Probing W-Boson and Top-Quark Mass Generation with Strong ZZ Scattering Signals

Micheal S. Berger[a] and Michael S. Chanowitz

Theoretical Physics Group, Physics Division, Lawrence Berkeley Laboratory, 1 Cyclotron Road, Berkeley, California 94720

(Received 15 October 1991)

The Z-boson pair signal from strong WW scattering, $WW \to ZZ$, is significantly enhanced by a contribution from gluon-gluon fusion, $gg \to ZZ$, if W-boson and t-quark masses are both generated by electroweak symmetry breaking condensates formed by quanta heavier than 1 TeV. By measuring the two components of the signal it will be possible to probe for different origins of the W-boson and t-quark masses.

PACS numbers: 13.85.Qk, 12.15.Ji, 14.80.Dq, 14.80.Er

The highly successful unified theory of weak and electromagnetic interactions [1] predicts the existence of a fifth force and an associated new class of particles, known generically as the symmetry breaking sector [2]. Quanta from the symmetry breaking sector form vacuum condensates that break the electroweak symmetry and generate the masses of the W and Z gauge bosons and of the quark and lepton matter fields. By studying WW scattering at high-energy colliders such as the SSC (Superconducting Super Collider) we will learn whether the symmetry breaking sector consists of weakly self-coupled Higgs bosons lighter than 1 TeV or of a rich spectrum of strongly coupled particles heavier than 1 TeV. In the latter case the longitudinal polarization states W_L and Z_L, that are in effect particles from the symmetry breaking sector, interact strongly with one another, necessarily giving rise to strong WW scattering signals [3] if all other quanta in the symmetry breaking sector are heavy ($\gtrsim 1$ TeV). The like-charge channel, $W^+W^+ + W^-W^-$, may be the most promising [3,4]. The strong scattering signal in the ZZ channel is smaller, at the edge of observability for the SSC design parameters. We show that the strong scattering signal from $W^+W^- \to ZZ$ is significantly enhanced by an analogous signal from the gluon-gluon fusion process $gg \to ZZ$ that probes a different aspect of the symmetry breaking mechanism. Signal and background cross sections are presented below for both the SSC and the CERN LHC (Large Hadron Collider).

It is possible to use the WW- and gg-induced processes to probe separately the mechanisms of gauge-boson and matter-field mass generation, that do not necessarily arise from the same symmetry breaking condensates. Condensates that contribute to the W and Z masses need not contribute at all to fermion masses, while any condensate that generates quark and lepton masses must contribute to but not necessarily dominate the W and Z masses. Model builders have rarely exercised the option but that is no assurance that nature has not. It will be possible to probe for multiple condensates in second-generation experiments with the SSC operating above its initial design luminosity.

In effect we are generalizing the two principal Higgs-boson production mechanisms, $gg \to H$ [5] and $WW \to H$ [6], to the case in which symmetry breaking is not due to Higgs bosons but to strongly interacting quanta above 1 TeV. While the generalization of Higgs-boson production by WW fusion to strong WW scattering [3] has been the subject of many studies, there has been little analogous study of gluon-gluon fusion [7]. In both instances the resonant Higgs-boson signal is replaced by a nonresonant signal consisting of a pair of longitudinally polarized gauge bosons. Feynman diagrams for gg fusion in the minimal standard model with one Higgs boson are shown in Fig. 1. The process proceeds predominantly via a virtual top-antitop quark pair (unless there are still heavier quarks, which would induce even larger signals). WW fusion probes the quanta which form the condensate that generates the W and Z masses, while gg fusion through a virtual $\bar{t}t$ pair probes the quanta whose condensate induces the top-quark mass.

