Proposals for Studying TeV $W_L W_L \rightarrow W_L W_L$
Interactions Experimentally†

C.–P. Yuan

Department of Physics and Astronomy, Michigan State University
East Lansing, Michigan 48824, USA

Abstract
We discuss how to experimentally study the electroweak symmetry breaking (EWSB) sector by observing $W_L W_L \rightarrow W_L W_L$ interactions in the TeV region. We discuss some general features of the event structure in the signal and the background events. Various techniques 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. Finally, we globally classify the sensitivities of the Large Hadron Collider and the Linear Colliders to probing the next-to-leading order bosonic operators of the electroweak chiral lagrangian used to parametrize models of strongly coupled EWSB sector.

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1 Introduction

The current low energy data are already sensitive to the $SU(2)_L \times U(1)_Y$ gauge interactions of the Standard Model (SM), but not yet sensitive to the electroweak symmetry breaking (EWSB) mechanism of the SM, i.e. the Higgs mechanism. Neither do we know anything about the origin of the fermion mass which is generated in the SM by the Yukawa interactions among the fermions and the Higgs boson. The existence of light resonance(s) originating from the EWSB sector with mass(es) well below the TeV scale is a possibility in the SM, and a necessity in its supersymmetric extensions (i.e. supersymmetry models). In both cases, these particles shall be detected at the high energy colliders such as the CERN Large Hadron Collider (LHC), a proton-proton collider, and the future electron (and photon) Linear Colliders (LC) [1]. However, the Higgs boson can be very heavy ($\sim 1$ TeV), subject to the triviality and the unitarity bounds [2], and its mass can merely serve as a cutoff at the TeV scale beyond which new physics must show up. If the EWSB is indeed driven by strong interactions and there is no new resonance well below the TeV scale, then the interactions among the longitudinal $W$’s must become strong in the TeV region. How to experimentally probe the strongly coupled EWSB sector is the subject of this article. Since for models with light resonance(s) in the symmetry breaking sector, the interactions among the Goldstone bosons in the TeV region cannot become strong, we shall not consider that class of models here.

In the spontaneous symmetry breaking sector, the would-be Goldstone bosons ($\phi$’s) characterize the broken symmetry of the theory, and become the longitudinal degree of freedom of the massive $W$-bosons. Consequently, a study of the symmetry breaking sector requires an understanding of the interactions of these would-be Goldstone bosons. According to the electroweak equivalence theorem (ET) [3, 4, 5], the S-matrix of $W_L W_L \rightarrow W_L W_L$ is the same as that of $\phi \phi \rightarrow \phi \phi$ in the limit of $E_W \gg M_W$, where $E_W$ is the energy of the $W$-boson in the center-of-mass frame of the $WW$ pair, and $M_W$ is the mass of the $W$-boson. Hence, to probe the EWSB sector, it is necessary to detect the longitudinal $W$ pairs produced via the $W_L W_L$ fusion mechanism [6] in the TeV region. Below, we will show how to detect the $W_L W_L \rightarrow W_L W_L$ signal.

In section 2, we discuss the possible signals predicted by various models of EWSB

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1 The potentially bad high energy behavior of the scattering matrix element (if without any light resonance) is cut off by the tail of the light resonance.

2 We shall use $W$ to denote either $W^\pm$ or $Z^0$, unless specified otherwise.
mechanism. In section 3, we discuss the large backgrounds involved in the detection of the signals. In section 4, we discuss the characteristic differences between the event structures of the signal and the background. In section 5, we give some recipes for detecting the signal predicted by various models. In section 6, we discuss the sensitivities of future high energy colliders to probing the EWSB sector. Section 7 contains our discussions and conclusions.

2 Signal

The event signature of the signal is a longitudinal $W$-pair produced in the final state. Assuming no light resonance(s) \[2\], the electroweak symmetry breaking sector in the TeV region may either contain a scalar- or vector-resonance, etc., or no resonance at all. For a model with a TeV scalar (spin-0,isospin-0) resonance, the most useful detection modes are the $W^+W^-$ and $Z^0Z^0$ modes which contain large isospin-0 channel contributions. For a model with a TeV vector (spin-1,isospin-1) 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. Actually, because of the small SM backgrounds for the $W^\pm W^\pm$ mode, this can become the most important detection mode if no TeV resonance is present in the EWSB sector.

