THE GAUGE BOSON SELF-INTERACTION AT LEP2, SSC, LHC; THE CASE of CUSTODIAL SU(2) SYMMETRY[1]

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ABSTRACT

It is emphasised that all anomalous three-gauge-boson couplings can be made SU(2)×U(1) gauge invariant provided no restriction is imposed on the dimensions of the operators used, which are presumably induced by the New Physics (NP) beyond the Standard Model. On the contrary, if the dimension of the allowed operators is not larger than six, then only a few specific combinations of the anomalous couplings satisfy the SU(2)×U(1) gauge symmetry. An interesting particular situation arises if it is assumed that NP satisfies also an exact global custodial SU(2) symmetry. In this case enhanced cross sections possibly due to strong interactions, may be realized at high energies, involving either the longitudinal or the transverse gauge bosons, or both.

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One of the most important problems of particle physics at present is to understand the mechanism responsible for the spontaneous breaking of the SU(2)×U(1) electroweak gauge symmetry, and the mechanism inducing the breaking of the flavour symmetry. To day we know very little about these mechanisms and their relation. In this respect, the present era of particle physics is reminiscent of the Ginzburg-Landau era for superconductivity. This gives us hope that the BCS epoch may also come some day, when New Physics (NP) hidden under the Higgs field will be revealed. If this is true, then the gauge boson self-interactions should carefully be studied, since they offer a prime candidate where something on the electroweak breaking mechanism may be learnt from. Such a study will in fact acquire a unique importance, if the possible new particles associated with NP are almost invisible or too heavy to be seen directly.

In general there are seven independent ZWW couplings and another seven γWW ones, provided the photon is taken off-shell. Six of these couplings violate the CP symmetry, while the remaining respect it[1)]. A modern representation of them may be found in Ref.2.

After the impressive successes of the Standard Model (SM), the first question to be investigated nowadays concerning these couplings, is whether they are compatible with SU(2)×U(1) gauge invariance. To this aim, we assume the standard group classification for all particles, including the usual Higgs doublet. On the basis of these, it has been found that every one of the three-gauge-boson couplings can be made SU(2)×U(1) gauge invariant by adding to it interactions involving in the unitary gauge more vector bosons and/or the physical Higgs field[3,4)]. In order to achieve this though, we need to combine operators of dimension up to 12 using a relative scale similar to the electroweak breaking scale[4)]

$$v = (\sqrt{2}G_F)^{½} \simeq 247 GeV \qquad (1)$$

The same result is also valid for any n-vertex involving only the usual fermions and gauge bosons. Again, any such vertex can be made SU(2)×U(1) gauge invariant by adding to it vertices involving (in the unitary gauge) more such particles and/or the physical Higgs. In all cases, we need to combine operators of different dimensions using a relative scale similar to v given in (1). Of course, this is natural only if the scale where NP is generated is also v.

We conclude therefore that if the scale where NP is generated is v, and if renormalizability is given up, then the predictive power of an SU(2)×U(1) spontaneously broken gauge symmetry is reduced to the predictive power of just electromagnetic gauge invariance. In other words, the spontaneous breaking of the SU(2)×U(1) gauge invariance is so strong in this case, that the original symmetry is completely forgotten and only electromagnetic gauge invariance is still remembered[3,4)].

On the other hand, if the scale where NP is generated is much higher than v, then the dimensions of the NP induced operators are restricted, so that the electroweak theory retains a predictive power stronger than that of the simple electromagnetic gauge invariance. In the remaining of this talk, I focus on this more realistic case, always remaining within the philosophy of the spontaneously broken $SU(2)\times U(1)$ gauge symmetry. As we go along, I progressively introduce additional assumptions, thereby producing specific examples of how NP may look like.

