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COMPLEMENTARITY OF RESONANT AND NONRESONANT STRONG WW SCATTERING AT SSC AND LHC *

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Abstract

Signals and backgrounds for strong WW scattering at the SSC and LHC are considered. Complementarity of resonant signals in the $I = 1$ WZ channel and nonresonant signals in the $I = 2$ W^+W^+ channel is illustrated using a chiral lagrangian with a $J = 1$ "ρ" resonance. Results are presented for purely leptonic final states in the $W^{\pm}Z$, $W^+W^+ + W^-W^-$, and ZZ channels.

INTRODUCTION

High energy physics today is in an extraordinary situation. The Standard Model (SM) is reliable but incomplete. For its completion it *predicts* 1) that a fifth force exists, 2) the mass range of the associated quanta, and 3) neither the precise mass nor the interaction strength but the relation between them. These properties are sufficient to guide the search. Like any prediction in science, this one too may fail. If so we will make an equally important discovery: a deeper theory hidden until now behind the SM, which will emerge by the same experimental program that we will follow to find the fifth force if it does exist. In this paper I assume the SM is correct. This presentation is necessarily brief; a more complete review and bibliography will appear elsewhere.[1]

The Higgs mechanism is the feature of the SM that requires a fifth force and implies its general properties. The Higgs mechanism requires a new sector of quanta with dynamics specified by an unknown Lagrangian I will call $\mathcal{L}_5$, that spontaneously breaks $SU(2)_L \times U(1)_Y$, giving rise to Goldstone bosons w^+, w^-, z that become the longitudinal gauge bosons W_L^+, W_L^-, Z_L . By measuring $W_L W_L$ scattering at $E \gg M_W$, we are effectively measuring ww scattering (i.e., the equivalence theorem) and are therefore probing the dynamics of $\mathcal{L}_5$.

Let M_5 be the typical mass scale of the quanta of $\mathcal{L}_5$. Then the $W_L W_L$ scattering amplitudes are determined by low energy theorems,[2,3] e.g., for the $J = 0$ partial wave

$$a_0(W_L^+ W_L^- \rightarrow Z_L Z_L) = \frac{1}{\rho}\frac{s}{16\pi v^2} \qquad (1)$$

(with $v = 0.247$ TeV) in the energy domain

$$M_W^2 \ll s \ll \text{minimum}\{M_5^2, (4\pi v)^2\} \qquad (2)$$

which may or may not exist in nature, depending on whether $M_5 \gg M_W$.

Partial wave unitarity requires the linear growth of $|a_0|$ to be damped before it exceeds unity at a "cutoff" scale $\Lambda_5 \leq 4\pi\sqrt{v} = 1.8$ TeV. The cutoff is enforced by the Higgs mechanism with $\Lambda_5 \simeq M_5$ where more precisely M_5

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is *the mass scale of the quanta of* $\mathcal{L}_5$ *that make the* $SU(2)_L \times U(1)_Y$ *breaking condensate that engenders* M_W. If $M_5 \ll 1.8$ TeV then $\mathcal{L}_5$ is weak and its quanta include one or more Higgs bosons with M_5 equal to the average Higgs boson mass (weighted by contribution to v). If $M_5 \geq 1$ TeV then $\mathcal{L}_5$ is strong, there is strong WW scattering for $s > 1$ TeV^2, and rather than Higgs bosons we expect a complex spectrum of quanta. Resonance formation then occurs in attractive channels at the energy scale of unitarity saturation, $a_J(M^2) \sim O(1)$, implying $M \sim 1$ - 3 TeV.

We detect a strong $\mathcal{L}_5$ by observing strong WW resonances and/or strong nonresonant WW scattering. Fortunately the two approaches are complementary: if the resonances are very heavy and difficult to observe there will be large signals in nonresonant channels.

COMPLEMENTARITY

If $\mathcal{L}_5$ contains no light quanta $\ll 1$ TeV such as Higgs bosons or pseudo Goldstone bosons, then in the absence of strong WW resonances the leading partial wave amplitudes, $a_{IJ} = a_{00}, a_{11}, a_{20}$, will smoothly saturate unitarity. Strong scattering cross sections are then estimated by extrapolating the low energy theorems. (The index I refers to the diagonal $SU(2)_{L+R}$ subgroup that is necessarily[3] a good symmetry of the Goldstone boson sector at low energy because $\rho \simeq 1$.)