Before we discuss the backgrounds, we have to specify the decay mode of the $W$-bosons in the final state. Let’s first concentrate on the cleanest final state, i.e. the pure leptonic decay mode. The branching ratios of $W^+ \rightarrow \ell^+\nu$ and $Z^0 \rightarrow \ell^+\ell^-$ are $2/9$ and $0.06$, respectively, for $\ell^+ = e^+$ or $\mu^+$. If the $Z^0Z^0$ pair signal is large enough, the $Z^0(\rightarrow \ell^+\ell^-)Z^0(\rightarrow \ell^+\ell^-)$ and $Z^0(\rightarrow \ell^+\ell^-)Z^0(\rightarrow \nu\bar{\nu})$ modes would be most useful at hadron colliders \[7\]. Otherwise, it is also necessary to include the $W^\pm W^\mp$, $W^\pm Z^0$ and $W^\pm W^\pm$ modes \[8\]. Although the pure leptonic mode gives the cleanest signal signature, its event rate is small because of the relatively small branching ratio. To improve the signal event rate for discriminating models of EWSB, one should also study the other decay modes, such as the lepton plus jet modes at the LHC and the LC, or the pure jet mode at the LC \[9\]. (Because of the large QCD background rate, the pure jet mode will be extremely difficult to utilize at hadron colliders.)
3 Backgrounds

For each decay mode of the $WW$ pair, the relevant backgrounds vary. But, in general, one of the dominant background processes is the \textit{intrinsic} electroweak background, which contains the same final state as the signal event. This background rate in the TeV region can be generated by calculating the Standard Model production rate of $f \bar{f} \rightarrow f \bar{f}WW$ with a light (e.g., 100 GeV) SM Higgs boson. For example, the $W_LW_L$ signal rate in the TeV region from a 1 TeV Higgs boson is equal to the difference between the event rates calculated using a 1 TeV Higgs boson and a 100 GeV Higgs boson.

The other important backgrounds are: the electroweak-QCD process $W + \text{jets}$ (which contains a “fake $W$” mimicked by two QCD jets), and the $t\bar{t}$ pair (which subsequently decays to a $WW$ pair), \textit{etc.} We now discuss these backgrounds in various $WW$ decay modes. Without the loss of generality, in the rest of this article we shall only consider the major background processes at the hadron collider LHC. The backgrounds at the Linear Collider (LC) are usually easier to deal with because the initial state does not involve strong QCD interactions.

3.1 $Z^0(\rightarrow \ell^+\ell^-)Z^0(\rightarrow \ell^+\ell^-)$ and $Z^0(\rightarrow \ell^+\ell^-)Z^0(\rightarrow \nu\bar{\nu})$ modes

The signature for the signal in this mode is either an event with four isolated leptons with high transverse momenta, or two isolated leptons associated with large missing transverse momentum in the event. The dominant background processes for this mode are $q\bar{q} \rightarrow Z^0Z^0X$, $gg \rightarrow Z^0Z^0X$ \footnote{Note: Please provide specific references here.}, where $X$ can be additional QCD jet(s). The final state $Z^0$ pairs produced from the above processes tend to be transversely polarized. Similarly, the $Z^0$ pairs produced from the \textit{intrinsic} electroweak background process are also mostly transversely polarized. This is because the coupling of a transverse $W$ boson to a light fermion (either quarks or leptons) is stronger than that of a longitudinal $W$ in the high energy region. Hence, to discriminate the above backgrounds from the signals, we have to study the polarization of the final state $W$ boson. For the same reason, the gauge boson emitted from the initial state fermions are likely to be transversely polarized. To improve the ratio of signal to background rates, some kinematic cuts (to be discussed in the next section) can be used to enhance the event sample in which the $W$ bosons emitted from the incoming fermions are mostly longitudinally polarized, and
therefore can enhance the $W_LW_L \rightarrow W_LW_L$ signal event.

Since it is easy to detect $Z^0 \rightarrow \ell^+\ell^-$ with a good accuracy, we do not expect backgrounds other than those discussed above to be large. Similarly, because of the large missing transverse momentum of the signal event, the $Z^0 \rightarrow \nu\bar{\nu}$ signature is difficult to mimic by the other SM background processes.

3.2 $W^+ (\rightarrow \ell^+\nu)W^- (\rightarrow \ell^-\bar{\nu})$ mode

For this mode, in addition to the background processes $q\bar{q} \rightarrow q\bar{q}W^+W^-$, $q\bar{q} \rightarrow W^+W^-X$ and $gg \rightarrow W^+W^-X$, the $t\bar{t} +$ jet process can also mimic the signal event because the final state top quark pair can decay into a $W^+W^-$ pair for the heavy top quark [8].

3.3 $W^\pm (\rightarrow \ell^\pm\nu)Z^0 (\rightarrow \ell^+\ell^-)$ and $W^\pm (\rightarrow \ell^\pm\nu)W^\pm (\rightarrow \ell^\pm\nu)$ modes

Besides the background processes similar to those discussed above, the $Z^0t\bar{t}$ event can also mimic the $W^\pm Z^0$ signal.