We next turn to the possibility that the NP induced three-gauge-boson interactions violate[5] CP. It is impossible to observe such interactions at LEP1, since the observables there depend only quadraticaly on the relevant couplings. On the contrary, at LEP2 there exist observables depending linearly on the CP violating interactions. These LEP2 observables are constructed by looking at $e^+e^- \to W^+W^-$ considering the case where W^- decays to leptons, while W^+ goes to jets. From these data we need to determine the imaginary part of the off-diagonal W^- density matrix elements in the helicity basis. These elements receive contributions not only from CP violating forces though, but also from phases induced by loops involving standard CP conserving amplitudes[6]. We do not need to calculate these later effects though; since they can be completely eliminated from the data by looking also at the corresponding W^+ density matrix, using the events where W^+ decays to leptons and W^- to quarks. Thus CP violation may be studied by measuring the quantities[5]

$$Im\rho^{W^-}_{+-}(\theta) - Im\rho^{W^+}_{-+}(\theta) \quad , \quad Im\rho^{W^-}_{+0}(\theta) - Im\rho^{W^+}_{-0}(\theta) \quad , \quad Im\rho^{W^-}_{-0}(\theta) - Im\rho^{W^+}_{+0}(\theta)) \quad , \qquad (2)$$

where θ is the angle of the produced W^- with respect to the e^- beam. A non-vanishing value of any of the quantities in (2) in any angular region, gives an unambiguous signal of CP violation. Since the standard CP violation due to the CKM matrix gives a negligible two-loop contribution in (2), we conclude that any observation of CP violation there should be due to an anomalous gauge boson self interaction. The possible existence of such a phenomenon seems less remote, if we note that two of the CP violating and $SU(2)\times U(1)$ gauge invariant operators have dimension = 6, which is the lowest possible for any operator contributing to an anomalous boson interaction[4]. Thus, the plausible assumption that the NP scale is high, cannot be used as an argument against CP violation.

Having finished with this, we now consider the case that NP respects the CP as well as the $SU(2)\times U(1)$ gauge symmetry. Furthermore, we assume that the scale where NP is generated is so high, that only interactions described by dimension = 6 operators should be taken into account in NP. Such operators have been extensively studied recently, and the universal conclusion is that the constrains from the LEP1 measurements are so strong , that only operators not contributing to the measured quantities at tree level are still allowed[7,8]. These allowed operators can only have small contributions through loops, and following the current jargon, we call them "blind"[7]. There exist 3 "blind" operators containing three-gauge-boson vertices[7], as well as additional ones involving vertices of the form HWW, HZZ, $H\gamma Z$ etc.

Of course, this is not enough to justify the effort looking for "blind" interactions at the new colliders. Unless a physical principle is found which indicates that at least some of the "blind" interactions are rather special, it would be natural to assume that all dim = 6 operators (blind and non-blind) are on the same footing and thus negligible. In the remaining of this talk I show that the assumption that NP satisfies also global custodial $SU(2)_c$ invariance, may offer such a principle[9,4]. Other arguments emphasising "blind" operators have also appeared[10].

$SU(2)_c$ was introduced long ago in order to provide a justification for the SM result that[11] $\varrho = 1$. It is a kind of hidden symmetry arising in SM if the fermions are discarded and the B_μ coupling satisfies $g' = 0$. The field $\bar{W}_\mu$ is invariant under $SU(2)_c$. Only the Higgs field $U = \sqrt{2}/v \cdot (\tilde{\phi}, \phi)$ transforms non-trivially, where ϕ denotes the usual Higgs doublet, $\tilde{\phi} = i\tau_2\phi^*$ and v is given in (1). Using this notation, the SM lagrangian is written as

$$\mathcal{L}_{SM} = -\frac{1}{2} \langle W_{\mu\nu} W^{\mu\nu} \rangle - \frac{v^2 M_H^2}{8} \left(\frac{1}{2} \langle UU^\dagger \rangle - 1 \right)^2 - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} + \frac{v^2}{4} \langle D^\mu U D_\mu U^\dagger \rangle + fermions \ , \qquad (3)$$

where $\langle A \rangle = \mathrm{tr}A$ and $W_{\mu\nu} = \bar{W}_{\mu\nu}\vec{\tau}$ is the usual non abelian field strength. We observe that only the first two terms in (3) respect $SU(2)_c$, while the remaining violate it.