Models illustrating the smooth approach to the unitarity limit include the "linear" model[2], the K-matrix unitarization model[4], scaled $\pi\pi$ data in nonresonant channels[2,4,5], and effective Lagrangians incorporating dimension 6 operators and/or one loop corrections[6]. These models provide large signals in *nonresonant* channels but are conservative in that they apply when more dramatic signals from light quanta or strong resonances are absent.

It is instructive to compare the linear model with $\pi\pi$ scattering data.[7] The model agrees well in the $I, J = 0, 0$ channel, probably a fortuitous result of the attractive dynamics in that channel. The model underestimates $|a_{11}|$ and overestimates $|a_{20}|$, *both* because of the $\rho(770)$: s-channel ρ exchange enhances $|a_{11}|$ while t- and u-channel exchanges suppress $|a_{20}|$, implying a complementary relationship between the two channels.

The effects of ρ exchange can be studied using a chiral Lagrangian with chiral invariant $\rho\pi\pi$ interaction.[8] Figure 1 shows that the model fits $\pi\pi$ data for $|a_{11}|$ and $|a_{20}|$ very well.

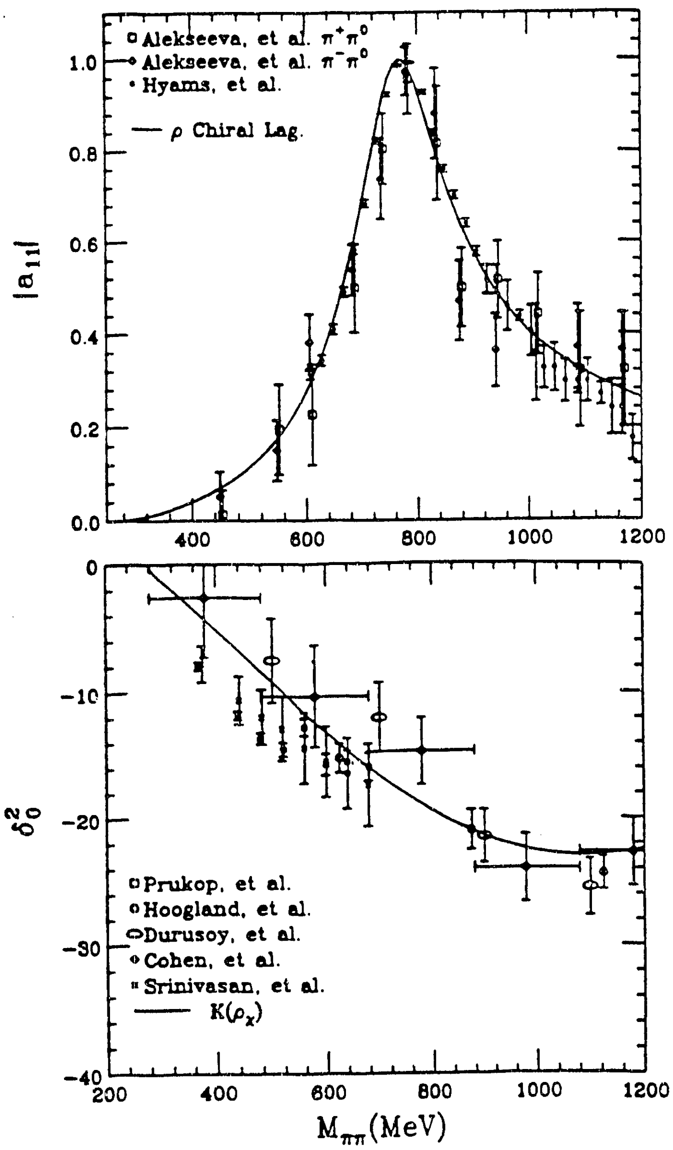

Figure 1.The ρ chiral Lagrangian model compared with $\pi\pi$ scattering data for $|a_{11}|$ and δ_{20} (W. Kilgore).

We will use the model to explore the effect of an analogous "ρ" resonance on $W_L W_L$ scattering.