For the purely leptonic decay mode of $W^\pm W^\pm$ [11], 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 production of the transversely polarized $W$-pairs from the *intrinsic* electroweak background process [11] or from the QCD-gluon exchange process [12], and the $W^\pm t\bar{t}$ production from the electroweak-QCD process [8].

3.4 $W^+ (\rightarrow \ell^+\nu)W^- (\rightarrow q_1\bar{q}_2)$ mode

The dominant background processes for this mode are $q\bar{q} \rightarrow q\bar{q}W^+W^-$, $q\bar{q} \rightarrow W^+W^-X$, and $gg \rightarrow W^+W^-X$ [13, 14, 15]. The signature for the signal in this mode is an isolated lepton with high transverse momentum $P_T$, a large missing transverse energy $E_T$, and two jets whose invariant mass is about the mass of the $W$-boson. The electroweak-QCD process $W^+ +$ jets can mimic the signal when the invariant mass of the two QCD jets is around $M_W$ [17, 18]. Other potential background processes for
this mode are the QCD processes $q\bar{q}$, $gg \rightarrow t\bar{t}X$, $Wt\bar{b}$ and $t\bar{t} + \text{jet(s)}$ [19, 20, 21, 22, 23], in which a $W$ boson can come from the decay of $t$ or $\bar{t}$.

### 3.5 $W^+(\rightarrow \ell^+\nu)Z^0(\rightarrow q\bar{q})$ mode

The signature of the signal in this mode is an isolated lepton with high $P_T$, a large missing transverse energy $\vec{E}_T$, and a two jet invariant mass around $M_Z$. The dominant background processes for this mode are similar to those for the $W^+(\rightarrow \ell^+\nu)W^- (\rightarrow q_1\bar{q}_2)$ mode discussed above. They are $q_1\bar{q}_2 \rightarrow W^+Z^0$, $W^+Z^0 + \text{jet(s)}$, $W^+ + \text{jets}$ and $Zt\bar{t}$ production processes [16, 17, 18, 24, 25].

To separate this signal from $W^+(\rightarrow \ell^+\nu)W^- (\rightarrow q_1\bar{q}_2)$ a good jet energy resolution is needed to distinguish the invariant mass of the two jets between $M_Z$ and $M_W$, which differ by about 10 GeV. Another technique to distinguish these two kinds of events is to measure the average electric charge of the jets, which has been applied successfully at LEP experiments [26].

As noted above, because of the large branching ratio, the pure jet mode from the $W$ boson decay can also be useful at the future lepton colliders [9], where the dominant background for the detection of the $W_LW_L \rightarrow W_LW_L$ signal event is again the intrinsic electroweak process.

In general, without imposing any kinematic cuts, the raw event rate of the signal is significantly smaller than that of the backgrounds. However, the signature of the signal can actually be distinguished from that of the backgrounds so that some kinematic cuts can be applied to suppress the backgrounds and enhance the signal-to-background ratio. We shall examine the characteristic differences between the event structures of the signal and the backgrounds in the next section.

### 4 How to Distinguish Signal from Background

The signature of the signal event can be distinguished from that of the background events in many ways. We first discuss differences in the global features of the signal and the background events, then point out some distinct kinematics of the signal events. To simplify our discussion, we shall only concentrate on the $W^+(\rightarrow \ell^+\nu)W^- (\rightarrow q_1\bar{q}_2)$ mode in this section.
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 1 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, 8]. As noted in the previous section, the $W$ boson pairs produced from the \textit{intrinsic} electroweak process $q\bar{q} \rightarrow q\bar{q}W^+W^-$ tend to be transversely polarized, and the initial state gauge bosons are likely to be transversely polarized as well. To see how the forward jet can be used to discriminate the signal from the background events, we consider the $W^+W^-$ fusion process as an example. Since the coupling of the $W^\pm$ boson and the incoming quark is purely left-handed, the out-going quark tends to go along with the incoming quark direction when emitting a longitudinal $W$ boson, and opposite direction when emitting a transverse (left-handed) $W$. This can be easily understood from the helicity conservation. Hence, in the \textit{intrinsic} background event, the out-going quark jet is less forward (and less energetic) than that in the signal event.

Furthermore, because the production mechanism of the signal event is purely electroweak, the charged particle multiplicity of the signal event is smaller than that of a typical electroweak-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 than two hard jets in the central rapidity region both because of the additional jets from the decay of $t$ and $\bar{t}$ and because of the stronger hadronic activity from the effect of QCD color structure of the event. Therefore, one can reject events with more than two hard jets produced in the central rapidity region to suppress the backgrounds. This was first suggested in Ref. [21] using a hadron level analysis to show how the $t\bar{t}$ background can be suppressed.

