Proposals for Studying TeV $W_L W_L \to W_L W_L$
Interactions Experimentally

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ABSTRACT

We discuss how to experimentally study the symmetry breaking sector by observing $W_L W_L \to W_L W_L$ interactions in the TeV region. We discuss some general features of the event structure in the signal and background events. Various tricks to enhance the signal–to–background ratio are also presented. We show how to detect longitudinal $W$–bosons either in the central rapidity region of the detector or in the beam pipe direction.

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1. Introduction

The Standard Electroweak Model has been tested and is very successful in explaining and predicting experimental data. However, we still do not have any understanding about the origin of the fermion masses or the spontaneous symmetry breaking mechanism (Higgs mechanism) of the Standard Model (SM). To probe the symmetry breaking sector, we need to detect the longitudinal $W$ pairs produced via the $W_LW_L$ fusion mechanism\(^{[1-3]}\) if a light Standard Model Higgs boson does not exist. (We shall use $W$ to denote either $W^\pm$ or $Z^0$ unless specified otherwise.) In the spontaneous symmetry breaking sector, the would–be Goldstone bosons ($\phi$’s) characterize the broken symmetry of the theory. These would–be Goldstone bosons become the longitudinally polarized $W$–bosons, and the $W$–bosons therefore become massive. Consequently, a study of the symmetry breaking sector requires an understanding of the interactions of these would–be Goldstone bosons. Their interactions become strong in the TeV region if no light resonances (Higgs bosons) exist. (In this article, we will not consider models with light resonances in the symmetry breaking sector.) In the limit $E_W \gg M_W$, the $S$–matrix of $W_LW_L \rightarrow W_LW_L$ is the same as that of $\phi\phi \rightarrow \phi\phi$, based on the electroweak equivalence theorem.\(^{[4-6]}\) ($E_W$ is the energy of the $W$–boson in the center–of–mass frame of the $WW$ pair. $M_W$ is the mass of the $W$–boson.) Therefore, it is important to study the $W_LW_L \rightarrow W_LW_L$ interactions in the TeV region.

In this article, we show how to detect the $W_LW_L \rightarrow W_LW_L$ signal. In section 2, we discuss the possible signals predicted by various models. In section 3, we discuss the backgrounds. In section 4, we discuss the characteristic differences between the event structures of the signal and the backgrounds. In section 5, we give recipes for detecting the signal predicted by various models. Section 6 contains our conclusions.
2. Signal

The event signature of the signal is a longitudinal $W$–pair produced in the final state. Here, we will not discuss the detection of a light resonance in the symmetry breaking sector as predicted by some models.\textsuperscript{[7]} In the TeV region, the symmetry breaking sector may either contain a scalar– or vector– resonance, etc., or no resonance at all. For a model with a TeV scalar resonance, the most useful modes are the $W^+W^-$ and $Z^0Z^0$ modes which contain large isospin–0 channel contributions. For a model with a TeV vector resonance, the most useful mode is the $W^\pm Z^0$ mode because it contains a large isospin–1 channel contribution. If there is no resonance present in the symmetry breaking sector, all the $WW$ modes are equally important, so the $W^\pm W^\pm$ mode is also useful. Before we discuss the backgrounds, we have to specify the decay mode of the $W$‘s. The branching ratio of $W^+ \rightarrow l^+\nu$ is 2/9 for $l^+ = e^+$ or $\mu^+$, and 0.06 for $Z^0 \rightarrow l^+l^-$. If the signal is large enough, the $Z^0(\rightarrow l^+l^-)Z^0(\rightarrow l^+l^-)$ and $Z^0(\rightarrow l^+l^-)Z^0(\rightarrow \nu\bar{\nu})$ modes would be most useful.\textsuperscript{[8]} Throughout this article, we have in mind mainly the $W^+(\rightarrow l^+\nu)W^-(\rightarrow q_1\bar{q}_2)$ mode unless specified otherwise.\textsuperscript{[9]} We also discuss the detection of the signal in the $W^+(\rightarrow l^+\nu)Z^0(\rightarrow q\bar{q})$ and $W^+(\rightarrow l^+\nu)W^+(\rightarrow l^+\nu)$ modes.