Strong WW scattering in the energy domain $M_W^2 \ll s_{WW} \ll \Lambda_{SB}^2$ between threshold and the typical mass scale of a strong symmetry breaking sector, $\Lambda_{SB} > 1$ TeV, is determined by low-energy theorems [8] analogous to the low-energy theorems for pion-pion scattering [9], e.g.,

$$\mathcal{M}(W_L^+W_L^- \to Z_LZ_L) = \frac{s}{\rho v^2}\left[1 + O\left(\frac{M_W^2}{s}, \frac{s}{16\pi^2 v^2}\right)\right], \tag{1}$$

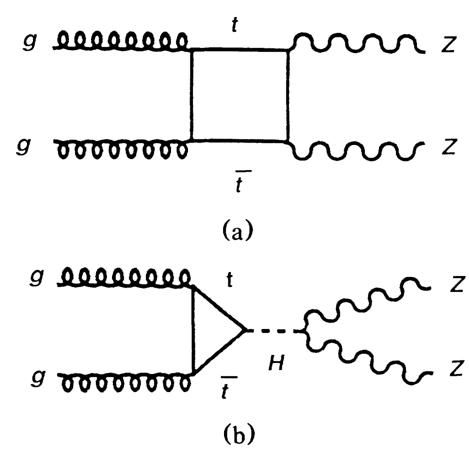

FIG. 1. Feynman diagrams for $gg \to ZZ$ via the top-quark loop.

where $\rho = M_W^2/M_Z^2\cos^2\theta_W \simeq 1$ and $v = 246$ GeV. The linear dependence on s would eventually violate partial wave unitarity and is precisely the "bad high-energy behavior" that is cured by spontaneous symmetry breaking [10].

In the minimal standard model [1] (with $\rho = 1$) the growth of the amplitude is cut off by the s-channel Higgs-boson exchange amplitude,

$$\mathcal{M}(W_L^+W_L^- \to H \to Z_LZ_L) = -\frac{s}{v^2}\frac{s}{s-m_H^2}, \tag{2}$$

that cancels Eq. (1) for $s \gg m_H^2$. More generally, in dynamical realizations of the Higgs mechanism the cancellation is provided by exchange (poles or cuts) of whatever quanta condense in the vacuum to induce the gauge-boson masses. By observing experimentally the scale at which the cutoff occurs, we probe the mass scale of the condensate-forming quanta. If the cutoff is deferred to between about 1 and 2 TeV (the upper bound fixed by partial wave unitarity [3]) then strong WW scattering occurs.

The analogous physics of gluon-gluon fusion is best understood by first considering the process $\bar{t}t \to Z_LZ_L$, that contributes to the imaginary part of the $gg \to Z_LZ_L$ amplitude by the unitarity relation

$$\mathrm{Im}\mathcal{M}(gg \to Z_LZ_L) = -\tfrac{1}{2}\sum_n \mathcal{M}^*(n \to gg)\mathcal{M}(n \to Z_LZ_L). \tag{3}$$

The contribution to Eq. (3) from the $n = \bar{t}t$ intermediate state can be visualized by cutting through the top-quark loops in Fig. 1. Omitting symmetry breaking sector interactions, the chirality-flip (equal helicity) amplitude $\bar{t}_+t_+ \to Z_LZ_L$ also has bad high-energy behavior (t_+ denotes a top quark with positive helicity),

$$\mathcal{M}(\bar{t}_+t_+ \to Z_LZ_L) = \sqrt{s}\,m_t/v^2. \tag{4}$$

Compared to Eq. (1) this bad high-energy behavior is less evil by a factor $\sqrt{s}$, a result of the factor m_t needed to flip the chirality [11]. In analogy to Eq. (2), good high-energy behavior is restored in the minimal model by adding the s-channel Higgs-boson exchange amplitude to Eq. (4),

$$\mathcal{M}(\bar{t}_+t_+ \to H \to Z_LZ_L) = -\frac{\sqrt{s}\,m_t}{v^2}\frac{s}{s-m_H^2}. \tag{5}$$

More generally the $\sqrt{s}$ growth is cut off by s-channel exchange of whatever the quanta are in the symmetry breaking sector which form the vacuum condensate that generates the top-quark mass. If those quanta are very heavy the $\bar{t}t \to Z_LZ_L$ amplitude grows to a larger value before being cut off.

