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Electroweak Vector Bosons: Standard Model and Beyond*

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ABSTRACT

Some recent developements in electroweak vector boson physics at future colliders are summarized. New vector boson pair production mechanisms at hadron colliders are discussed. Three gauge boson production processes provide tests of triple and quartic vector boson couplings. New electroweak bosons associated with models which go beyond the standard one may lead to observabale effects at future e^+e^- , ep and hadron colliders if their mass is smaller than a few TeV. The structure of the $WW\gamma$ and WWZ vertex can be measured in W^+W^- production at LEP200, and in $W^\pm\gamma$ and $W^\pm Z$ production at the LHC and SSC.

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Electroweak Vector Bosons: Standard Model and Beyond

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1. Introduction

In my talk I would like to review some recent developments in electroweak vector boson physics at future colliders. In the first part I will concentrate on Standard Model (SM) issues. In the second part I will go beyond the SM and discuss possibilities to discover effects of new electroweak bosons and anomalous $WW\gamma$ and WWZ couplings at LEP/SLC, HERA and LHC/SSC.

2. Standard Model Electroweak Boson Physics

There are two main topics of interest in W - and Z -boson physics at future colliders:

- i) Processes involving electroweak vector bosons often contribute to the background of new physics signals. In particular, they constitute the main background for Higgs boson production at future hadron colliders such as the LHC (pp collisions at $\sqrt{s} \approx 17$ TeV) or the SSC (pp collisions at $\sqrt{s} = 40$ TeV).
- ii) $W^\pm$ and Z processes which provide new ways to test the SM.

In the following I shall discuss three examples which illustrate these points.

$pp \rightarrow W^+W^-, ZZ$

Continuum production of W and Z pairs constitutes a very important background for the detection of a heavy Higgs boson with mass $M_H > 2M_W$ at future hadron colliders [1]. A precise knowledge of the rate for these processes is therefore very important in order to find out whether a Higgs boson with a given mass can be found at the LHC or SSC.

At the tree level, W^+W^- and ZZ production proceeds via $q\bar{q}$ annihilation. The relevant Feynman diagrams are shown in Fig. 1a and 1b. The diagrams of Fig. 1b involve the triple gauge boson vertex and contribute in the SM only in the W^+W^- case. At the one loop level gluon fusion contributes in addition to W and Z pair production (see Fig. 1c,d). Although the virtual quark loop graphs are suppressed by α_s^2 , W^+W^- and ZZ production via gluon fusion can be competitive with the production from tree level $q\bar{q}$ annihilation at the proposed supercolliders. This is possible because the gluon-gluon luminosity far exceeds that for quark-antiquark collisions at low x . An example of this is $\gamma\gamma$ pair production [2]. For photon pair invariant masses less than ~ 250 GeV, the $gg \rightarrow \gamma\gamma$ process gives a larger cross section than $q\bar{q} \rightarrow \gamma\gamma$. If the top quark is light, $gg \rightarrow \gamma\gamma$ is further enhanced.

In principle a similar situation may also occur for $gg \rightarrow W^+W^-, ZZ$ at small m_{WW} and m_{ZZ} . Presently, full analytic calculations of the matrix elements for

Fig. 1: Feynman graphs for $q\bar{q} \rightarrow W^+W^-, ZZ$ (a,b) and $gg \rightarrow W^+W^-, ZZ$ (c,d).

$gg \rightarrow W^+W^-, ZZ$ do not exist. A crude estimate of the importance of $gg \rightarrow ZZ$ relative to $q\bar{q} \rightarrow ZZ$ can be obtained from the double ratio [3]

$$R = \frac{\sigma(gg \rightarrow ZZ)/\sigma(q\bar{q} \rightarrow ZZ)}{\sigma(gg \rightarrow \gamma\gamma)/\sigma(q\bar{q} \rightarrow \gamma\gamma)} . \quad (1)$$

R is quite insensitive to quark and gluon luminosities, Z mass effects and the value of α_s . It is thus essentially determined by the squares of the weak and electric charges, appearing in the following combinations

$$\frac{\sigma(gg \rightarrow ZZ)}{\sigma(gg \rightarrow \gamma\gamma)} \approx \frac{\left(\sum_q v_q^2 + a_q^2\right)^2}{\frac{1}{2} \left(\sum_q e_q^2\right)^2} , \quad (2)$$

$$\frac{\sigma(q\bar{q} \rightarrow ZZ)}{\sigma(q\bar{q} \rightarrow \gamma\gamma)} \approx \frac{\sum_q (v_q^2 + a_q^2)^2 + 4v_q^2 a_q^2}{\frac{1}{2} \sum_q e_q^4} . \quad (3)$$