Consider for instance minimal technicolor with one techniquark doublet. (Nonminimal models have lighter resonances which are more easily observed.) For $N_{TC} = 4$, large N scaling implies $(m_\rho, \Gamma_\rho) = (1.78, 0.33)$ TeV, while the heaviest ρ_{TC}, for $N_{TC} = 2$, has $(m_\rho, \Gamma_\rho) = (2.52, 0.92)$ TeV. Though unlikely according to popular prejudice, strong WW resonances could be even heavier. To explore

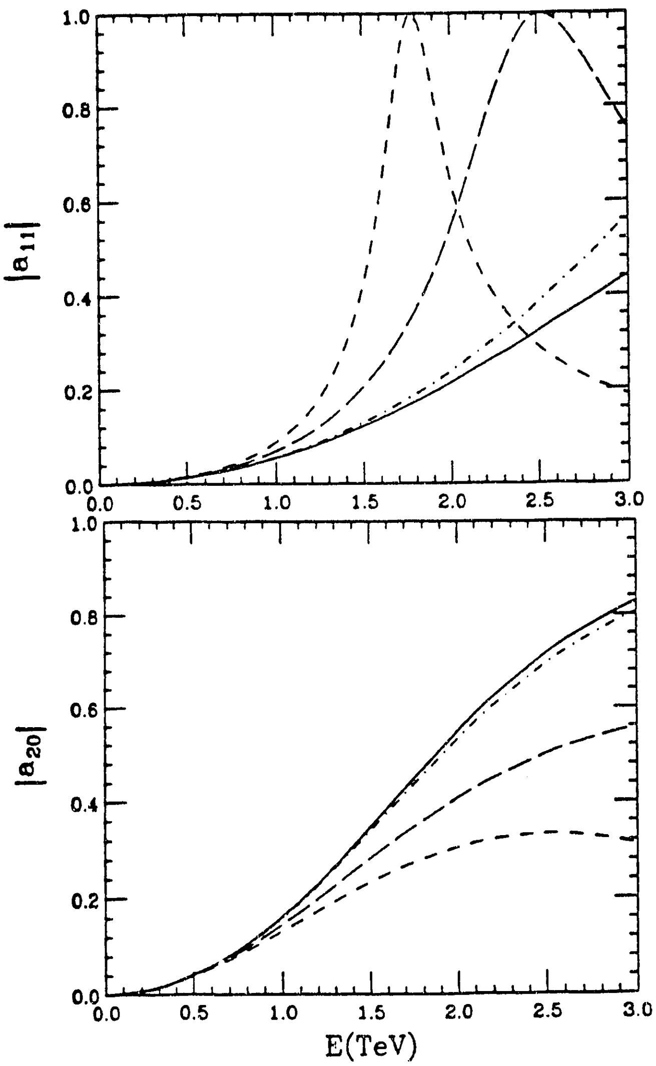

Figure 2. $|a_{11}|$ and δ_{20} for the chiral invariant ρ exchange model with $m_\rho = 1.78$ (dashes), $m_\rho = 2.52$ (long dashes) and $m_\rho = 4.0$ (dot-dash). The nonresonant K-LET model is indicated by the solid line.

that possibility I also consider a "ρ" of mass 4 TeV, with a width of 0.98 TeV determined assuming a "ρ"ww coupling equal to $f_{\rho\pi\pi}$ from hadronic physics. To ensure elastic unitarity the real parts are computed with $\Gamma_\rho = 0$ and the K-matrix prescription is then used to compute the imaginary parts.[9] For resonance dominance this prescription is equivalent to the usual broad-resonance Breit-Wigner prescription, in which the term $m_\rho \Gamma_\rho$ in the B-W denominator is replaced by $\sqrt{s}\Gamma_\rho(\sqrt{s})$.

Figure 2 displays $|a_{11}|$ and $|a_{20}|$ for the three "ρ" cases and for the nonresonant K-matrix unitarization of the low energy theorem amplitudes (K-LET). The 4 TeV "ρ" is nearly indistinguishable from the nonresonant K-LET model below 3 TeV. The complementarity of the two channels is evident: the $\rho_{TC}(1.78)$ provides a spectacular signal in a_{11} but suppresses the signal in a_{20}, while the "ρ"(4.0) provides a minimal signal in a_{11} but allows a large signal to emerge in a_{20}.