The simplicity of the analogy is complicated by the fact that in gg fusion the top quarks are virtual. In particular, the $\sqrt{s}$ bad high-energy behavior of Eq. (4) does not induce bad high-energy behavior in $\mathcal{M}(gg \to Z_LZ_L)$ because the factor $\mathcal{M}(gg \to \bar{t}t)$ in the unitarity relation Eq. (3) is proportional to $m_t/\sqrt{s}$ in the chirality-flip channel. Glover and van der Bij [12] find by explicit calculation of the box diagrams a contribution to $\mathcal{M}(gg \to Z_LZ_L)$ proportional to $m_t^2\ln^2 s$, which is engendered by Eq. (4) and is canceled for $s > m_H^2$ by an opposite contribution from the triangle amplitude Fig. 1(b), just as Eq. (5) cancels Eq. (4). In general then $\sigma(gg \to ZZ)$ is sensitive to the masses of the quanta that form the m_t-generating vacuum condensate, with a larger high-energy cross section if the masses of the m_t-generating quanta are very heavy.

Suppose first that a single condensate generates gauge-boson and matter-field masses. We use the model [3] of strong WW scattering in which the low-energy amplitude, Eq. (1), is taken to represent the absolute value of the $J = 0$ partial wave, $|a_0|$, up to the energy at which unitarity is saturated, $s_0 = 16\pi v^2 \simeq (1.75\ \mathrm{TeV})^2$, beyond which $|a_0|$ is set equal to 1,

$$|a_0(W_L^+W_L^- \to Z_LZ_L)| = \frac{s}{16\pi v^2}\theta(s_0 - s) + \theta(s - s_0). \tag{6}$$

For pion-pion scattering in the $I = J = 0$ channel the analogous model provides an excellent fit to the data—see fit a to $|T_{00}|$ in Fig. 4 of Ref. [13]. To represent $gg \to Z_LZ_L$ we similarly cut off the $\sqrt{s}$ growth of Eq. (4) at $s = s_0$, beyond which the factor $\sqrt{s}$ is replaced by a constant factor $s_0^{1/2}$. The effect on $gg \to ZZ$ is to retain only the box graphs with the term [14] engendered by Eq. (4) multiplied by a factor $(s_0/s)^{1/2}$ for $s > s_0$. If M_W and m_t are induced by condensates at different scales we introduce correspondingly different cutoffs for WW and gg fusion.

We consider the decay channel [3,15] $ZZ \to e^+e^-/\mu^+\mu^- + \bar{\nu}\nu$, defined experimentally by an observed central Z with large transverse momentum opposite the large missing transverse energy. The branching ratio is 0.025, about 6 times larger than the four-charged-lepton decay mode to e's or μ's.

We include three contributions to the background as in recent analyses of Higgs-boson detection in the ZZ decay channel [16]. The first is quark-antiquark annihilation, $\bar{q}q \to ZZ$. The second consists of the contributions to $gg \to ZZ$ that do not depend on the symmetry breaking sector, including production of Z_TZ_T and Z_TZ_L boson pairs as well as Z_LZ_L pairs produced via the chirality-*nonflip* $\bar{t}t \to Z_LZ_L$ amplitude proportional to m_t^2. Third is the $O(\alpha_W^2)$ amplitude [17] for $qq \to qqZZ$. It and the $gg \to ZZ$ background are obtained from the standard model with a light Higgs boson, $m_H \lesssim 100$ GeV, since only the symmetry-breaking-independent amplitudes of the light-Higgs-boson model contribute to the cross section with the cuts specified below [18].