3. Backgrounds

For each decay mode of the $WW$ pair, the relevant backgrounds vary. But, in general, the dominant background processes are the “intrinsic” background which also contains a $WW$ pair in the final state, the electroweak–QCD process, $W+\text{jets}$, which contains a “fake $W$” mimicked by two QCD jets, and QCD processes such as $t\bar{t}$ production with subsequent decay to a $WW$ pair. We now discuss these backgrounds in various $WW$ modes separately.
3.1. $W^+(→ l^+ ν)W^-(→ q_1 q_2)$ MODE

The intrinsic background processes for this mode are $q_1 q_2 → W^+ W^−$, $gg → W^+ W^−$, and $W^+ W^− + jets$. The signature for the signal in this mode is an isolated lepton with high transverse momentum $P_T$, and two jets which can be reconstructed as the decay products of a $W^-$-boson. $W^+ + jets$ processes can mimic the signal when the invariant mass of the two QCD jets is around $M_W$. Other potential background processes for this mode are the QCD processes $q_1 q_2 → t \bar{t}$, $Wt \bar{t}$ and $t \bar{t} + jet$. For a heavy top quark, the two $W$’s produced from the decay of $t$ and $\bar{t}$ can also mimic the signal.

3.2. $W^+(→ l^+ ν)Z^0(→ qq)$ MODE

The signature of the signal in this mode is an isolated lepton with high $P_T$, a large missing transverse energy $E_T$, and a two jet invariant mass around $M_Z$. The dominant background processes for this mode are similar to those for the $W^+(→ l^+ ν)W^-(→ q_1 q_2)$ mode discussed above. They are $q_1 q_2 → W^+ Z^0$, $W^+ Z^0 + jets$, $W^+ + jets$ and $Zt \bar{t}$ production processes.

3.3. $W^+(→ l^+ ν)W^+(→ l^+ ν)$ MODE

For the purely leptonic decay mode of $W^+ W^+$, the signature is two like-sign isolated leptons with high $P_T$ and large $E_T$. There are no low-order backgrounds from quark–antiquark or gluon–gluon fusion processes. However, other backgrounds can be important, such as the QCD–gluon exchange process, the production of the transversely polarized $W$–pairs from the standard electroweak mechanism, and the $W^+ \bar{t} \bar{t}$ production from the electroweak–QCD process.

Without imposing any kinematic cuts to suppress the background processes, the raw event rate of the signal is usually significantly smaller than that of the backgrounds. However, the signature of the signal can actually be distinguished from that of the backgrounds. We shall examine the characteristic differences between the event structures of the signal and the backgrounds in the next section.
4. How to distinguish the signal from background events

The signature of a signal event can be distinguished from that of background events in many ways. We first discuss differences in the global features of the signal and background events, then point out some distinct kinematics of the signal events.

4.1. Global features

The signal of interest is the $WW$ pair produced from the $W$–fusion process. The spectator quark jet that emitted the $W$–boson in the $W$–fusion process tends to go into the high rapidity region. This jet typically has a high energy, about a TeV, for $M_{WW} \sim 1$ TeV. ($M_{WW}$ is the invariant mass of the $WW$ pair.) Therefore, one can tag this forward jet to suppress backgrounds.\[27,28,9\]

