THEORETICAL OVERVIEW ON DIBOSON PRODUCTION\[†\]

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Abstract

Precise measurements of weak vector bosons self couplings give a hint on the electroweak symmetry breaking sector. We first stress that present data from LEP and TEVATRON clearly indicate that weak bosons are self interacting. We then review the limits on the trilinear and quadrilinear couplings expected at LEP2, $e^+e^-$ linear colliders and LHC.

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Electroweak gauge bosons are well suited to test in a subtle way two fundamental
principles: gauge invariance and electroweak symmetry breaking mechanism- hereafter
denoted as EWSB. The first one gives the strength of the trilinear and quadrilinear gauge
bosons couplings - whose existence is due to the non abelian structure of the gauge
group- whereas the longitudinal components of W and Z bosons directly probe the EWSB
mechanism (linear or non linear realization?).

1 Restrictions from present data

Since the standard model- hereafter denoted as SM- has been tested at one loop level, we
have now evidence that gauge bosons are self interacting. First evidence came already
in 1994 when it was shown [1] that the sin²θW(MZ) value predicted without taking into
account bosonic loops deviates from data by 7σ. As of today, the three dimensional plot
shown in figure 1 clearly indicates the need for bosonic loops to match the SM with precise
data on M_W, sin²θW(MZ) and the leptonic width Γ_l[2]. There are seven independent
ZW W form factors and six γWW besides the electric charge. Restricting our analysis to
C and P conserving VWW couplings we parametrize the lagrangian as [3]:

\[ L_{VWW} = -ie[A_\mu(W^-\mu\nu W_\nu^+ - W^+\mu\nu W^-_\nu) + (1 + \Delta\kappa)F_{\mu\nu}W^+_{\mu\nu}\]
\[ + \cot\theta_W(1 + \Delta g^Z_1)Z_\mu(W^-\mu\nu W_\nu^+ - W^+\mu\nu W^-_\nu) + (1 + \Delta\kappa_Z)Z_{\mu\nu}W^+_{\mu\nu}\]
\[ + \frac{1}{M_W^2}(\lambda_\gamma F^{\nu\lambda} + \cot\theta_W\lambda_Z Z^{\nu\lambda})W^+_{\lambda\mu}W^-_{\nu\mu} \]  

(1)

In the SM ∆g^Z_1 = 0, ∆κ_V = 0 and λ_V = 0, whereas no self interaction among gauge
bosons would lead to ∆κ_V = −1 and λ_V = 0. Tevatron collider [4], assuming λ_γ = λ_Z
and κ_γ = κ_Z, has excluded ∆κ_V = −1 since −0.7 ≤ ∆κ ≤ 0.89 and −0.44 ≤ λ ≤ 0.44.
For the moment the sensitivity to the Higgs mass is weak: 65.2GeV ≤ M_H ≤ 440GeV [3],
and the preference for small Higgs masses rely entirely on observables which differ from
SM expectations by 2 − 3σ i.e. \( R_b = \frac{\Gamma(Z\rightarrow bb)}{\Gamma_{\text{hadronic}}} \), \( R_c = \frac{\Gamma(Z\rightarrow cc)}{\Gamma_{\text{hadronic}}} \) and the left right asymmetry
\( A_{LR} \).

In order to probe the EWSB a precise measurement of trilinear and quadrilinear
gauge boson couplings is mandatory. For this purpose we will introduce the notion of
effective lagrangian, which gives a general description of the phenomenon without knowing
precisely its origin or the underlying theory[3], [4]. The inputs are the known symmetries
at low energies and the particle content. At the electroweak scale we have to keep SU(2) ×
U(1) invariance and the custodial SU(2) symmetry- since ∆ρ ≤ 410^{-3} indicates that weak
isospin breaking effects are small. The residual interactions affecting the self couplings
are described by operators \( O_i \):

\[ L_{eff} = \sum_n \sum_i \frac{f_i^{(n)}}{\Lambda^n} O_i^{(n+4)} \]

(2)
where \( \Lambda \) is the scale for new physics. Since we consider low energies (smaller than \( \Lambda \)) we will restrict our analysis to dimension 6 operators. The introduction of anomalous couplings leads to a violation of unitarity which is cured either by introducing form factors or imposing unitarity constraints on the couplings.