The sign of the interference between the LET amplitude and resonance exchange contributions depends on the resonance quantum numbers, but it is generally true that the amplitude approaches a smooth unitarization of the LET (e.g., the K-LET) as $M_5 \to \infty$. This is the limit in which the "conservative" nonresonant models apply. A heavy "ρ" is a worst case example since "ρ" exchange interferes destructively with the a_{20} threshold amplitude so that the limiting behavior is approached from below as the "ρ" mass is increased. Resonances that interfere constructively in the channel would provide bigger signals.

SIGNALS

In this section I will briefly review signals and backgrounds at the SSC and LHC, in the $W^\pm Z$, $W^+W^+ + W^-W^-$, and ZZ final states. Signals are computed using the ET-EWA approximation (i.e., the combined equivalence theorem-effective W approximation) with HMRSB structure functions evaluated at $Q^2 = M_W^2$. Only final states with both gauge bosons decaying leptonically are considered. Except for the central jet veto[4] (CJV) considered in the W^+W^+ channel, the cuts apply only to leptonic variables.

My criterion for a significant signal is

$$\sigma^{\uparrow} = S/\sqrt{B} \geq 5 \qquad (3)$$

$$\sigma^{\downarrow} = S/\sqrt{S+B} \geq 3, \qquad (4)$$

respectively the standard deviations for the background to fluctuate up to a false signal or for the signal plus background to fluctuate down to the level of the background alone. The criterion is corrected below for the acceptance in each channel. In addition $S \geq B$ is required because of the theoretical uncertainty in the backgrounds, expected to be known to within $\leq \pm 30\%$ after "calibration" studies at the SSC and LHC.

"ρ" $\rightarrow WZ$

Consider "ρ" $\rightarrow WZ \rightarrow l\nu + \bar{l}l$ with $l = e, \mu$ ($BR = 0.014$). Production mechanisms are $\bar{q}q$ annihilation[10] and WZ fusion[3], the latter computed using the chiral Lagrangian with contributions from a_{11} and a_{20}. Elastic unitarity is imposed with the K-matrix prescription described above. The dominant background (and the only one considered here) is $\bar{q}q \rightarrow WZ$. A simple cut on the WZ invariant mass and the gauge boson rapidities ($y_{W,Z} \leq 1.5$) suffices to demonstrate the observability of the signal. (The WZ mass is measurable only up to a twofold ambiguity; a more realistic and effective procedure is to cut on the charged lepton transverse momenta.)

The acceptance estimate[11] is $0.85 \times 0.95 \simeq 0.8$ so the significance criterion for the uncorrected cross sections is $\sigma^{\uparrow} \geq 5.5$ and $\sigma^{\downarrow} \geq 3.3$. The results are shown in figure 3 and table 1.

Table 1. Yields of $\rho^{\pm}$ signal and background events per 10 fb^{-1} at the SSC and LHC. Cuts are $|y_W| < 1.5$, $|y_Z| < 1.5$, and M_{WZ} as indicated.

$\sqrt{s}$	M_ρ	M_{WZ}	S	B	$\sigma^{\uparrow}, \sigma^{\downarrow}$
40	1.78	>1.0	30	9.3	10, 4.8
TeV	2.52	> 1.2	15	5.3	6.3, 3.3
	4.0	> 1.0	10	5.3	4.4, 2.6
16	1.78	> 1.0	5.5	3.2	3.0, 1.9
TeV	2.52	> 1.2	1.7	1.6	1.4, 0.9
	4.0	> 1.6	0.5	0.5	0.7, 0.5

With 10 fb^{-1} at the SSC the $\rho_{TC}(1.78)$ signal far exceeds the criterion, the $\rho_{TC}(2.52)$ signal just meets it, and the "ρ"(4.0) requires 17 fb^{-1}. To just meet the criterion at the LHC, 33, 160, and 570 fb^{-1} are needed for the three cases respectively.