A similar trick of vetoing extra jets in the central rapidity region was also applied at the parton level [29, 8] for studying the pure leptonic decay mode of $W$'s. 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]. The same idea was later packaged in the context of selecting events with
“rapidity gap” to enhance the signal-to-background ratio \[32\].

In the $W$-fusion process, the typical transverse momentum of the final state $W$-pair is about $M_W/2$ \[27\]. 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 of a few hundred GeV. Therefore, the two $W$’s (either both real or one real and one fake) produced in the background event are less back-to-back in the transverse plane than those in the signal event.

4.2 Isolated Lepton in $W^+ \rightarrow \ell^+ \nu$

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, requiring an isolated lepton with high $P_T$ is a useful method to suppress the backgrounds. This requirement together with large missing transverse energy in the event insures the presence of a $W$-boson. Finally, it is also important to be able to measure the sign of the lepton charge to reduce the backgrounds for the detection of the $W^+ \rightarrow (\ell^+ \nu)W^+ \rightarrow (\ell^+ \nu)$ mode \[8\].

4.3 $W \rightarrow q_1\bar{q}_2$ decay mode

To identify the signal, we have to reconstruct the two highest $P_T$ jets in the central rapidity region to obtain 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 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 various models of EWSB sector.

It was shown in Ref. \[33\] that a large fraction ($\sim 65\%$ for a 175 GeV top quark) of the $W$ bosons from the top quark decays is longitudinally polarized.\[3\] This can in principle complicate the above method of using the fraction of longitudinally $W$ bosons

3 The same conclusion also holds for the QCD background event with “fake $W$”, which usually consists of one hard jet and one soft jet. Hence, after boosting these two jets back into the rest frame of the “fake $W$”, its angular distribution resembles that from a transverse $W$ boson.

4 The ratio of the longitudinal versus the transverse $W$’s from top quark decays is about $m_t^2/(2M_W^2)$.\[4\]
to detect the signal. Fortunately, after imposing the global cuts such as vetoing the central jet and tagging the forward jet, the $t\bar{t}$ backgrounds are small. (If necessary, it can be further suppressed by vetoing event with $b$ jet, because for every background event with top quark there is always a $b$ quark from the SM top decay.) To suppress the $W^+t\bar{b}$ and $W^-\bar{t}b$ backgrounds, which have smaller raw production rate than the $t\bar{t}$ event, the same tricks can be used. Furthermore, the top quark produced in the $W^+t\bar{b}$ event is mostly left-handed polarized because the coupling of $t-b-W$ is purely left-handed in the SM. The kinematic cut of vetoing events with additional jets in the central rapidity region will reduce the fraction of the events in which the $W$ boson from the top quark (with energy of the order 1 TeV) decay is longitudinally polarized. This is because in the rest frame of a left-handedly polarized top quark, which decays into a longitudinal $W$-boson, the decay $b$-quark prefers to move along the moving direction of the top quark in the center-of-mass frame of the $W^+t$ pair. Hence, such a background event will produce an additional hard jet in the central rapidity region.

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. We shall not reproduce those analyses but only sketch the ideas of various techniques 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 previously performed in the literature. If the signal event rates are large enough to observe the purely leptonic mode, then studying the symmetry breaking sector at the LHC shall be possible. However, a parton level study in Ref. 8 shows that the event rates are generally small after imposing the necessary kinematic cuts to suppress the backgrounds. To clearly identify the EWSB mechanism from the $W_L^+W_L^- \rightarrow W_L^+W_L^-$ interactions, the $\ell^\pm +$ jet mode of the $WW$ pair should also be studied because of its larger branching ratio than the pure leptonic mode. That is the decay mode we shall concentrate on in the following section for discussing the detection of various models of EWSB sector.

5 Various Models

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5 At the LC, because its initial state is colorless, the pure jet decay mode (with the largest branching ratio) of the $W$ boson can also be useful.
5.1 A TeV Scalar Resonance

Based on the triviality argument [34], the mass of the SM Higgs boson cannot be much larger than $\sim 650$ GeV, otherwise the theory would be inconsistent. (If the SM is an effective theory valid up to the energy scale much higher than 1 TeV, then this number is even lower.) However, one may consider an effective theory, such as an electroweak chiral lagrangian, in which a TeV scalar (spin-0, isospin-0) resonance couples to the would-be Goldstone bosons in the same way as the Higgs boson in the Standard Model [35, 36, 8]. (The mass and the width of the scalar resonance are the two free parameters in this model.) Then one can ask how to detect such a TeV scalar resonance. This study was already done at the hadron level in Ref. [31].