Here, e_q is the electric charge and $v_q(a_q)$ is the vector (axial vector) coupling constant of the Z -boson and the quark q , normalized to the electric charge unit e . The sum in eqs. (2) and (3) runs over the quarks in the loop. Using $\sin^2 \theta_W = 0.23$ one then finds

$$R \approx 1.0 . \quad (4)$$

Since

$$\frac{\sigma(gg \rightarrow \gamma\gamma)}{\sigma(q\bar{q} \rightarrow \gamma\gamma)} \approx 1 , \quad (5)$$

we thus expect that $\sigma(gg \rightarrow ZZ)$ is of the same order as $\sigma(q\bar{q} \rightarrow ZZ)$.

The result of the naive estimate presented above is supported by a calculation where the $gg \rightarrow ZZ$ matrix elements are evaluated numerically [4]. It also works reasonably well for γZ production [5].

A calculation of R for the box graph contribution to $gg \rightarrow W^+W^-$ (Fig. 1c) gives $R \approx 0.7$. Of course, since the triangle diagram of Fig. 1d also contributes to W pair production via gluon fusion, this value does not really mean anything. It indicates, however, that unless there are strong cancellations between box and triangle graphs, $gg \rightarrow W^+W^-$ may play a significant role in W pair production at future hadron colliders.

Hadronic Production of Electroweak Vector Boson Pairs at Large Transverse Momentum

Electroweak boson pairs produced together with a large transverse momentum jet are another example for processes which contribute to the Higgs background at the LHC and SSC. Using helicity amplitude techniques, the matrix elements for $V_1 V_2 j$ production at hadron colliders, including the decay of W - and Z -bosons into massless fermion-antifermion final states, were recently calculated for all possible vector boson pair combinations [6]

$$V_1 V_2 = \gamma\gamma, Z\gamma, ZZ, W^\pm\gamma, W^+W^-, W^\pm Z. \quad (6)$$

$pp \rightarrow W^+W^-j, ZZj$ with the jet produced in the central detector, for example, may be a potentially important background for a heavy Higgs boson which is generated at large p_T , e.g. from $gg \rightarrow Hg$ [7]. If the jet is emitted in forward direction, $pp \rightarrow W^+W^-j, W^\pm Zj$ and ZZj may be background processes which are relevant for "Higgs tagging" [6,8].

Of course, if one the W 's or Z 's in $pp \rightarrow Hj \rightarrow WW(ZZ)j$ decays hadronically, $W(Z)jjj$ production with $m_{jj} \approx M_W(M_Z)$ is the potentially most dangerous background. Complete helicity amplitudes for these processes have recently been presented in [9].

In Table 1 total $V_1 V_2 j$ production rates for pp collisions at $\sqrt{s} = 40$ TeV are listed as a function of the minimum transverse momentum $p_{TVV}^{\min}$ of the vector boson pair. They are compared with the cross section for the corresponding $2 \rightarrow 2$ process $q\bar{q} \rightarrow V_1 V_2$. The cuts in Table 1 roughly simulate detector response and eliminate the soft region $p_{TVV} \ll m_{VV}$ where virtual and multiple gluon processes become important.

Table 1: Cross sections for $V_1 V_2$ production from $q\bar{q}$ annihilation, and $V_1 V_2 j$ production for a minimum p_{TVV} of 100, 200 and 300 GeV at the SSC. In addition a cut of $p_{TVV} > 0.3 \cdot m_{VV}$ is imposed in the $V_1 V_2 j$ case. W, Z and the jet must have rapidity $|y| < 2.5$ while the photon is required to have $p_T > 50$ GeV, $|y| < 2.5$ and to be separated from the jet and other photons by $\cos\Theta_{\gamma j} < 0.9$ and $\cos\Theta_{\gamma\gamma} < 0.9$.

process	σ [pb]	$p_{TVV}^{\min}$ process	100 GeV σ [pb]	200 GeV σ [pb]	300 GeV σ [pb]
$\gamma\gamma$	5.16	$\gamma\gamma j$	1.37	0.37	0.15
$Z\gamma$	8.24	$Z\gamma j$	2.35	0.73	0.30
ZZ	13.00	ZZj	2.43	0.84	0.36
$W^\pm\gamma$	8.66	$W^\pm\gamma j$	15.52	6.55	3.18
W^+W^-	78.9	W^+W^-j	27.3	11.0	5.00
$W^\pm Z$	33.0	$W^\pm Zj$	22.5	10.4	5.10