$W^+W^+ + W^-W^-$

The W^+W^+ channel has the largest leptonic branching ratio, $\simeq 0.05$ to e's and/or μ's, and no $\bar{q}q$ annihilation background. The signature is striking: two isolated, high p_T, like-sign leptons in an event with no other significant activity (jet or lepton) in the central region. The dominant backgrounds are

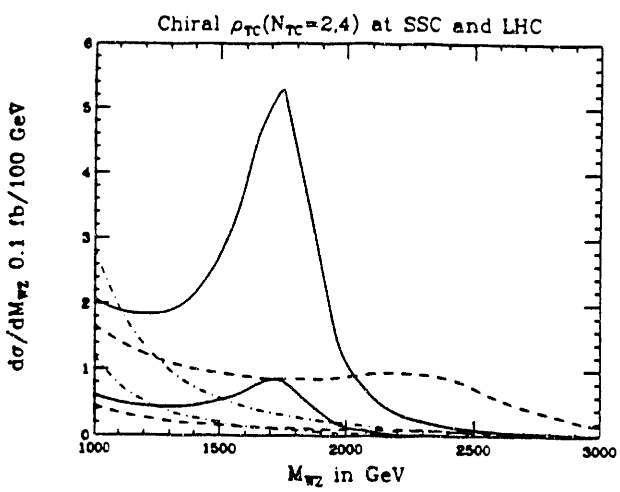

Figure 3. WZ cross section at SSC and LHC with $|y_{W,Z}| < 1.5$ for $\rho(1.78)$ (solid), $\rho(2.52)$ (dashes), and $\bar{q}q$ background (dot-dash).

Table 2. Cumulative effect of cuts on linear model signal and background for W^+W^+ only at the SSC. Entries are events per 10 fb^{-1}.

Cut	Signal	Bkgd.
$\lvert y_l \rvert < 2$	71	560
$p_{Tl} > 0.1$ TeV	44	49
$\cos\varphi_{ll} < -0.975$	32	9.1
CJV	27	2.4

the $O(\alpha_W^2)$[12] and $O(\alpha_W \alpha_S)$[13] amplitudes for $qq \to qqWW$. The former is essentially the W^+W^+ pair cross section from $SU(2)_L \times U(1)_Y$ gauge interactions, computed using the standard model with a light Higgs boson, e.g., $m_H \leq 0.1$ TeV. Other backgrounds, from W^+W^- with lepton charge mismeasured and from $\bar{t}t$ production, require detector simulation. Studies presented in the SDC TDR[11] show that they can be controlled.

A powerful set of cuts that efficiently though indirectly exploits the longitudinal polarization of the signal has emerged from the efforts of three collaborations.[4,5,14]. The most useful variables are the lepton transverse momentum p_{Tl} and the azimuthal angle between the two leptons ϕ_{ll}[14]. The CJV[4] also effectively exploits the W polarization; since the CJV signal efficiency may be affected by QCD corrections I present results with and without it. The truth probably lies closer to the results with CJV, but the necessary calculations have not been done. The successive effect of these cuts is illustrated in table 2. Even without the CJV they reduce the background by $\simeq O(10^2)$ while decreasing the signal by little more than a factor 2.

Assuming 85% detection efficiency for a single isolated lepton,[11] eqs. (3-4) applied to the uncorrected yields become $\sigma^{\uparrow} > 6$ and $\sigma^{\downarrow} > 3.5$. Typical results for the linear, K-LET, and scaled $\pi\pi$ data models are shown in table 3. In addition to $y_l < 2$ the cuts are $p_{Tl} > 0.2$ TeV and $\cos\phi_{ll} < -0.975$ for the linear and K-LET models and $p_{Tl} > 0.1$ TeV and $\cos\phi_{ll} < -0.90$ for the $\pi\pi$ model. The observability criterion is exceeded by a large margin at the SSC in all cases but one — the $\pi\pi$ model without CJV for which the criterion is just satisfied. At the LHC both the signals and signal:background ratios are less favorable, and about 70 fb^{-1} would be needed just to meet the minimum criterion for $\sigma^{\downarrow}$.

Results for the chiral invariant ρ exchange model are given in table 4. The cuts optimize the signal without CJV. For the SSC they are $p_{Tl} > 0.1$ TeV and $\cos\phi_{ll} < -0.925$ for $\rho(1.78)$ and $\rho(2.52)$, and $p_{Tl} > 0.2$ TeV and $\cos\phi_{ll} < -0.975$ for $\rho(4.0)$. Each case meets the minimum criterion with 10 fb^{-1} except $\rho(1.78)$ without CJV which would require 17 fb^{-1} but is readily observable with a big signal in the WZ channel (table 1). As expected from figure 2. the SSC yields for $\rho(4.0)$ (table 4) are within 5% of the K-LET yields (table 3). Comparing with the WZ yields in table 1, we see that 10 fb^{-1} suffices to detect the signal for any value of m_ρ in at least one of the two (complementary) channels.

