple to quarks through the derivative of an axial vector coupling In this case w, z amplitudes vanish explicitly as $p/m_Q \to 0$ unless there are anomalies (or explicit chiral symmetry breaking) In this formulation, the calculation reduces to the more modern calculations[21] of $\pi^\circ \to \gamma\gamma$ (and is equivalent to a direct calculation of $gg \to Z_L$ in the unitary gauge). For "light" quarks (L) only the anomaly A(Q) contributes, while for $m_Q^2 \gtrsim p_t^2$, the anomaly exactly cancels the mass dependent contribution $I(Q_H)$, giving a contribution to $gg \to z$ proportional to

$$\Sigma_L A(Q_L) = -\Sigma_L A(Q_H) = \Sigma_H I(Q_H), \qquad (23)$$

which is the same as (22); the first equality in (23) holds because the theory is by construction anomaly free when summed over all quarks.

We are really interested in multi W_L, Z_L production. Up to mass dependent effects, the production of an odd number of w, z is completely determined[22] by the axial anomalies, and, roughly, a non-zero amplitude should be found if some quark doublet satisfies $m_{Q1}^2 \lesssim s \lesssim m_{Q2}^2$, where $\sqrt{s}$ is the total cm energy of the di-gluon system We already know from the strength of the neutral current couplings and the Z and W masses that quark doublet mass splittings cannot exceed a few hundred GeV. However, when mass dependent effects are included,[5] there may be some window for an observable effect.

Gluon fusion to a "parity-even" system of w, z and Higgs is governed by the trace anomaly rather than the axial anomaly, and the presence of a trace anomaly does not invalidate the soft meson theorems of chiral symmetry. Since gluon fusion into, say, a pair of z's is proportional to $(\tau_3)^2$ for each quark, no cancellation can occur between members of a doublet, so the decoupling theorem must hold for each quark loop separately, and it is probable that gluon fusion to 2n(w, z) alone will be suppressed as s/m_H^2 or s/m_Q^2.

It therefore seems likely that the gluon fusion process is most promising as a source of multiple "light" Higgs,[19] or, possibly for $2m_W < m_H << \mathrm{TeV}$, a source of multi-W events via Higgs decay. Results of explicit calculations[4,5] will give a more precise answer.

Conclusions

The lesson for SSC experimentation, is, as before,[1] that identification of W's and Z's is a crucial issue. Further questions that should be pursued include:

At what level of production can multi ($N \ge 3$) W, Z events be detected? This requires more serious study of multi-jet ($N_{jet} \ge 3$), W, Z + multi-jet, 2(W, Z) + jet, etc. backgrounds, as well as the effects of rapidity cuts on various classes of events.

Are the general features of a strongly interacting W, Z sector discernable without event-by-event identification? Signals include an enhanced W, Z yield, an enhanced Z/W ratio, and an enhanced component of longitudinally polarized Z's in the tail ($\sqrt{\hat{s}} \gtrsim 500$ GeV) of the effective center of mass spectrum. The question is whether these effects are sufficiently pronounced that deviations from purely gauge interaction effects could be extracted by comparing, say, events containing one or more leptonic decays with total transverse energy greater than or less than 500 GeV.

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References

1. M.K. Gaillard, these proceedings and references therein.

2. WW fusion as a mechanism for Higgs production was first considered in the context of e^+e^- colliders by D.R.T. Jones and S.T. Petcov, Phys. Lett. 84B, 440 (1979).

3. M.B. Gavela, contribution to this workshop.

4. O. Alvarez, M. Claudson and R. Ingermanson, in progress.

5. M.B. Gavela and J. Gunion, in progress.

6. E. Eichten, I. Hinchliffe, K. Lane and C. Quigg, FERMILAB-Pub-84/17-T, LBL-16875, DOE/ER 01545-345, to be published in Rev. Mod. Phys. (1984).

7. S. Dimopoulos, Nucl. Phys. B168, 69 (1980); S. Dimopoulos, S. Raby and G.L. Kane, Nucl. Phys. B182, 77 (1981).

8. R. Jaffe, contribution to this workshop.

9. S. Weinberg, Phys. Rev. Lett. 17, 616 (1966).

10. N.M. Cason, et al., Phys. Rev. D28, 1586 (1983).

11. M.S. Chanowitz and M.K. Gaillard, LBL-17496, UCB-PTH-84/5.

12. H. Georgi, these proceedings and references therein.

13. J. Ellis, private communication, has suggested that alternative SIW scenarios could be modeled by the choice of scale transformation properties of the effective scalar Lagrangians.

14. M. Aizenman, Phys. Rev. Lett 47, 1 (1981) and Commun. Math. Phys. 86, 1 (1982); J. Fröhlich, Nucl. Phys. B200, 281 (1982).

15. W.A. Bardeen and M. Moshe, Phys. Rev. D28, 1372 (1983).

16. N. Manton, these proceedings, and references therein.

17. J. Ellis, contribution to this workshop.

18. J. Ellis and B. Renner, Nucl. Phys. B13, 108 (1969).

19 K. Lane, these proceedings.

20 H. Fukuda and Y. Miyamoto, Prog. Theor. Phys. 4, 347 (1949); J. Steinberger, Phys. Rev. 76, 1180 (1949).

21. J. Schwinger, Phys. Rev. 82, 664 (1951); L. Rosenberg, Phys. Rev. 129, 2786 (1963); J. Bell and R. Jackiw, Nuovo Cimento 60A, 47 (1969); S. Adler, Phys. Rev. 177, 2426 (1969).

22. W.A. Bardeen, Phys. Rev. 184, 1491 (1969); J. Wess and B. Zumino, Phys. Lett. B37, 95 (1971).

23. Strongly Interacting Higgs Subgroup members: O. Alvarez, T.A. Appelquist, R. Barbieri, M. Bowick, N. Byers, R.N. Cahn, J. Ellis, M.K. Gaillard, M.B. Gavela, H. Georgi, R.L. Jaffe, N. Manton, M. Peskin, T.N. Pham, J. Rosner, M. Suzuki.

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TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720