Table 1 demonstrates that the $V_1 V_2 j$ rates for $p_{TVV}^{\min} = 100$ GeV are generally large so that these processes represent an important source for gauge boson pair production at hadron supercolliders; typically the cross sections are a factor 4 to 5 smaller than for the corresponding $2 \rightarrow 2$ process. In the W photon case the cross

Fig 2: Total cross section for $e^+e^- \rightarrow VVV$; $WW\gamma$ and $ZZ\gamma$ have cuts $p_{T\gamma} > 20 \text{ GeV}$ and $|y_\gamma| < 2$ (from [11]).

section of $W^\pm\gamma j$ is for $p_{TW\gamma}^{\min} = 100 \text{ GeV}$ even bigger than the one of $q\bar{q} \rightarrow W^\pm\gamma$. This anomalous behavior can be traced back to the radiation zero [10] present in the differential cross section of $q\bar{q} \rightarrow W^\pm\gamma$ and which suppresses the total rate substantially. Such an effect is not present in other gauge boson pair production processes, or when a high p_T jet is produced in addition to the $W\gamma$ pair.

Triple Gauge Boson Production at e^+e^- and pp Supercolliders

It is well known that the production of gauge boson pairs at e^+e^- and pp colliders will provide crucial tests of the SM. I will discuss this in more detail somewhat later. However at supercolliders with high energy and high luminosity it may also be possible to study the production of three electroweak vector bosons [11,12]. This could be interesting for the following reasons:

- i) There are more triple gauge boson couplings involved than, for example, in $e^+e^- \rightarrow W^+W^-$. Hence, more restrictive tests of SM predictions may be possible.
- ii) In processes with at least one W -boson in the final state the four gauge boson coupling could, at least in principle, be tested.
- iii) In all processes without real photons the Higgs sector enters directly, even in the zero fermion mass limit. In ZZZ production at e^+e^- colliders, for example, the cross section can be resonance enhanced by up to one order of magnitude [11].

Triple gauge boson production at e^+e^- and pp colliders has recently been investigated in detail by several groups [11,12] with, generally, promising results. In Fig. 2 we show the cross sections versus the center of mass energy $\sqrt{s}$ for $e^+e^- \rightarrow ZZZ$, $ZZ\gamma$, WWZ and $WW\gamma$. The cross section for triple Z production is very small, but for $WW\gamma$ and WWZ it is large enough that a few hundred events could be seen with an integrated luminosity of 10^4 pb^{-1} .

3. Beyond the Standard Model

3.1 New Electroweak Bosons: Expectations from Future Colliders

Models which go beyond the standard one often predict the existence of new charged and/or neutral massive weak vector bosons, in addition to the usual W - and Z -bosons. Examples are

- i) Superstring inspired E_6 models: Such models often contain a Z' -boson associated with a broken $U(1)$ group [13].
- ii) Left-right symmetric models: They predict the existence of charged and neutral vector bosons $W_R^\pm$ and Z_R associated with the $SU(2)_R$ group.
- iii) Models with a strongly interacting Higgs sector: Here an additional weak isotriplet $V^{\pm,0}$ of bound state vector bosons is formed [14].
- iv) Composite weak boson models [15]: Independently of the underlying preon theory such models always predict the existence of excited W 's and Z 's [16]. In some of them one also expects isoscalar bosons $Y(Y_L)$ associated with the weak hypercharge or its lefthanded part [17], or, if the W - and Z -constituents are colored objects, color octet partners of $W^\pm$ and Z [18].

Usually the new vector bosons have masses in the few hundred GeV or, at most, in the few TeV range. They may thus lead to observable effects in experiments at future e^+e^- , ep and hadron machines.

LEP/SLC and LEP200

At the next generation of e^+e^- colliders, LEP/SLC ($\sqrt{s} \approx M_Z$) and LEP200 ($\sqrt{s} \approx 190$ GeV), only virtual effects of new neutral electroweak bosons are expected to show up. They manifest themselves in two ways:

- 1) The physical Z -boson feels the mixing in of the new boson. As a result the mass and the leptonic width $\Gamma(Z \rightarrow \ell^+\ell^-)$, $\ell = e, \mu, \tau$, of the Z will differ from the SM prediction.
- 2) Due to the exchange of the additional vector boson, the $e^+e^- \rightarrow \mu^+\mu^-$ cross section and, even more importantly, the electroweak forward-backward and left-right asymmetry A_{FB} and A_{LR} may be significantly changed.