As already stated, we assume that the effective lagrangian induced by NP is invariant under the gauge $SU(2)\times U(1)$ and the global $SU(2)_c$ and CP transformations. Thus, NP can involve neither the B_μ nor the fermion fields. In fact, as far as the gauge boson pair production at LEP2 and SSC/LHC is concerned, the relevant NP effective lagrangian is given by[9]

$$\mathcal{L}_{NP} = \lambda_W \frac{g_2}{M_W^2} O_W + d_{UW} O_{UW} \ , \qquad (4)$$

where

$$O_W = -\frac{2i}{3} \left\langle W^{\nu\lambda} W_{\lambda\mu} W^\mu{}_\nu \right\rangle \quad , \quad O_{UW} = \left\langle (UU^\dagger - 1) W_{\mu\nu} W^{\mu\nu} \right\rangle \ , \qquad (5)$$

and operators with dim>6 have been neglected. Thus, the $SU(2)_c$ invariance of NP implies that $\mathcal{L}_{Np}$ is dominated by two blind operators. Non-blind operators are excluded because they violate the assumed symmetries of $\mathcal{L}_{Np}$. The effects of the operator O_{UW}, which gives only Higgs exchange contributions to the vector boson pair production at SSC/LHC, have not been fully studied yet[12]. In the remaining we will concentrate on[9] O_W. This operator has also been encountered before in a somewhat different context[13].

At this point it is interesting to compare O_W with the operator $(\langle UU^\dagger \rangle/2 - 1)^2$ appearing in the second term of (3). Both these operators respect $SU(2)_c$. The second one has attracted considerable interest for some time by now, since it was noticed that it induces strong interactions among the longitudinal gauge bosons at high energies in case[14] $M_H > 1$TeV. The operator O_W on the other hand, enhances the production of transverse gauge bosons at high energies. Thus, on the basis of $SU(2)_c$ we may have at high energies enhanced cross sections, or even strong interactions, either among the longitudinal or among the transverse gauge bosons.

LEP1 precision measurements constrain λ_W through one-loop contributions which give[7] $|\lambda_W| < 1$. Similar results are also derived from LEP1 for the strength of other "blind" operators[8]. Studying $e^+e^- \to W^+W^-$ in higher leptonic colliders will be able to decrease the O_W upper bound to $|\lambda_W| < 0.1$ from[16] LEP2, and $|\lambda_W| < .01$ from[2] ee500. In all cases, O_W contributes mainly to the transverse gauge boson production in this process.

Important information on O_W may also be obtained by studying gauge boson pair production at[9] SSC/LHC. The relevant process is $pp \to V_1V_2...$, where the available channels are $W^\pm Z$, $W^\pm\gamma$, W^+W^-, W^+W^+, W^-W^-, ZZ and $\gamma\gamma$. In all cases two production mechanisms are possible; namely quark annihilation $q_i\bar{q}_j \to V_1V_2$, and vector boson fusion $V_3V_4 \to V_1V_2$. In the kinematical range of interest for SSC/LHC, both mechanisms give comparable

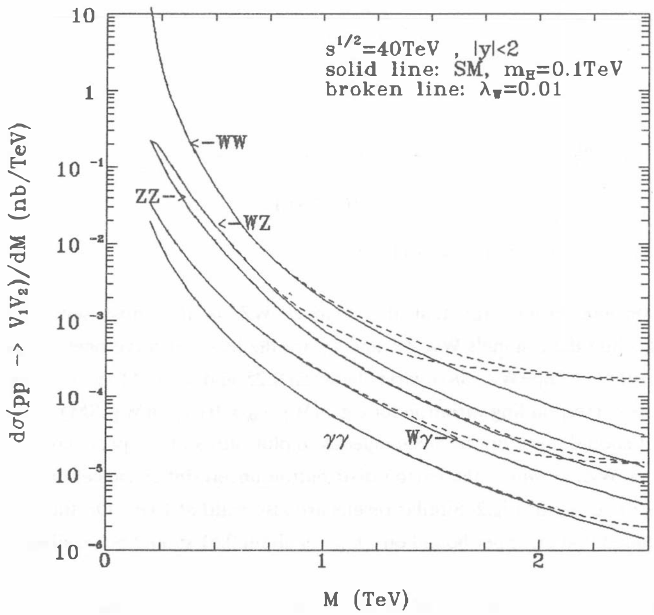

Figure 1 Production cross sections for various channels.