The LHC cuts in table 4 are $p_{Tl} > 0.15$ TeV and $\cos\phi_{ll} < -0.95$ for all three models. The $\rho(1.78)$ signal would require 160 fb^{-1} just to meet the minimum criterion, while the $\rho(4.0)$ signal would require 55 fb^{-1}. With $\simeq$ 100 fb^{-1} the LHC could meet the minimum criterion for each model in at least one of the WZ or W^+W^+ channels,[1] assuming the relevant measurements can really be carried out at $10^{34}cm^{-1}s^{-1}$ (and with the efficiencies assumed here). In addition to instrumentation issues, the $\bar{t}t$ backgrounds that have been studied at 10^{33} cm^{-2} sec^{-1} have yet to be simulated at 10^{34}.

<u>ZZ</u>

Very heavy Higgs bosons and strong scattering into the ZZ final state are best detected

Table 3. Signal (S) and background (B) $W^+W^+ + W^-W^-$ events per 10 fb^{-1} at SSC and LHC for the indicated models. Cuts are specified in the text.

$\sqrt{s}$ TeV	Model	No CJV S	No CJV B	No CJV $\sigma^\uparrow, \sigma^\downarrow$	CJV S	CJV B	CJV $\sigma^\uparrow, \sigma^\downarrow$
40	Linear	30	3.5	16, 5.2	26	0.8	29, 5
	K	23	3.5	12, 4.4	20	0.8	23, 4.4
	$\pi\pi$	33	26	6.5, 4.3	27	6.5	11, 4.7
16	Linear	2.5	0.5	3.5, 1.4	2.1	0.09	6.9, 1.4
	K	2.0	0.5	2.8, 1.3	1.7	0.09	5.5, 1.3
	$\pi\pi$	5.0	5.4	2.2, 1.6	3.9	1.0	3.9, 1.8

Table 4. Signal (S) and background (B) $W^+W^+ + W^-W^-$ events per 10 fb^{-1} at SSC and LHC for the ρ exchange model. Cuts are specified in the text.

$\sqrt{s}$ TeV	M_ρ TeV	No CJV S	No CJV B	No CJV $\sigma^\uparrow, \sigma^\downarrow$	CJV S	CJV B	CJV $\sigma^\uparrow, \sigma^\downarrow$
40	1.78	22	23	4.6, 3.3	18	5.7	7.6, 3.7
	2.52	31	23	6.4, 4.2	25	5.7	11, 4.5
	4.0	22	3.5	11, 4.3	20	0.8	21, 4.4
16	1.78	1.8	1.5	1.5, 1.0	1.4	0.3	2.8, 1.1
	2.52	2.4	1.5	2.0, 1.2	1.9	0.3	3.7, 1.3
	4.0	3.3	1.5	2.7, 1.5	2.6	0.3	5.1, 1.5

Table 5. Linear model signals and background ZZ events per 10 fb^{-1} at SSC and LHC for various values of m_t. Cuts are $|y_l| < 2$ and $p_{Tl} > 75$ GeV. For the SSC $M_{TZ} > 700$ GeV and for the LHC $M_{TZ} > 600$ GeV.

$\sqrt{s}$ TeV	m_t GeV	Signal gg	Signal WW	Bkgd	$\sigma^\uparrow$	$\sigma^\downarrow$
40	100	4.1	17.3	29.4	4.0	3.0
	150	10.1	17.3	30.3	5.0	3.6
	200	16.7	17.3	32.2	6.0	4.2
16	100	0.75	1.83	8.98	0.9	0.8
	150	1.72	1.83	9.11	1.2	1.0
	200	2.41	1.83	9.49	1.4	1.2

in the "neutrino" mode, $ZZ \to l^+l^- + \bar{\nu}\nu$ with $l = e$ or μ. The net branching ratio from the ZZ initial state is 0.025, 6 times larger than the $l^+l^- + l^+l^-$ final state. The signature — a high p_T Z boson recoiling against missing p_T with no other significant jet activity in the central rapidity region — is experimentally clean. Backgrounds from $Z + jets$ and from mismeasurement of the missing E_T have been carefully studied and found to be controllable at 10^{33} cm^{-2} sec^{-1} for the SDC.[11] For the 1 TeV Standard Model Higgs boson with $m_t = 150$ GeV, a cut of $y_l < 2$, $p_{Tl} > 75$ GeV and transverse mass $M_T > 600$ GeV provides a 14σ signal with 96 signal events and 44 background events for 10 fb^{-1} at the SSC.