Both our analysis and recent Higgs-boson detection studies [16] neglect higher-order mixed QCD-electroweak backgrounds that should eventually be considered. The $O(\alpha_S^2\alpha_W^2)$ cross sections [17,19] can be significantly reduced by a double central jet veto at negligible cost to

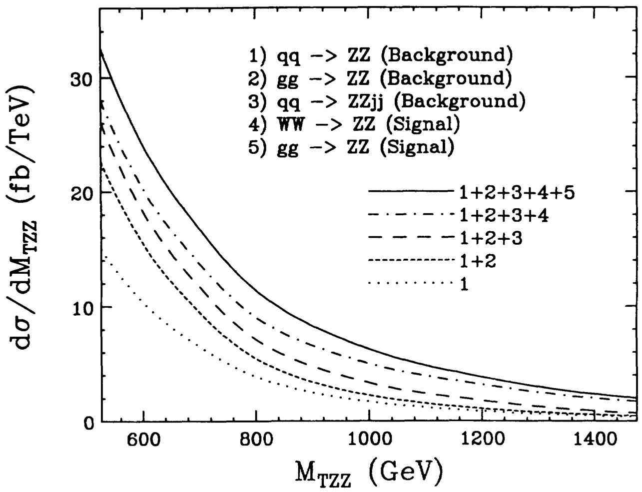

FIG. 2. Signal and background components for inclusive production of $ZZ \to \bar{l}l + \bar{\nu}\nu$ at the SSC. The differential cross section is plotted with respect to the transverse ZZ mass, with cuts $|y_l| < 2$ and $p_{Tl} > 75$ GeV.

the signal [20]. Similarly Ohnemus and Owens [21] find that a central jet veto reduces the $O(\alpha_W^2 \alpha_S)$ $\bar{q}q \to ZZ$ cross section to below the level of the tree approximation despite the increase in the inclusive ZZ cross section indicated by the K factor [21,22]. Since a central jet veto will be included in a more complete treatment we do not rescale $\sigma(\bar{q}q \to ZZ)$ by K.

Contributions to signal and background at the SSC are displayed in Fig. 2 for $m_t = 150$ GeV. We plot the differential cross section (including the decay branching ratio, 0.025) with respect to the transverse ZZ mass, $M_{TZZ} = 2(p_{TZ}^2 + M_Z^2)^{1/2}$, where p_{TZ} is the transverse momentum of the observed Z. The lepton rapidity and transverse momentum cuts are $|y_l| < 2$ and $p_{Tl} > 75$ GeV. The gg fusion component of the signal is clearly substantial.

Table I exhibits event yields per 10^4 pb^{-1} at the SSC and LHC for $m_t = 100$, 150, and 200 GeV with cuts to optimize the statistical significance [23]. The statistical significance for signal S and background B events is given by $\sigma^{\uparrow} = S/\sqrt{B}$, the number of standard deviations for the background to fluctuate up to give a false signal, and $\sigma^{\downarrow} = S/\sqrt{S+B}$, for downward fluctuations of $S+B$ to the level of B alone. Neither the Z detection efficiency [24], $\simeq 95\%$, nor the additional $\simeq 15\%$ contribution of the four-charged-lepton decay mode are included. At the SSC we find $\sigma^{\uparrow} \simeq 4$, 5, and 6 for $m_t = 100$, 150, and 200 GeV, which would be diminished by 1, 2, and 3, respectively, if the gg fusion component of the signal did not contribute. The signal-to-background ratio is approximately 1:1. It is important not only with respect to the statistical significance but also because of the systematic theoretical uncertainty in the background, estimated at $\simeq 30\%$ after a broad variety of measurements of standard processes have been performed *in situ* at the SSC or

TABLE I. Signal and background in events per 10^4 pb^{-1}. Cuts are $|y_l| < 2$ and $p_{Tl} > 75$ GeV. For the SSC $M_{TZZ} > 700$ GeV and for the LHC $M_{TZZ} > 600$ GeV. Statistical significance $\sigma^{\uparrow}, \sigma^{\downarrow}$ is defined in the text.