contributions for all possible channels. Adding the contributions from both mechanisms we give in[9] Fig1 the production cross sections for the various channels at SSC. Solid lines describe the SM result, while the broken lines departing from them at $M \approx 0.75$TeV give the corresponding results for $\lambda_W = 0.01$. The pp energy and the cuts on the rapidity of each final boson are indicated in the figures. The additional cut $p_{T\gamma} > 0.15$TeV has also been applied in channels involving a final photon[15].

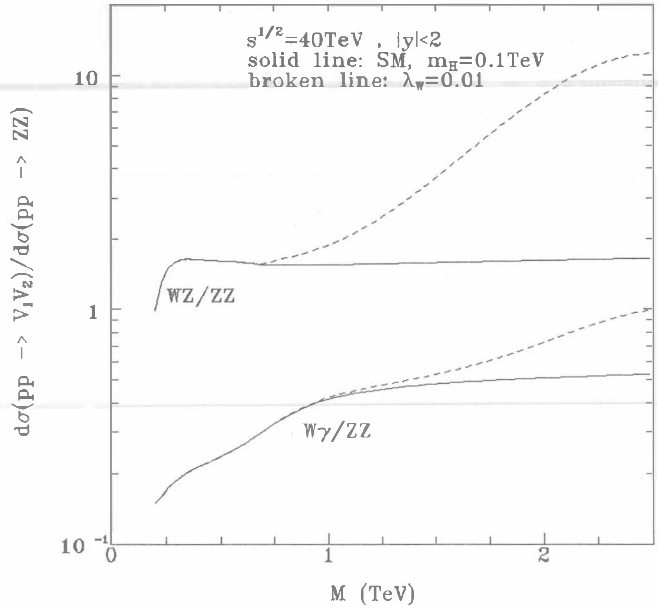

Figure 2 Ratios of production cross sections.

We conclude from Fig1 that the channel WZ is the most sensitive to O_W contributions, while the channels $W\gamma$, ZZ and $\gamma\gamma$ are the least sensitive ones. Thus, the ratio $\sigma(pp\rightarrow WZ, \lambda_W = 0.01)/\sigma(pp\rightarrow WZ, SM)$ varies between 1.25 and 10 as M varies between 1 and 2TeV; while the corresponding variation for e.g. $\sigma(W\gamma, \lambda_W = 0.01)/\sigma(W\gamma, SM)$ is only between 1.03 and 1.7. It should therefore be advantageous to plot ratios of the production of channels like WZ/ZZ or $WZ/\gamma\gamma$ where the parton distribution uncertainties cancel out. An example of such ratios[9)] is given in Fig.2. Similar results are also valid at LHC. On the basis of these we have concluded that an upper bound on $|\lambda_W|$ of about 0.01 should be feasible at both SSC and LHC[9)].

We should emphasize that in all cases, O_W affects mainly the transverse gauge bosons. Thus O_W tends to induce large corrections to SM, mainly by inducing strong production of transverse gauge bosons[9)]. Its effects depend only on λ_W, and are independent of the Higgs mass M_H. On the other hand if $M_H > 1$TeV, then the Higgs self interaction in $\mathcal{L}_{SM}$ participates in NP by inducing strong interactions among the longitudinal gauge bosons[14)]. Depending therefore on the values of (M_H, λ_W), the $SU(2)_c$ symmetry of NP anticipates new powerful interactions at the TeV scale among either the longitudinal or the transverse gauge bosons, or both.

Finally, I should also emphasize that at the very least, the above treatment of the $SU(2)_c$ symmetry should be considered as an example indicating that it is always possible to postulate plausible principles which single out "blind" operators for the description of the gauge boson interactions induced by NP. Thus, the fact that the NP contributions from the non-blind operators vanish, should not hinder the study of the blind ones, in our attempt to discover hints for the New Physics beyond the Standard Model.

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