M_Z , $\Gamma(Z \rightarrow \ell^+\ell^-)$, A_{FB} and, if longitudinal polarization for the electron beam is available, A_{LR} can all be measured with high precision at LEP/SLC and LEP200. Figure 3 illustrates how A_{FB} may be influenced by an additional neutral vector boson. Here A_{FB} is shown as a function of $\sqrt{s}$ for the SM (solid line) and two types of isoscalar vector bosons, Y (dashed lines) and Y_L (dotted lines), which are coupled to the weak hypercharge current and its left-handed part, respectively. As mentioned before, such particles appear in certain composite weak boson models. From Fig. 3 it becomes obvious that a precise measurement of A_{FB} , in particular at LEP200, will severely restrict the allowed values for the mass and the coupling constant of $Y(Y_L)$. Combining the constraints from present neutral current experiments with what one expects from Z -mass and $A_{FB}(A_{LR})$ measurements at LEP/SLC and LEP200, one can show [19] that such particles with a mass of up to 1 TeV can be excluded, if no deviations from the SM are found at the next generation of e^+e^- colliders. A very similar analysis was also performed for excited W 's [20], the bound state vector boson triplet of the strongly interacting Higgs model [14], right-handed W 's [21] and superstring inspired E_6 Z' -bosons [13].

Fig. 3: $A_{FB}^{e^+e^- \rightarrow \mu^+\mu^-}$ versus $\sqrt{s}$ for the SM, Y (dashed lines) and Y_L (dotted lines) bosons (from [19]). The numbers attached to the curves denote the $Y(Y_L)$ mass in GeV. The $Y(Y_L)$ fermion coupling constant was chosen to be equal to the W fermion coupling constant.

HERA

The effect of non-standard weak boson exchange on the differential cross section at HERA ($e_{L,R}^\pm p$ collisions at $\sqrt{s} = 314$ GeV) and various asymmetries which can be formed if polarized $e^\pm$ beams are available have recently been studied in detail for the HERA Workshop [22] with the following conclusions:

- 1) For unpolarized beams HERA is sensitive to $Y(W_R, Z_R)$ exchange for boson masses up to 600 GeV (300 GeV), but very insensitive to V^0 , Z' and excited Z -boson exchange.
- 2) For polarized beams one typically obtains limits in the 200...450 GeV range, depending on the nature of the new vector boson. These bounds are only slightly better than existing ones from neutral current and $\bar{p}p$ collider data. The only exception is the Y -boson where one can see deviations from the SM for masses up to 800 GeV with polarized beams.

Hadron Colliders

Whereas next generation e^+e^- and ep machines will be only sensitive to virtual effects of new vector bosons, present and future hadron colliders may actually be capable of producing such particles. The strategy for hunting non-standard electroweak vector bosons at hadron colliders is basically the same which led to the discovery of $W^\pm$ and Z at the CERN $\bar{p}p$ collider. Neutral vector bosons are signalled by a charged lepton pair with invariant mass equal to the vector boson mass M . Charged vector bosons result in a charged lepton plus missing transverse momentum final state with the transverse mass distribution peaking near M . Since there is practically no background, the maximum vector boson mass which is accessible at a hadron collider is essentially limited by statistics only. In general, the improved CERN $\bar{p}p$ collider and the Tevatron will be sensitive to non-standard vector bosons with masses in the few hundred GeV region while the planned supercolliders will test the few TeV range. Precise limits which will be achievable depend, of course, on the fermion vector boson coupling strength, and on the leptonic branching ratio of the non-standard vector boson.

Fig. 4: Feynman diagrams for the process $e^+e^- \rightarrow W^+W^-$.

3.2 Probing $WW\gamma$ and WWZ Couplings at Future Colliders

An important objective of future colliders is a model independent determination of the $WW\gamma$ and WWZ couplings, either to confirm the SM predictions, or to pin down signals of new physics. The most general $WW\gamma$ (WWZ) effective Lagrangian for massless fermions is described by 7 independent couplings [23]. Three of them respect the discrete symmetries C , P and T separately, two violate P and CP , one violates C and CP , and one is C and P odd, but CP even. Within the SM, at tree level, the triple gauge boson vertex is completely fixed by the gauge theory structure of the model.