Some of these operators are already constrained at LEP1\[8\], since they affect gauge boson two point functions. We shall first discuss the scenario of a linear realization of EWSB through a Higgs doublet \( \Phi \). Precisely the operator

\[
O = \frac{ig}{2}(D_\mu \Phi)^+ \vec{\tau} \tilde{W}^{\mu\nu} D_\nu \Phi
\]

is restricted by the parameter \( \epsilon_1 \)[9] whereas the variable \( \epsilon_3 \) restricts

\[
O_{BW} = \frac{ig'}{2}(D_\mu \Phi)^+ B^{\mu\nu} D_\nu \Phi
\]

\( B \) being the \( U(1) \) field and \( W \) the \( SU(2) \) field. The coefficient \( f_\Phi \) is of the order of \( 10^{-1} \) whereas \( f_{BW} \) is of the order of 1 [7]. The operators describing the self interactions which do not contribute to the two point functions are:

\[
O_W = \frac{ig}{2}(D_\mu \Phi)^+ \vec{\tau} \tilde{W}^{\mu\nu} D_\nu \Phi
\]

and

\[
O_{WWW} = Tr\left[\frac{ig}{2} \vec{\tau} \tilde{W}_\mu \frac{ig}{2} \vec{\tau} \tilde{W}_\nu \frac{ig}{2} \vec{\tau} \tilde{W}_\rho \right]
\]

Their contribution to the parameters\[3\] of \( L_{WWW} \) given in eq.1 reads:

\[
\Delta \kappa_\gamma = (f_B + f_W) \frac{M_W^2}{2\Lambda^2}
\]

\[
\Delta g_1^Z = f_W \frac{M_Z^2}{2\Lambda^2}
\]

\[
\Delta \kappa_Z = [f_W - \sin^2 \theta_W (f_B + f_W)] \frac{M_Z^2}{2\Lambda^2}
\]

\[
\lambda_\gamma = \lambda_Z = f_{WWW} \frac{3g^2M_W^2}{2\Lambda^2}
\]

The present limits on the coefficients of these operators are:

\[
f_{\frac{v^2}{\Lambda^2}} \simeq 10
\]

We shall see later how future colliders will improve this sensitivity. Let us now consider the non linear realization of EWSB where the Higgs part of the lagrangian is replaced by:

\[
L_{EWSB} = \frac{v^2}{4} Tr(D^\mu \Sigma + D_\mu \Sigma)
\]

where \( \Sigma = \exp(i \vec{\tau} \vec{\pi} v) \). LEP1, through \( \epsilon_3 \), constrains the operator:

\[
O_{10} = \frac{g g'}{16 \pi^2} Tr(B_{\mu\nu} \Sigma^+ W^{\mu\nu} \Sigma)
\]
The coefficient $L_{10}$ lies in the range $-0.7 \leq L_{10} \leq 2.4$. Instead of $O_W$ and $O_B$ we have now to consider the operators:

$$O_{9R} = \frac{ig'}{16\pi^2} Tr(B^{\mu\nu} D_\mu \Sigma^+ D_\nu \Sigma)$$  \hspace{1cm} (13)

and

$$O_{9L} = \frac{ig}{16\pi^2} Tr(W^{\mu\nu} D_\mu \Sigma^+ D_\nu \Sigma)$$  \hspace{1cm} (14)

Their contribution to the trilinear gauge couplings parametrized by $L_{VWW}$ given in eq.[3] reads:

$$\Delta g^Z_1 = L_{9L}(\frac{e^2}{\sin^2 \theta_W})(\frac{1}{32\pi^2 \cos^2 \theta_W})$$  \hspace{1cm} (15)

and

$$\Delta \kappa_Z = (L_{9L} + L_{9R})(\frac{e^2}{\sin^2 \theta_W})(\frac{1}{32\pi^2})$$  \hspace{1cm} (16)

Present limits are weak: $L_9 \simeq 10^3$.