Because the production of the signal is purely electroweak, the charged particle multiplicity of the signal event is smaller than that of a typical QCD process such as $q\bar{q} \rightarrow gW^+W^- (\rightarrow q_1\bar{q}_2)$ or $qq \rightarrow qW^+q_1\bar{q}_2$. Because of the small hadronic activity in the signal event, in the central rapidity region there will be fewer hard QCD jets produced. At the parton level, they are the two quark jets produced from the $W$–boson decay plus soft gluon radiation. However, for the background process such as $t\bar{t}$ production, there will be more jets produced in the central rapidity region both because there are additional jets ($b$ and $\bar{b}$ jets) from the decay of $t$ and $\bar{t}$ and because of the stronger hadronic activity from QCD effects. Therefore, one can reject events with more hard jets produced in the central region to suppress the backgrounds. This was first suggested in Ref. 19 using a hadron level analysis to show that the $t\bar{t}$ background can be handled.\[29,9\]

A similar trick of vetoing extra jets in the central rapidity region when studying the pure leptonic decay mode of $W$’s was also analyzed at the parton level.\[29,9\] An equivalent way of making use of the global difference in the hadronic activity of the events is to apply cuts on the number of charged particles. This was first pointed out in Refs. 30 and 31.
In the $W$–fusion process, the typical transverse momentum of the final state $W$–pair is about $M_W$.\[^{27}\] However, in the TeV region, the $P_T$ of the $W$–pair produced from the background process, such as $q\bar{q} \rightarrow gWW$, can be $\sim$ a few hundred GeV. Therefore, the two $W$’s (either both real or one real and one fake) produced in the background process are less back–to–back in the transverse plane than those of the signal.

4.2. **Isolated Lepton in $W^+ \rightarrow l^+\nu$**

Because the background event typically has more hadronic activity in the central rapidity region, the lepton produced from the $W$–boson decay is usually less isolated than that in the signal event. Therefore, demanding an isolated lepton with high $P_T$ is a useful method to suppress the backgrounds. This requirement together with large missing transverse energy $\not{E}_T$ in the event assures the presence of a $W$–boson in the event. Also, the sign of the lepton charge can be important, as in detecting the $W^+(\rightarrow l^+\nu)W^+(\rightarrow l^+\nu)$ mode.

4.3. **$W \rightarrow q_1\bar{q}_2$**

To identify the signal, we have to reconstruct the two highest $P_T$ jets in the central rapidity region and form the invariant mass of the $W$–boson. It has been shown\[^{31}\] that an efficient way of finding these two jets is to first find a big cone jet with invariant mass around $M_W$, then demand that there are two jets with smaller cone size inside this big cone jet. Because we must measure any new activity in $W_LW_L \rightarrow W_LW_L$, and because the $W$–boson (or “fake $W$”) in the background event is mainly transversely polarized,\[^{31}\] one must measure the fraction of longitudinally polarized $W$–bosons in the $WW$ pair data sample and compare with that predicted by the model of interest.

In the next section, we show how to observe the signals predicted by various models of the symmetry breaking sector. Some of them were studied at the hadron level, some at the parton level. I will not reproduce those analyses but sketch
the ideas of various “tricks” used in detecting $W_L W_L \rightarrow W_L W_L$ interactions. The procedures discussed here are not necessarily the ones used in the analyses performed in the literature. If the signal event rates are large enough to observe the purely leptonic mode, then studying the symmetry breaking sector will not be difficult.\[^9\] Here we assume, however, that it is necessary to study the $l^\pm + \text{jets}$ mode of the $WW$ pair.