If $\mathcal{L}_5$ is strongly interacting and if a single symmetry breaking condensate gives mass to both the weak gauge bosons and to the top quark, then the ZZ signal has *two* components.[15] Just as WW fusion probes the mass scale of the quanta which generate the condensate that gives mass to W and Z, gg fusion via a $\bar{t}t$ loop probes the quanta which generate the t quark mass. If only one condensate does both jobs, the gg fusion contribution enhances the strong scattering signal in the ZZ final state. This generalizes the two familiar Higgs boson production mechanisms, $gg \to H$ and $WW \to H$, to dynamical symmetry breaking with strong $\mathcal{L}_5$.

Results[15] are given in table 5. Backgrounds considered are $\bar{q}q$ annihilation, gg fusion, and the $O(\alpha_W^2)$ amplitude for $qq \to qqZZ$, the latter two computed in the Standard Model with a light ($\leq$ 100 GeV) Higgs boson. The efficiency correction is offset by the additional contribution from $ZZ \to l^+l^- + l^+l^-$ that is not included in table 5, so eqs. (3-4) apply directly. For $m_t \geq 150$ GeV there are significant signals at the SSC with 10 fb^{-1} thanks to the big enhancement from gg fusion.

The LHC signals with 10 fb^{-1} are not significant. To enforce $S \geq B$ the p_{Tl} cut must be raised to 200 GeV, and 350 fb^{-1} are then required to satisfy eqs. (3-4). E.g., for $m_t = 150$ GeV the LHC with 350 fb^{-1} yields 28 signal and 31 background events, virtually identical to the SSC values in table 5 for 10 fb^{-1}. In addition the $Z + jets$ background requires study at such high luminosity.

With luminosity above 10^{33} at the SSC it becomes possible to probe for multiple condensates. E.g., if m_t is generated by a light Higgs boson while M_W is generated dynamically[1,15] then only WW fusion contributes to the ZZ signal. For $m_t = 150$ GeV and 50 fb^{-1} the signal exceeds eqs. (3-4) ($\sigma^\uparrow = 7$ and $\sigma^\downarrow = 6$) and differs by 3σ from the one condensate model. We do not satisfy $S > B$ since $S/B = 0.6$, but that may suffice given the years of experience likely to precede such measurements.

It is unlikely that this measurement could be done at the LHC. To satisfy $\sigma^\uparrow \geq 5$ for the two condensate model with $S/B = 0.6$ would require more than 1000 fb^{-1} at the LHC.[1]

CONCLUSION

The fifth force predicted by the Standard Model must begin to emerge at $\leq$ 2 TeV in WW scattering. If that prediction fails, the Standard Model will be supplanted by a deeper theory that will begin to emerge in the same energy region. With 10 fb^{-1} the SSC has capability for the full range of possible signals: strong WW scattering above 1 TeV or new quanta from $\mathcal{L}_5$ below 1 TeV. The strong scattering signals can occur in complementary resonant and/or nonresonant channels.

The practicability of measurements with $\geq 10^{34}$ cm^{-2} sec^{-1} is beyond the scope of this paper. In addition to accelerator and detector hardware questions there are backgrounds — some mentioned above — which have been studied for 10^{33} cm^{-2} sec^{-1} but require study at 10^{34}. It may take years of experience to learn to do physics in the 10^{34} environment. If

100 fb^{-1} data samples are eventually achieved and the relevant backgrounds are overcome, the LHC could meet the minimum observability criterion for the models discussed here in at least one of the W^+W^+ and WZ channels, while $\simeq$ 350 fb^{-1} would be needed in the ZZ channel. Luminosity $\geq 10^{34}$ at the SSC would enable the detailed studies of $\mathcal{L}_5$ that will be needed after the initial discovery whether $\mathcal{L}_5$ is weak or strong. That program could extend productively for several decades into the next century.

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