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

LHC [25]. At the SSC a 30% systematic uncertainty in the background would not overwhelm the signal.

The LHC signals for 10^4 pb^{-1} are not statistically significant. For $m_t = 150$ GeV a luminosity increase by a factor $(5.0/1.2)^2 = 17$ would bring statistical parity with the SSC for $\sigma^{\uparrow}$. But for the cuts in Table I the LHC signal-to-background ratio is between 1:4 and 1:2, so that the signal could not be reliably extracted given a 30% theoretical uncertainty in the background. Raising the lepton transverse momentum cut from 75 to 200 GeV increases the signal-to-background ratio to nearly 1:1 but with a factor of 4.5 loss in signal. The LHC would then achieve a value of $\sigma^{\uparrow}$ equal to that of the SSC if the luminosity were increased by a factor of 35: For 35×10^4 pb^{-1} the LHC has 27.7 signal and 30.8 background events, very similar to the SSC values in Table I for 10^4 pb^{-1}. The remaining question is whether the measurements are actually feasible with good efficiency at such high luminosity. In addition to instrumental issues, the background from Z+jets requires attention (see Barnett, Einsweiler, and Hinchliffe [15]).

Experiments at the SSC are also preparing for luminosity above the initial 10^{33}-cm^{-2}sec^{-1} design value [26]. In addition to more robust yields, higher luminosity would allow a more detailed analysis of the signal. By isolating the WW and gg fusion components we probe the possibility of different origins for gauge-boson and quark masses. For instance, m_t could arise from a light Higgs boson with a small vacuum expectation value, $v' \ll 246$ GeV, and a strong $H\bar{t}t$ coupling, while M_W and M_Z were mostly formed dynamically by physics above 1 TeV. Then the ZZ signal far above m_H would have no gg fusion component. In Table I with $m_t = 150$ GeV the $27.4 + 30.3 = 57.7$ events including 10.1 from the gg fusion signal would only be a 1.5σ fluctuation of the $17.3 + 30.3 = 47.6$ events predicted in the absence of the gg fusion signal, but with a factor of 10 more luminosity the difference is a 4.5σ effect. Since the gg contribution to the signal is $\simeq 30\%$ of the background, the initially anticipated 30% theoretical uncertainty would have to be substantially reduced. An alternative method less sensitive to the size of the background is to use double [27] or single (Barger *et al.* [16]) jet tagging to separate the gg and WW components.

We have found that if the weak-boson and top-quark masses are generated by a condensate formed by quanta heavier than 1 TeV, then at the SSC with 10^4 pb^{-1} or at the LHC with 35×10^4 pb^{-1} there is a significant signal in the ZZ channel from the sum of WW and gg fusion, complementing the strong scattering signal in the W^+W^+ channel. Second-generation measurements with the SSC operating above initial design luminosity could also distinguish between the two production mechanisms, shedding light on the possibility of different origins for the gauge-boson and quark masses.

We wish to thank E. W. N. Glover for providing the computer code of Ref. [12] and V. Barger and K. Cheung for discussions. This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of High Energy Physics, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

[a]Present address: High Energy Physics, Phenomenology Institute, University of Wisconsin, Madison, WI 53706.

[1] S. Weinberg, Phys. Rev. Lett. **19**, 1264 (1967); A. Salam, in *Proceedings of the Eighth Nobel Symposium*, edited by N. Svartholm (Almqvist & Wiksells, Stockholm, 1968), p. 367.

[2] For a review, see M. S. Chanowitz, Annu. Rev. Nucl. Part. Sci. **38**, 323 (1988).

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

[4] V. Barger *et al.*, Phys. Rev. D **42**, 3052 (1990); D. Dicus, J. F. Gunion, and R. Vega, Phys. Lett. B **258**, 475 (1991); M. S. Berger and M. S. Chanowitz, Phys. Lett. B **263**, 509 (1991). The latter paper reports larger yields than the first principally because of the choice of cuts and of nucleon Q^2 scale—see M. S. Berger and M. S. Chanowitz, Phys. Lett. B **267**, 416 (1991). The second paper only considers Higgs-boson exchange rather than the strong scattering models that predict much larger signals.