5. Various Models

5.1. A TeV Scalar Resonance

In the Standard Model, the mass of the Higgs boson cannot be much larger than $\sim 630$ GeV, otherwise the theory would be inconsistent, based on the triviality argument.\[^{32}\] (If there is any higher scale in the theory, this number is even lower.) However, one may consider a TeV scalar resonance in an electroweak chiral lagrangian whose coupling to the would-be Goldstone bosons is the same as that in the Standard Model.\[^{33,34,9}\] (The mass and width of the scalar resonance are two free parameters in this model.) Then one can ask how to detect such a TeV scalar resonance. This study has been performed at the hadron level in Ref. 31. The tricks of enhancing the ratio of signal to background are as follows. Let us consider the $W^+ (\rightarrow l^+ \nu) W^- (\rightarrow q_1 \bar{q}_2)$ mode for this model. First of all, we trigger on a high $P_T$ lepton. The lepton is said to be isolated if there is no more than a certain amount of hadronic energy inside a cone of size $\Delta R$ surrounding the lepton. $\Delta R = \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2}$, $\phi$ is the azimuthal angle and $\eta$ is the pseudo-rapidity.) A TeV resonance produces a $W$–boson with typical $P_T$ on the order of $\sim 1/2$ TeV, therefore, the $P_T$ of the lepton from the $W$–decay is on the order of a few hundred GeV. The cut on the $P_T$ of an isolated lepton alone can suppress a large fraction of $t\bar{t}$ background events because the lepton produced from the decay of the $W$–boson typically has $P_T \sim m_t/3$, where $m_t$ is the mass of the top quark. Besides, the lepton is also less isolated in the $t\bar{t}$ event than that in the signal event. After selecting the events with a high $P_T$ isolated lepton, we can make use of the fact that the
background event contains more hadronic activity than the signal event to suppress more background. One can make a cut on the charged particle multiplicity of the event to enhance the signal–to–background ratio. Another way of making use of this fact is to demand that there is only one big cone jet in the central rapidity region of the detector. The background process typically produces more hard jets than the signal. One can then veto the events with more than one big cone jet in the central rapidity region. The $W^+ + jets$ and $t\bar{t}$ background processes can further be suppressed by demanding that the large cone jet has invariant mass $\sim M_W$ and high $P_T$. Inside this big cone jet, one can further demand two small cone jets corresponding to the two decay quark jets of the $W$–boson. It is essential not to bias the information on the polarization of the $W$–boson because discovering any new physics present requires measuring the $W$ polarization. It has been shown that one can measure the fraction of longitudinal $W$’s in the candidate $W$ samples to distinguish various models if the event rate is not too small.\cite{31} It is important to separate signal from background by general topological aspects of events rather than by cuts. One of the techniques which would not bias the polarization of the $W$–boson is counting the charged particle multiplicity inside the big cone jet. A real $W$–boson decays into a color singlet state of $q\bar{q}$ with the same multiplicity regardless of its energy. Therefore the charged particle multiplicity of these two jets is less than that of a pair of non–singlet QCD jets (either quark or gluon jets) which form a big cone jet and exhibit more hadronic activity. This provides an additional tool in suppressing the background.

Up to this point, we have only discussed the event structure in the central rapidity region. As discussed in the previous section, in the large rapidity region the signal event tends to have an energetic forward jet. It has been shown that tagging one such forward jet can further suppress the background at very little cost to the signal event rate.\cite{9} Furthermore, with rapidity coverage down to 5, one can have a good measurement on $E_T$.\cite{35} Because the typical $E_T$ due to the neutrino from the $W$–boson decay is on the order of a few hundred GeV, the mis–measurement of neutrino transverse momentum due to the underlying hadronic
activity is negligible. Knowing $E_T$ and the momentum of the lepton, one can determine the longitudinal momentum of the neutrino up to a two–fold solution by constraining the invariant mass of the lepton and neutrino to be $M_W$. From the invariant mass of $l$, $\nu$, $q_1$, and $\bar{q}_2$, one can reconstruct $M_{WW}$ and distinguish different signals from the background. As pointed out earlier, the best way to detect new physics is to measure the fraction ($f_L$) of longitudinal $W$’s in the event sample. A specific model will give a distinct distribution of $f_L$ as a function of $M_{WW}$. Some examples were shown in Ref. 31.