Checking the Three Gauge Boson Vertex at LEP200

A suitable process to study $WW\gamma$ and WWZ couplings at LEP200 is W pair production [23]. At the tree level $e^+e^- \rightarrow W^+W^-$ proceeds via photon-, Z - and neutrino exchange (see Fig. 4). The interference between these graphs and in particular the large gauge cancellations between them make this reaction sensitive to deviations of the $WW\gamma$ and WWZ vertices from the SM. However, since the center of mass energy at LEP200 ($\sqrt{s} \approx 190$ GeV) is only slightly above the W pair threshold, threshold effects dominate and limit the sensitivity to anomalous couplings. In particular, CP violating terms are only marginally observable at LEP200. Furthermore, large cancellations among different anomalous contributions to the helicity amplitudes may take place, unless longitudinal or transverse beam polarization is available [24]. As a result, experiments at LEP200 can measure anomalous $WW\gamma$ and WWZ couplings only with an accuracy of $\pm 0.1 \dots \pm 0.7$.

W -mass measurements, on the other hand, benefit from the dominance of threshold effects at LEP200. As demonstrated in [25], even in the presence of large anomalous couplings the mass of the W -boson can still be measured with high precision from the shape of $\sigma(e^+e^- \rightarrow W^+W^-)$ near the W pair threshold.

Testing the $WW\gamma$ and WWZ Vertex at the LHC and SSC

Due to the large center of mass energies available, the limits achievable on anomalous three vector boson couplings at LEP200 may be improved significantly at the LHC or SSC by studying $W^\pm\gamma$ [26] and $W^\pm Z$ production [27]. At the tree level these reactions proceed via $q\bar{q}$ annihilation with t -channel quark and s -channel W exchange. $W\gamma$ production is therefore only sensitive to $WW\gamma$, and WZ production only to WWZ couplings. Furthermore, electromagnetic gauge invariance restricts the number of independent couplings from 7 to 4 in the $W\gamma$ case.

Anomalous three vector boson couplings result in contributions to the helicity amplitudes which grow with energy and, eventually, violate unitarity if constant couplings are assumed. This means that any anomalous coupling has to be introduced as a form factor which vanishes at high energies. Partial wave unitarity applied to $f\bar{f} \rightarrow W\gamma$, WZ and WW then results in upper bounds for the low energy values of the form factor [28].

Fig. 5: Photon p_T spectrum in $pp \rightarrow W^+\gamma X$ at the SSC (from [26]). For a definition of the anomalous couplings κ (dashed line), $\tilde{\kappa}$ (dash-dotted line), λ (long-dashed line) and $\tilde{\lambda}$ (dotted line), and the form factor which was used see [26].

Since multi-TeV hadron colliders cover a wide range of center of mass energies, this form factor behavior should not be neglected in a realistic study. The effects of anomalous $WW\gamma$ couplings are illustrated in Fig. 5 where the photon p_T spectrum in $pp \rightarrow W^+\gamma$ at $\sqrt{s} = 40$ TeV is shown for a representative choice of anomalous couplings and a dipole form factor with cut-off scale $\Lambda = 2$ TeV, which essentially is the scale above which the form factor starts to decrease [26]. Only one $WW\gamma$ coupling at a time is chosen different from the SM prediction. For comparison the SM curve is included as a solid line. It is obvious from Fig. 5 that the photon p_T spectrum in $W\gamma$ production is a very sensitive indicator for anomalies in the $WW\gamma$ vertex. A quantitative analysis shows that the LEP200 limits for anomalous $WW\gamma$ couplings may be improved by up to *two orders of magnitude* if no deviations from the SM are observed in $W\gamma$ production at the LHC or SSC [26]. A very similar conclusion is also reached for WWZ couplings from WZ production [27].

4. Conclusions

Future colliders are very well suited to look for new electroweak bosons and to test $WW\gamma$ and WWZ self-interactions. LEP/SLC, LEP200 and HERA are mainly sensitive to virtual effects of new bosons, whereas hadron colliders are “discovery machines” for such particles. $W\gamma$ and WZ production at both the SSC and the LHC provide excellent tools to investigate the $WW\gamma$ and WWZ couplings.

There are also good prospects to find the SM Higgs boson either at LEP200 [29] or, if its mass is larger than $2M_W$, at the planned hadron supercolliders. However, a more detailed investigation of the background, in particular for new search techniques such as “Higgs tagging”, seems to be necessary to reach definite conclusions.

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