2 Prospects at future colliders.

LEP2 is now starting to operate and will probe directly the self interactions of electroweak gauge bosons. The most interesting reaction is $e^+e^- \rightarrow W^+W^-$. The calculations performed by the LEP2 working group [11] have taken into account initial state radiation, $W$ width effects and the background from four fermion final state, since the optimal deacy channel is $jjl\nu$. At $\sqrt{S} = 190$GeV and for an integrated luminosity of $500pb^{-1}$ limits on $L_9$ have improved: $-30 \leq L_{9L} \leq 30$ and $-300 \leq L_{9R} \leq 750$. A more energetic $e^+e^-$ linear collider, like a NLC operating at $\sqrt{S} = 500$GeV and for an integrated luminosity of $10fb^{-1}$ will drastically constrain the parameters. The mode $\gamma\gamma \rightarrow W^+W^-$ helps to constrain $L_{9R}$. This is explicitely shown in figure 2 from [12].

Moving from 500GeV to the TeV range allows to gain one order of magnitude. The best limits at $\sqrt{S} = 1.5TeV$ with an integrated luminosity of $190fb^{-1}$ are obtained by keeping all resonant diagrams from the semi leptonic final state [13]. As shown in figure 3, the sensitivity reached is much better than the one expected at LHC where the mode $pp \rightarrow WZ$ restricts $L_{9R}$ in the range: $-2 \leq L_{9R} \leq 3$.

A comment is in order now concerning hadronic colliders. It has recently been shown [14], [15] that QCD corrections may be huge. This is the case for $W\gamma$ final state whose next-to-leading correction increases the Born prediction from 20% at $\sqrt{S} = 2TeV$ up to 300% at $\sqrt{S} = 40TeV$. This huge effect affects the two body cross section characterized by a radiation amplitude zero(i.e. an exact amplitude zero for some values of the scattering angle), for which the $2 \rightarrow 3$ subprocesses fill the dip in the $\gamma$ rapidity distribution at LHC. The ZZ, $W^+W^-$ and WZ final states are also affected. The approximate amplitude zero in the WZ final state suppresses the Born cross section and therefore NLO corrections

3
are larger than for ZZ or WW processes. Collinear splittings like \( qg \to Zq \) followed by \( q \to q' W \) induce an increase of the order of:

\[
\frac{g^2}{4\pi \sin^2 \theta_W} \ln^2 \left( \frac{P_T^2}{M_W^2} \right)
\]

(where \( P_T \) is the gauge boson transverse momentum) precisely in the large \( P_T \) range sensitive to anomalous trilinear gauge bosons couplings. The way to solve this problem is to cut on the extra jet, leading to the definition of a \( \text{WW}/\text{WZ} + 0\text{jet} \) cross section, increasing the Born cross section by at most 20%. Let me stress that the reaction \( e^+ e^- \to W_L^+ W_L^- \) (resp. \( W_L^+ W_T^- \)) probes \( \Delta \kappa_V \) (resp. \( g_Z^2 \)), whereas \( p\bar{p} \to W_L^\pm Z_L \) probes \( g_Z^2 \).

Transversely polarized gauge bosons test \( \lambda_V \). The advantage of reactions like \( p\bar{p} \to W_T \) or \( e^+ e^- \to \gamma \nu\bar{\nu}, Z\nu\bar{\nu} \) is that they probe independently \( \gamma WW \) and \( ZWW \) trilinear couplings.