5.2. A TeV vector Resonance

An example of this type of resonance is a techni–rho in the techni–color model. What we have in mind is a vector resonance in the electroweak chiral lagrangian. The mass and width of the vector resonance are two free parameters in this model. Because this resonance gives a large contribution in the isospin–1 channel, the useful mode in which to look for such a resonance is the $W^\pm Z^0$ mode. If the signal event rate is large enough, the resonance can be observed by the purely leptonic decay mode $W^+ (\rightarrow l^+ \nu) Z^0 (\rightarrow l^+ l^-)$ because all the leptons in this mode have $P_T \sim$ few hundred GeV and the leptons are isolated. If the $W^+ (\rightarrow l^+ \nu) Z^0 (\rightarrow q\bar{q})$ mode is necessary for the signal to be observed, the strategies discussed in the previous subsection for the $W^+ (\rightarrow l^+ \nu) W^- (\rightarrow q_1 \bar{q}_2)$ mode can be applied in this case as well. Needless to say, the invariant mass of two jets peaks around $M_Z$ not $M_W$. It could be very valuable to improve techniques to separate $W (\rightarrow jj)$ from $Z (\rightarrow jj)$ using mass resolution and jet charge measurement as pioneered in the JADE and ALPHA detectors.
5.3. **No Resonance**

If there is no resonance, then all the $WW$ modes should be measured to study the dynamic symmetry breaking sector. For instance, one may use a chiral lagrangian model with the lowest order two–derivative term to describe the $WW$ interactions. This model is known as the low energy theorem model. The methods of detecting the signal from this model using the $W^+ (\rightarrow l^+ \nu) W^- (\rightarrow q_1 \bar{q}_2)$ mode in the TeV region were presented in Ref. 31. The tricks of observing this signal are identical to those discussed in the previous subsections. Similar tricks can be applied to observe the signal using the $W^+ (\rightarrow l^+ \nu) Z^0 (\rightarrow q\bar{q})$ mode. It has also been argued that one can study the purely leptonic mode $W^+ (\rightarrow l^+ \nu) W^+ (\rightarrow l^+ \nu)$ in the multi–TeV region to probe the symmetry breaking sector of the low energy theorem model if the signal is large enough. The dominant backgrounds for this mode are $W^+ t \bar{t}$, QCD–gluon exchange and standard electroweak processes. To trigger this signal event, one demands two like–sign charged leptons with high $P_T (\sim \text{few hundred GeV})$. One further requires these leptons to be isolated and vetos events with additional high $P_T$ jets in the central rapidity region. Since there are two missing neutrinos in this event, the signal event has large $E_T$, and it is difficult to reconstruct the $W$–boson and measure its polarization. Therefore, in the absence of a “bump” structure in any distribution, we have to know the background event rate well to study the symmetry breaking sector using this mode unless the signal rate is large. Similarly, measuring the charged or total particle multiplicity of the event and tagging a forward jet can further improve the ratio of signal to background.

Particularly for this case of no resonance, where the signal is not large, it is very important to avoid cuts that reduce the signal or bias a polarization measurement. There is a further technique, proposed in Ref. 31, that will probably have to be used to study the no–resonance case, and can improve our ability to study the examples discussed above. This technique takes advantage of the fact that the Standard Model is well tested, and will be much better tested in the TeV region by the time
the study of $W_LW_L$ interactions is under way. Thus, every event of a real or fake $W_LW_L$ interaction is either a SM one or new physics. The real SM ones (from $q\bar{q}, gg \rightarrow WW, Wjj, t\bar{t}$, etc.) can all be calculated and independently measured (in other modes or other regions of kinematic variables). Thus one can make global cuts such as requiring a high energy spectator jet and low total event multiplicity, as discussed above, and then examine all remaining candidate events to see if they are consistent with SM processes or if they suggest new physics, in particular new sources of longitudinal $W$’s. In principle, only one new number needs to be measured: the fraction of $W_LW_L$ events compared to the total number of all $WW$ events including real and fake $W$’s. This can be done by the usual approach of a maximum likelihood analysis, or probably even better by the emerging neural network techniques,[38] for which it appears to be ideally suited.

Ultimately, recognizing that in the TeV region every event is either well understood Standard Model physics or new physics will be the most powerful approach to discovering any deviations from the perturbative Standard Model predictions.