The tricks of enhancing the ratio of signal to background are as follows. 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 $P_T$ at the order of $\sim 1/2$ TeV, therefore, the $P_T$ of the lepton from the $W$-decay is at the order of a few hundred GeV. The kinematic 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. Furthermore, the lepton is also less isolated in the $t\bar{t}$ event than that in the signal event. After selecting the events with an isolated lepton with high $P_T$, we can make use of the fact that the background event contains more hadronic activity than the signal event to further suppress the background. One can make a cut on the charged particle multiplicity of the event to enhance the signal-to-background ratio. The alternative 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 [31]. The background process typically produces more hard jets than the signal, hence vetoing the events with more than one big cone jet in the central rapidity region is also a useful technique. The $W^+ + \text{jets}$ 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 requires two small cone jets corresponding to the two decay quark jets of the $W$-boson.

As discussed above, measuring the polarization of the $W$ bosons in the final state can be a very useful tool for detecting and discriminating mechanisms of EWSB. Therefore,
the best strategy for analyzing the experimental data is not to bias the information on the polarization of the $W$ boson. Some of the methods that can preserve the information on the polarization of the $W$ boson were presented in Ref. [31]. It was shown that it is possible to measure the fraction of longitudinal $W$’s in the candidate $W$ samples to distinguish various models of EWSB sector. One of the techniques which would not bias the polarization of the $W$-boson is to count 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, hence the charged particle multiplicity of these two jets is less than that of a pair of non-singlet QCD jets (which form the “fake $W$”), either quark or gluon jets. Furthermore, the QCD background events usually have more complicated color structure at the parton level, so that the hadron multiplicity of the background event is generally larger than that of the signal event in which the $WW$ system is a color singlet state. Since the above methods only rely on the global features of the events, they will not bias the information on the $W$ boson polarization.

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 [8].

Furthermore, with rapidity coverage down to 5, one can have a good measurement on the missing energy ($E_T$). Because the typical $E_T$ due to the neutrino from the $W$-boson, with energy $\sim 1$ TeV, decay is of 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 $M_W$ [31]. From the invariant mass of $\ell, \nu, q_1, \text{and } \bar{q}_2$, one can reconstruct $M_{WW}$ to discriminate background from signal events. If the width of the heavy resonance is small[6] then one can detect a “bump” in the $M_{WW}$ distributions. However, if its width is too large, then the best way to detect this new physics effect is to measure the fraction ($f_L$) of longitudinal $W$’s in the event sample.

5.2 A TeV Vector Resonance

[6] For a SM Higgs boson with mass $m_H$ in units of TeV, its decay width would be about equal to $m_H^3/2$, which is not small.
An example of this type of resonance is a techni-rho in the techni-color model [37]. What we have in mind here is a vector (spin-1, isospin-1) resonance in the electroweak chiral lagrangian. The mass and the width of the vector resonance are the two free parameters in this model. Because this resonance gives a large contribution in the isospin-1 channel, the most useful mode 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 pure leptonic decay mode $W^+ (\rightarrow \ell^+ \nu) Z^0 (\rightarrow \ell^+ \ell^-)$ in which all the leptons have $P_T \sim$ few hundred GeV and are well isolated. If the $W^+ (\rightarrow \ell^+ \nu) Z^0 (\rightarrow q \bar{q})$ mode is necessary for the signal to be observed, the strategies discussed in the previous subsection for the $W^+ (\rightarrow \ell^+ \nu) W^- (\rightarrow q_1 \bar{q_2})$ mode can be applied in this case as well. Needless to say, in this case, the invariant mass of the two jets peaks around $M_Z$ not $M_W$. It could be very valuable to improve the techniques that separate $W (\rightarrow jj)$ from $Z (\rightarrow jj)$ by identifying the average electric charge of each of the two decay jets. Obviously, the two jets from the $Z^0$ boson decay should have the same electric charges.

5.3 No Resonance

If there is no resonance at all, the interactions among the longitudinal $W$’s become strong in the TeV region. Although the non-resonance scenario is among the most difficult cases to probe, this does not imply in any sense that it is less likely than the others to describe the underlying dynamics of the electroweak symmetry breaking. For example, it was argued in Ref. [47] that the non-resonance scenario may be likely to happen. Within this non-resonance scenario, the electroweak chiral lagrangian (EWCL) provides the most economic way to parameterize models of strongly coupled EWSB sector. The model with only the lowest order term (containing two derivatives) in the EWCL is known as the low energy theorem model. The signal of this model can be detected from studying the $W^+ (\rightarrow \ell^+ \nu) W^- (\rightarrow q_1 \bar{q_2})$ mode in the TeV region Ref. [31]. The techniques of observing this signal are identical to those discussed above.