We shall finally focus on some specific models. The first one is supersymmetry, hereafter denoted as SUSY. Trilinear gauge boson couplings are sensitive to SUSY at one loop level. In order to get a gauge independent and finite result satisfying unitarity one has to add contributions from boxes having a vector like structure: this the pinch technique \cite{17}. These contributions have to be compared to the SM ones, which are sensitive to top and Higgs masses. The SM one loop corrections are small:

\[
\Delta \kappa_V \sim 510^{-3}, \Delta \kappa_Z \sim 310^{-3}, \lambda_V \sim 10^{-3}
\]

The principal source for deviations arises from neutralinos and charginos \cite{18}. The most favourable situation occurs when \( M_1 < m_0, A_0 \), where \( M_1 \) (resp. \( m_0 \)) is the common gaugino (resp. scalar) mass at the GUT scale whereas \( A_0 \) is the trilinear soft breaking term. One can reach \( \Delta \kappa_V \sim 10^{-2} \).

We shall discuss now technicolor models: only naive QCD scaled versions are ruled out by present data. Due to the heavy top mass and precise LEP1/SLC data two attractive models have recently emerged: topcolor assisted technicolor \cite{19} and the non commutating extended technicolor \cite{20}. The first one differs from SM by a new interaction of type \( SU(3) \times U(1) \) leading to colorons which affect top production, and to an extra Z which may affect diboson production if it couples strongly to light fermions \cite{21}. The non commuting extended technicolor model is based on the assumption that the ETC group does not commute with \( SU(2)_W \), this can be realized for example by assigning the technifermions in a right handed doublet. This model can explain the \( R_b \) deviations from SM. All technicolor models predict the existence of a rich spectrum of new particles like pseudogoldstone bosons, technirho, technieta... Their existence may affect diboson production \cite{22}. As an example production of pairs of longitudinally polarized Z bosons from gluon gluon subprocess could be strongly enhanced in the mass range above the colored pseudogoldstone boson threshold \cite{23}. Nevertheless a quantitative study of the phenomenological consequences for diboson production from those viable models is lacking.
Quartic couplings.

Quartic couplings which violate $SU(2)$ custodial symmetry have already been strongly constrained at LEP1 at the level of $10^{-2}$ and a linear $e^+e^-$ collider will not improve these limits\[^2\]. At LHC a gain in sensitivity of roughly one order of magnitude is expected from the other operators i.e.: 

$$\alpha_1[Tr(V_{\mu}V_{\nu})]^2 \text{ and } \alpha_2([Tr(V_{\mu}V_{\nu})]^2,$$

where $V_{\mu} = (D_{\mu}\Sigma)\Sigma^\dagger$.

4 Conclusions

To conclude, we have already evidence that electroweak gauge bosons are self interacting. The model independent way to parametrize the self couplings among gauge bosons is to use effective lagrangians. To constrain operators contributing to trilinear couplings at the same level as those contributing to two point functions are already constrained by LEP, an $e^+e^-$ linear collider at $\sqrt{s} = 500GeV$ with an integrated luminosity of $50 fb^{-1}$ is ideal and should be more efficient than LHC. LEP limits on quartic couplings will only be improved by LHC.

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Figure Captions

Fig. 1 Need for bosonic loops from present electroweak data [2]. The ball is the 68% CL of data. The net that the ball hints is the full SM prediction with a top mass varying from 100 GeV by steps of 20 GeV and a Higgs mass varying from 100 GeV to 1 TeV (from left to right). The line with cubes corresponds to the purely fermionic contribution.

Fig. 2 Expected bounds on $L_{9L}$ and $L_{9R}$ from LEP2 and a linear collider at $\sqrt{S} = 500 GeV$ [12].

Fig. 3 Expected bounds on $L_{9L}$ and $L_{9R}$ from linear colliders at $\sqrt{S} = 500 GeV$ and at $\sqrt{S} = 1.5 TeV$ compared to LHC [12].