5.4. Beam Pipe $W$’s

So far, we have only discussed signal events with high $P_T$ $W$–bosons produced in the central rapidity region. If there are many inelastic channels open in the $WW$ scattering process,[39,40,37] then based on the optical theorem, the imaginary part of the forward elastic scattering amplitude is related to the total cross section, and therefore will not be small.[37] This implies that it is possible for the final state $W$’s to predominantly go down the beam pipe when produced from $W^+W^- \rightarrow W^+W^-$ elastic scattering. Assuming this to be the case, it is important to know how to detect such beam pipe $W$’s in the TeV region.

The typical transverse momentum of the $W \rightarrow f_1f_2$ decay products is about $M_W/2$. For $M_{WW} > 2M_W$, the typical opening angle between the decay products of one of the $W$’s is about $4M_W/M_{WW}$. Therefore, the absolute value of the rapidity of the decay products is likely to be within the range 2.5 to 4 for $M_{WW} \sim 1$
TeV. With appropriate effort they can be detected (perhaps not in every detector, but certainly in some detector eventually). To suppress the backgrounds, one can veto events with any jets or leptons in the central rapidity region, $|\eta| \leq 2.5$. Another signature of the signal event is the appearance of an energetic quark jet, the quark recoiling after emitting one of the interacting $W$’s, with rapidity in the range 3 to 5. One can thus further suppress QCD and electroweak backgrounds by tagging one forward (or backward) jet. The background due to $W$’s emitted in a minimum bias event can also be suppressed, because, unlike the longitudinal $W$’s of the signal, these $W$’s tend to be transversely polarized. As a result, one of their decay products tends to be boosted more than the other, and is likely to be lost down the beam pipe, say, $|\eta| > 5$. Combining these techniques, we conclude that it may be feasible to detect longitudinal $W$ scattering even in models in which $W$’s tend to be scattered predominantly along the beam pipe direction.\(^{41}\)

5.5. Conclusions

We have discussed how to experimentally study the symmetry breaking sector by observing $W_L W_L \rightarrow W_L W_L$ interactions in the TeV region, emphasizing general features of the event structure in the signal and background events. Various tricks to enhance the ratio of signal to background were presented. We showed how to detect longitudinal $W$–bosons either in the central rapidity region of the detector or in the beam pipe direction. We conclude that if there is no light resonance present then it is possible to study the symmetry breaking sector in the TeV region even when the $W_L W_L$ scattering is not resonant, as may be the most likely outcome.\(^{42}\) However, to ensure a complete study of the symmetry breaking sector, the beam pipe $W$’s also need to be measured if no signal events are found in the central rapidity region.

Most of the proposals discussed here have been examined at the parton level but not in detector simulations.\(^{43}\) They have been demonstrated to be promising techniques, but we cannot be sure they will work until the detector simulations
are carried out by experimentalists. Fortunately, there will be plenty of time to do those studies before the data is available.