In Ref. [8], it was shown that it is possible to study the pure leptonic mode $W^+ (\rightarrow \ell^+ \nu) W^+ (\rightarrow \ell^+ \nu)$ in the multi-TeV region to test the low energy theorem model as long as the integrated luminosity (or, the event rate) is large enough. The dominant backgrounds for this mode are the intrinsic background, $W^+ t \bar{t}$, and QCD-gluon exchange processes. 

\footnote{For the techniques used in identifying the average electric charge of a QCD jet, see, for example, Ref. [26].}
The signal event can be triggered by two like-sign charged leptons with high $P_T$ ($\sim$ few hundred GeV). One can further require these leptons to be isolated and veto events with additional high $P_T$ jets in the central rapidity region. There are two missing neutrinos in the event so that it is difficult to reconstruct the $W$-boson and measure its polarization. Hence, in the absence of a “bump” structure in any distribution, one has to know the background event rate well to study the EWSB sector, unless the signal rate is very large. Similarly, measuring the charged or total particle multiplicity of the event and tagging a forward jet can further improve the signal-to-background ratio.

Particularly for the case of no resonance, when the signal rate is not large, it is important to avoid imposing kinematic cuts which greatly reduce the signal or bias the polarization information of the $W$ bosons in the data sample. The specific technique for measuring $f_L$, as proposed in Ref. [31], will probably have to be used to study the non-resonance case, and to probe the EWSB sector. This technique takes advantage of the fact that the SM is well tested, and will be much better tested in the TeV region by the time the study of $W_L W_L$ interactions is under way. Every event of a real or fake $W_L W_L$ interaction will be clearly identified as originating either from SM or new physics. The real SM events (from $q\bar{q}, gg \to WW, Wjj, t\bar{t}$, etc.) can all be calculated and independently measured. Thus, one can first make global cuts such as requiring a high energy spectator jet and low total particle multiplicity, 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 quantity needs to be measured: the fraction of $W_L W_L$ 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 this analysis appears to be ideally suited.

Ultimately, recognizing that in the TeV region every event must originate from either the well understood Standard Model physics or beyond 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 opened in the $WW$ scattering process [39, 40, 41], then based on the optical theorem, the imaginary part of
the forward elastic scattering amplitude is related to the total cross section, and will not be small [41]. This implies that it is possible for the final state \( W \)'s to predominantly go down to the beam pipe when produced from \( W^+W^- \to W^+W^- \) 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 decay particle in \( W \to f_1f_2 \) 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 should be detectable (perhaps not in every detector, but certainly in some detectors 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 speculate 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 [42].

### 6 Sensitivities of High Energy Colliders to EWSB Sector

In the previous sections, we have discussed various methods suitable for detecting the strongly coupled EWSB sector, of which a few models were briefly discussed as well. Among them, the most difficult one to detect is the no-resonance model, in which there is no resonance below the TeV scale. Here, we shall consider this most difficult case and investigate the type of colliders and scattering processes needed to completely probing the EWSB sector.

Below the scale of any new heavy resonance, the EWSB sector can be parametrized by means of the EWCL in which the \( SU(2)_L \times U(1)_Y \) gauge symmetry is nonlinearly re-
alized. Without experimental observation of any new light resonance in the EWSB sector, this effective field theory approach provides the most economic description of the possible new physics effects and is thus complementary to those specific model build-

ings. Hereafter, we shall concentrate on the effective bosonic operators, among which the leading order operators are model-independent, while the other 15 next-to-leading-order (NLO) operators depend on the details of models. Furthermore, the 12 NLO operators \( \mathcal{L}^{(2)\prime} \) and \( \mathcal{L}_{1-11} \) are \( CP \)-conserving, and the 3 operators \( \mathcal{L}_{12-14} \) are \( CP \)-violating. Among those operators which contribute to the quartic Goldstone boson interactions, the operators \( \mathcal{L}_{4,5} \) is \( SU(2)_C \) invariant, while the operators \( \mathcal{L}_{6,7,10} \) violate the \( SU(2)_C \) custodial symmetry.

Given the EWCL, we have to examine which are the colliders and processes that should be used to sensitively probe the complete set of the NLO operators. This was recently performed in Ref. [5], in which two important techniques were used. First, it was shown in Ref. [5] that the intrinsic connection between measuring the longitudinal weak-boson scatterings and probing the symmetry breaking sector can be clearly formulated by noting the physical implication of the electroweak Equivalence Theorem [3]. Second, based on this new formulation of the ET, it becomes straightforward to discriminate processes which are not sensitive to the EWSB by simply examining the high energy behavior of the physical S-matrices for the scattering processes using the generalized Weinberg’s counting rules derived in Ref. [14]. We note that Weinberg’s counting rules were derived for non-linear sigma model, in contrast, the generalized Weinberg’s counting rules were derived for electroweak chiral lagrangian which is a gauge theory and contains not only the scalar fields but also the vector and the fermion fields.