[5] H. M. Georgi *et al.*, Phys. Rev. Lett. **40**, 692 (1978).

[6] R. N. Cahn and S. Dawson, Phys. Lett. **136B**, 196 (1984).

[7] While preparing this manuscript we learned of a recent paper by J. Bagger, S. Dawson, and G. Valencia [Phys. Rev. Lett. **67**, 2256 (1991)], considering $gg\rightarrow ZZ$ mediated by pseudo Goldstone bosons (PGB's) different from the t-quark-mediated process that occurs whether there are colored PGB's or not and specifically probes the mechanism of t-quark mass generation. Our results are consistent with their Fig. 2 for the t-quark-mediated contribution.

[8] M. S. Chanowitz, M. Golden, and H. Georgi, Phys. Rev. D **36**, 1490 (1987); Phys. Rev. Lett. **57**, 2344 (1986).

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

[10] The connection is the basis of one proof of the low-energy theorems in Ref. [8].

[11] The unitarity constraint from Eq. (4) is correspondingly weaker—see M.S. Chanowtiz and T. Appelquist, Phys. Rev. Lett. **59**, 2405 (1987).

[12] E. W. N. Glover and J. J. van der Bij, Nucl. Phys. **B321**, 561 (1989).

[13] J. Donoghue, C. Ramirez, and G. Valencia, Phys. Rev. D **38**, 2195 (1988).

[14] The relevant term, with both real and imaginary parts, is $C(s)$ in Eq. 3.24 of Ref. [12].

[15] M. S. Chanowitz and R. N. Cahn, Phys. Rev. Lett. **56**, 1327 (1986); R. M. Barnett, K. Einsweiler, and I. Hinchliffe, SCC Report No. SSC-SDC-90-00099, 1990 (unpublished).

[16] U. Baur and E. W. N. Glover, Phys. Rev. D **44**, 99 (1991); V. Barger *et al.*, Phys. Rev. D **44**, 1426 (1991).

[17] U. Baur and E. W. N. Glover, Nucl. Phys. **B347**, 12 (1991); Barger *et al.* (Ref. [16]).

[18] We use the code of Baur and Glover (Ref. [17]) and the matrix element from the code of Glover and van der Bij (Ref. [12]) to compute the $gg\rightarrow ZZ$ and $qq\rightarrow qqZZ$ backgrounds.

[19] V. Barger *et al.*, Phys. Rev. D **41**, 2782 (1990).

[20] In particular we have studied a veto of events containing two jets with $|y_j| < 2.5$ and $P_{Tj} > 100$ GeV.

[21] J. Ohnemus and J. F. Owens, Phys. Rev. D **43**, 3626 (1991).

[22] B. Mele, P. Nason, and G. Ridolfi, Nucl. Phys. **B357**, 409 (1991).

[23] The results are not very sensitive to the form of the cutoff, e.g., for $m_t = 150$ GeV the contribution from $s > s_0$ is 0.37 gg- and 3.10 WW-induced events.

[24] Solenoidal Detector Collaboration, E. L. Berger *et al.*, Letter of Intent No. SDC-90-00151, 1990 (unpublished).

[25] R. N. Cahn *et al.*, in *Experiments, Detectors, and Experimental Areas for the Supercollider*, edited by R. Donaldson and M. Gilchriese (World Scientific, Singapore, 1987), p. 20.

[26] Site Specific Conceptual Design Report, edited by J. Sandord, SSC-SR-1051, 1990 (unpublished).

[27] R. N. Cahn *et al.*, Phys. Rev. D **35**, 1626 (1987); R. Kleiss and W. Stirling, Phys. Lett. B **200**, 193 (1988).