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REFERENCES

1. R. N. Cahn and S. Dawson, Phys. Lett. B136, 196 (1984), Phys. Lett. B138, 464(E) (1984).
2. M. S. Chanowitz and M. K. Gaillard, Phys. Lett. B142, 85 (1984); G. L. Kane, W. W. Repko and W. R. Rolnick, Phys. Lett. B148, 367 (1984); S. Dawson, Nucl. Phys. B249, 42 (1985).
3. J. Lindfors, Z. Phys. C28, 427 (1985); W. B. Rolnick, Nucl. Phys. B274, 171 (1986); P. W. Johnson, F. I. Olness and Wu–Ki Tung, Phys. Rev. D36, 291 (1987); Z. Kunszt and D. E. Soper, Nucl. Phys. B296, 253 (1988); A. Abbasabadi, W. W. Repko, D. A. Dicus and R. Vega, Phys. Rev. D38, 2770 (1988); S. Dawson, Phys. Lett. B217, 347 (1989).
4. J. M. Cornwall, D. N. Levin, and G. Tiktopoulos, Phys. Rev. D10, 1145 (1974); C. Vayonakis, Lett. Nuovo Cimento 17, 383 (1976); B. W. Lee, C. Quigg, and H. Thacker, Phys. Rev. D16, 1519 (1977).
5. M. S. Chanowitz and M. K. Gaillard, Nucl. Phys. B261, 379 (1985);
   G. J. Gounaris, R. Kogerler, and H. Neufeld, Phys. Rev. D34, 3257 (1986).
6. Y.–P. Yao and C.–P. Yuan, Phys. Rev. D38, 2237 (1988); J. Bagger and C.
   R. Schmidt, Phys. Rev. D41, 264 (1990); H. Veltman, Phys. Rev. D41, 2294
   (1990); H.–J. He, Y.–P. Kuang and Xiaoyuan Li, CCAST preprint, 1992.
7. For instance, a light resonance may exist in the Standard Model, or the
   Minimal Supersymmetric Model, etc. For a review, see J. F. Gunion, H. E.
   Haber, G. L. Kane and S. Dawson, The Higgs Hunter’s Guide, (Addison–
   Wesley, Menlo Park, 1990).
8. R. N. Cahn and M. S. Chanowitz, Phys. Rev. Lett. 56, 1327 (1986); U. Baur
   and E. W. N. Glover, Phys. Rev. D44, 99 (1991), and the references therein.
9. For studies on the purely leptonic mode of WW, see J. Bagger, V. Barger,
   K. Cheung, J. Gunion, T. Han, G. Ladinsky, R. Rosenfeld and C.–P. Yuan,
   in preparation, and the references therein.
10. K. O. Mikaelian, M. A. Samuel, D. Brown, Nuovo Cim. Lett. 27 (1980) 211.
11. C. Kao and D. A. Dicus, Phys. Rev. D43 (1991) 1555.
12. D. A. Dicus and R. Vega, Phys. Rev. Lett. 57, 1110 (1986); J. F. Gunion, J.
    Kalinowski and A. Tofighi-Niaki, Phys. Rev. Lett. 57, 2351 (1986).
13. U. Baur, E. W. N. Glover and J. J. van der Bij, Nucl. Phys. B318 (1989)
    106; V. Barger, T. Han, J. Ohnemus and D. Zeppenfeld, Phys. Rev. D41
    (1990) 2782, and the references therein.
14. S. D. Ellis, R. Kleiss and W. J. Stirling, Phys. Lett. B14B (1985) 435; J.
    F. Gunion, Z. Kunszt and M. Soldate, Phys. Lett. B16B (1985) 389; B18B
    (1986) 427 (E).
15. F. A. Berends, W. T. Giele, H. Kuijf, R. Kleiss and W. J. Stirling, Phys.
    Lett. B224 (1989) 237; V. Barger, T. Han, J. Ohnemus and D. Zeppenfeld,
    Phys. Rev. Lett. 62 (1989) 1971; Phys. Rev. D40 (1989) 2888; D41 (1990)
    1715 (E), and the references therein.
16. B. C. Combridge, Phys. Scr. 20 (1979) 5.

17. E. Eichten, I. Hinchliffe, K. Lane and C. Quigg, Rev. Mod. Phys. 56 (1984) 579; 58 (1986) 1065 (E).

18. P. Nason, S. Dawson and R. K. Ellis, Nucl. Phys. B303 (1988) 607; B327 (1989) 49; W. Beenakker, H. Kuijf, W. L. van Neerven and J. Smith, Phys. Rev. D40 (1989) 54; R. Meng, G. A. Schuler, J. Smith and W. L. van Neerven, Nucl. Phys. B339 (1990) 325.

19. R. Kauffman and C.–P. Yuan, Phys. Rev. D42 (1990) 956.

20. G. A. Ladinsky and C.–P. Yuan, Phys. Rev. D43 (1991) 789.

21. V. Barger, K. Cheung, T. Han and R. Phillips, Phys. Rev. D42 (1990) 3052; D. Dicus, J. F. Gunion, L. H. Orr and R. Vega, Nucl. Phys. B377 (1992) 31, and the references therein.