The conclusion of Ref. [14] can be summarized in Table 1, in which the leading contributions (marked by √) can be sensitively probed, while the sub-leading contributions (marked by △) can only be marginally sensitively probed. (\( L/T \) denotes the longitudinal/transverse polarizations of \( W^\pm, Z^0 \) bosons.) To save space, Table 1 does not contain those processes to which the NLO operators only contribute sub-leading amplitudes. Some of these processes are \( WW \to W\gamma, Z\gamma + \text{perm.} \) and \( f\bar{f}^{(*)} \to W\gamma, WW\gamma, WZ\gamma \), which all have one external transverse \( \gamma \)-line and are at most marginally sensitive. Further conclusions can be drawn as follows:

(1). At LC(0.5), which is a LC with \( \sqrt{S} = 0.5 \) TeV, \( \mathcal{L}_{2,3,9} \) can be sensitively probed via \( e^-e^+ \to W^-_L W^+_L \).

(2). For \( V_L V_L \to V_L V_L \) scattering amplitudes, the model-dependent operators \( \mathcal{L}_{4,5} \) and
$\mathcal{L}_{6,7}$ can be probed most sensitively. $\mathcal{L}_{10}$ can only be sensitively probed via the scattering process $Z_L Z_L \rightarrow Z_L Z_L$ which is easier to detect at the LC(1.5) [a $e^- e^+$ or $e^- e^-$ collider with $\sqrt{S} = 1.5 \text{ TeV}$] than at the LHC(14) [a pp collider with $\sqrt{S} = 14 \text{ TeV}$].

(3). The contributions from $\mathcal{L}^{(2)\prime}$ and $\mathcal{L}_{2,3,9}$ to the pure $4V_L$-scattering processes lose the $E$-power dependence by a factor of 2. Hence, the pure $4V_L$-channel is not sensitive to these operators. [Note that $\mathcal{L}_{2,3,9}$ can be sensitively probed via $f \bar{f} \rightarrow W_L^+ W_L^-$ process at LC(0.5) and LHC(14).] The pure $4V_L$-channel cannot probe $\mathcal{L}_{1,8,11-14}$ which can only be probed via processes with $V_T$('s). Among $\mathcal{L}_{1,8,11-14}$, the contributions from $\mathcal{L}_{11,12}$ to processes with $V_T$('s) are most important, although their contributions are relatively suppressed by a factor $g f_\pi / E$ as compared to the leading contributions from $\mathcal{L}_{4,5}$ to pure $4V_L$-scatterings. Where the vacuum expectation value $f_\pi = 246 \text{ GeV}$. $\mathcal{L}_{1,8,13,14}$ are generally suppressed by higher powers of $g f_\pi / E$ and are thus the least sensitive. The above conclusions hold for both LHC(14) and LC(1.5).

(4). At LHC(14), $\mathcal{L}_{11,12}$ can be sensitively probed via $qq' \rightarrow W^\pm Z$ whose final state is not electrically neutral. Since this final state is not accessible at LC, LC(0.5) is not be sensitive to these operators. To sensitively probe $\mathcal{L}_{11,12}$ at LC(1.5), one has to measure $e^- e^+ \rightarrow W_L^- W_L^+ Z_L$.

(5). To sensitively probe $\mathcal{L}_{13,14}$, a high energy $e^- \gamma$ linear collider is needed for studying the processes $e^- \gamma \rightarrow \nu_e W_L^- Z_L, e^- W_L^- W_L^+$, in which the backgrounds are much less severe than processes like $\gamma \gamma \rightarrow W_L^+ W_L^-$ at a $\gamma \gamma$ collider.

We also note that to measure the individual coefficient of the NLO operator, one has to be able to separate, for example, the $W^+ W^- \rightarrow Z^0 Z^0$ and the $Z^0 Z^0 \rightarrow Z^0 Z^0$ production processes. Although this task can be easily done at the LC by detecting a forward tagged lepton, it shall be a great challenge at the LHC because both the up- and down-type quarks from the initial state contribute to the scattering processes. From the above conclusion, we speculate that if there is no new resonance below the TeV scale and the coefficients of the NLO operators are not much larger than that suggested by the naive dimensional analysis, the LHC alone may not be able to sensitively measure all these operators, and linear colliders are needed to complementarily cover the rest of the NLO operators. In fact, the different phases of $500 \text{ GeV}$ and $1.5 \text{ TeV}$ energies are suppressed by higher powers of $g f_\pi / E$ and are thus the least sensitive. The above conclusions hold for both LHC(14) and LC(1.5).

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8The amplitude of $\gamma \gamma \rightarrow W_L^+ W_L^-$ is of the order of $e^2 \frac{g^2}{2 \Delta^2}$, to which the operators $\mathcal{L}_{13,14}$ (and also $\mathcal{L}_{1,2,3,8,9}$) can contribute. Thus, this process can be useful for probing $\mathcal{L}_{13,14}$ at a $\gamma \gamma$ collider after effectively suppressing its background.

9To further reach a detailed quantitative conclusion, an elaborate and precise numerical study on all signal/background rates is necessary.
at the LC are necessary because they will be sensitive to different NLO operators. An electron-photon (or a photon-photon) collider is also useful for measuring some of the NLO operators that distinguish models of strongly coupled EWSB sector.

7 Discussions and Conclusions

If there is no light resonance present in the EWSB sector, the $W_L W_L \to W_L W_L$ scatterings must become strong in the TeV region. We have discussed how to experimentally study the strongly coupled electroweak symmetry breaking sector by observing $W_L W_L \to W_L W_L$ interactions in the TeV region, emphasizing general features of the event structure in the signal and background events. Various techniques of enhancing the ratio of signal to background were also 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 showed that it is possible to study the electroweak 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 [47]. 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. In the previous section, we also discussed the sensitivities of the future high energy colliders, such as the LHC and the LC, to probing the strongly coupled EWSB sector which is parameterized by the NLO operators of the electroweak chiral lagrangian.

Most of the proposals discussed here have been examined at the parton level but not in detector simulations [48]. 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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Table 1 Probing the EWSB Sector at High Energy Colliders: A Global Classification for the NLO Bosonic Operators

(Notations: √ = Leading contributions, △ = Sub-leading contributions, and ⊥ = Low-energy contributions.)
(Notes: † Here, $L_{13}$ or $L_{14}$ does not contribute at this order. ‡ At LHC(14), $W^+W^+ → W^+W^+$ should also be included.)

| Operators | $L(2)' L_{1,13} L_2 L_3 L_{4,5} L_{6,7} L_{8,14} L_9 L_{10} L_{11,12}$ | Processes |
|-----------|-------------------------------------------------|------------|
| LEP-I (S,T,U) | ⊥ ⊥ † ⊥ ⊥ ⊥ ⊥ | $e^-e^+ → Z → ff$ |
| LEP-II | ⊥ ⊥ ⊥ ⊥ ⊥ ⊥ ⊥ | $e^-e^+ → W^-W^+$ |
| LC(0.5)/LHC(14) | √ √ √ ⊥ ⊥ | $W^-W^- → W^-W^+$ |
| LC(1.5)/LHC(14) | √√√ △ △ △ △ △ △ △ | $f \bar{f} → W^-W^+/(LL)$ |
| | √ √ ⊥ ⊥ ⊥ | $f \bar{f} → W^-W^+/(LT)$ |
| | √ √ | $f \bar{f} → ZZZ/(LLL)$ |
| | ⊥ ⊥ ⊥ △ | $f \bar{f} → ZZZ/(LLT)$ |
| | ⊥ | $W^-W^- → W^-W^-/(LLLL)$ ‡ |
| | ⊥ | $W^-W^- → W^-W^-/(LLLT)$ ‡ |
| | √ | $W^-W^- → ZZ$ & perm./(LLLL) |
| | ⊥ | $W^-W^- → ZZ$ & perm./(LLLT) |
| | √ | $ZZ → ZZ/(LLLL)$ |
| | ⊥ | $ZZ → ZZ/(LLLT)$ |
| LHC(14) | △ △ △ △ △ △ △ | $q \bar{q}' → W^\pm Z/(LL)$ |
| | △ △ △ △ △ △ △ | $q \bar{q}' → W^\pm Z/(LT)$ |
| | △ △ △ △ △ △ △ | $q \bar{q}' → W^-W^+/LLL$ |
| | △ △ △ △ △ △ △ | $q \bar{q}' → W^-W^+/LLT$ |
| | △ △ △ △ △ △ △ | $q \bar{q}' → W^-W^+/LLL$ |
| | △ △ △ △ △ △ △ | $q \bar{q}' → W^-W^+/LLT$ |
| | △ △ △ △ △ △ △ | $e^-e^- → W^-Z/(LL)$ |
| | △ △ △ △ △ △ △ | $e^-e^- → W^-W^+/LLL$ |
| LC($e^-γ$) | √ √ √ √ √ | $γγ → W^-W^+/LL$ |
| LC(γγ) | √ √ √ | $γγ → W^-W^+/LL$ |