22. R. W. Brown, D. Sahdev, K. O. Mikaelian, Phys. Rev. D20 (1979) 1164.

23. V. Barger, K. Cheung, T. Han, A. Stange and D. Zeppenfeld, Phys. Rev. D46 (1991) 2028, and the references therein.

24. M. S. Chanowitz and M. Golden, Phys. Rev. Lett. 61 (1988) 1053; 63 (1989) 466 (E); V. Barger, K. Cheung, T. Han and R. J. N. Phillips, Phys. Rev. D42 (1990) 3052, and the references therein.

25. D. Dicus and R. Vega, Phys. Lett. 217 (1989) 194.

26. R. Vega and D. A. Dicus, Nucl. Phys. B329 (1990) 533.

27. R. N. Cahn, S. D. Ellis, R. Kleiss, W. J. Stirling, Phys. Rev. D35, 1626 (1987).

28. V. Barger, T. Han, and R. J. N. Phillips, Phys. Rev. D37, 2005 (1988); R. Kleiss and W. J. Stirling, Phys. Lett. B200, 193 (1988); U. Baur and E. W. N. Glover, Nucl. Phys. B347, 12 (1990); D. Dicus, J. Gunion, L. Orr, and R. Vega, Nucl. Phys. B377 (1992) 31.
29. V. Barger, K. Cheung, T. Han, and R. J. N. Phillips, Phys. Rev. D\textbf{42}, 3052 (1990); D. Dicus, J. Gunion, and R. Vega, Phys. Lett. B\textbf{258}, 475 (1991).

30. J. F. Gunion, G. L. Kane, H. F.-W. Sadrozinski, A. Seiden, A. J. Weinstein, and C.–P. Yuan, Phys. Rev. D\textbf{40}, 2223 (1989).

31. G. L. Kane and C.–P. Yuan, Phys. Rev. D\textbf{40}, 2231 (1989).

32. R. Dashen and H. Neuberger, Phys. Rev. Lett. 50 (1983) 1897; M. Lindner, Z. Phys. C\textbf{31} (1986) 295, and the references therein.

33. S. Weinberg, Phys. Rev. 166 (1968) 1568; S. Coleman, J. Wess and B. Zumino, Phys. Rev. 177 (1969) 2239; C. Callan, S. Coleman, J. Wess and B. Zumino, Phys. Rev. 177 (1969) 2247.

34. J. Gasser and H. Leutwyler, Ann. Phys. 158 (1984) 142; Nucl. Phys. B\textbf{250} (1985) 465; J. Bagger, S. Dawson and G. Valencia, JHU-TIPAC-920009, 1992.

35. F. E. Paige, BNL-46828, 1991.

36. E. Farhi and L. Susskind, Phys. Rept. 74 (1981) 277; A review of the current status of technicolor models is given by B. Holdom, Model Building in Technicolor, lectures given at the Nagoya Spring School, 1991, DPNU-91-27.

37. S. G. Naculich and C.–P. Yuan, Phys. Lett. B\textbf{293} (1992) 405.

38. B. Denby, Fermilab-92/121, 1992.

39. R. S. Chivukula and M. Golden, Phys. Lett. B\textbf{267} (1991) 233.

40. S. G. Naculich and C.–P. Yuan, Phys. Lett. B\textbf{293} (1992) 395.

41. G. Kane, S. Mrenna, S. G. Naculich and C.–P. Yuan, in preparation.

42. H. Veltman and M. Veltman, Acta. Phys. Polon. B\textbf{22}, 669 (1991).

43. Some studies beyond the parton level were listed in Ref. 31. For more references, see, for example, Solenoidal Detector Collaboration, Technical Design Report, SDC-92-201, 1992, and GEM Collaboration, Letter of Intent, SSCL-SR-1184, 1991.