THE BESS MODEL AT $e^+e^-$ COLLIDERS

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We consider the possibility of detecting vector resonances from a strong electroweak sector, in the framework of the BESS model, at future $e^+e^-$ colliders up to the TeV range. If the mass $M_V$ of the new vector boson multiplet is not far above or if it is below the maximum machine energy, such a contribution would be manifest. The process of $W$-pair production by $e^+e^-$ annihilation allows for sensitive tests of the strong sector, especially if the $W$ polarizations are reconstructed.
1. THE BESS MODEL

We consider the sensitivity of $e^+e^-$ linear colliders, for different total center of mass energies and luminosities, to the BESS model which corresponds to a breaking of the electroweak symmetry due to a strongly interacting sector [1]. In BESS the electroweak symmetry breaking is obtained via a non-linear realization and no Higgs particles are present. The nonlinear realization can be seen classically as the limit of infinite Higgs mass for the corresponding linear realization of the standard model. The effective lagrangian based, in its minimal version on the nonlinear breaking $SU(2)_L \otimes SU(2)_R \otimes SU(2)_V \to SU(2)_D$, provides new gauge bosons ($V^\pm, V^0$) that, together with the hypothesis that quantum effects provide their kinetic terms, appear as dynamical bound states of the strongly interacting sector. These new gauge bosons can be produced as real resonances if their mass is below the collider energy. Because of beamstrahlung and synchrotron radiation, in a high energy collider, one expects to see dominant peaks below the maximum c.m. energy even without having to tune the beam energies. If instead the masses of the $V$ bosons are higher than the maximum c.m. energy, they would give rise to indirect effects in the $e^+e^- \to f^+f^-$ and $e^+e^- \to W^+W^-$ cross sections, due to their mixing with the electroweak gauge bosons and their fermion couplings. Our description of the vector resonances provides a quite general background for testing the idea of a strong interacting electroweak sector and for example, after specialization of the parameters, it can describe a standard techni-$\rho$ state.

The BESS model contains as additional parameters the mass $M_V$ of the new bosons which are a degenerate triplet of an additional $SU(2)$ gauge group, their gauge coupling $g''$ which is assumed to be much larger than $g$ and $g'$, and a parameter $b$ specifying the direct coupling of $V$ to fermions. The standard model (SM) is formally recovered in the limit $g'' \to \infty$, and $b = 0$. Mixings of the ordinary gauge bosons to the $V$’s are of the order $O(g/g'')$. Due to these mixings, $V$ bosons are coupled to fermions even for $b = 0$. Furthermore these couplings are still present in the $M_V \to \infty$ limit, and therefore the new gauge boson effects do not decouple in the large mass limit.

The precise measurements of the electroweak parameters done at LEP give the possibility of finding some hints for going beyond the standard model. Through mixing effects the contribution of vector resonances from the strong sector affects masses and couplings of ordinary gauge bosons. Therefore precise measurements of the width of $Z$, its mass and forward backward asymmetries, performed at LEP, allow for restrictions on the unknown parameters of the BESS model: the mass $M_V$, the direct coupling to fermions $b$, and the gauge coupling constant $g''$ of the $V$ bosons.

BESS is a non-renormalizable effective theory and when radiative corrections are considered, a cut-off $\Lambda$ has to be introduced. This cut-off plays the role of the parameter $m_H$, the Higgs mass of the SM. We shall assume for BESS the same one-loop radiative corrections of the standard model interpreting $m_H$ as the cut-off.

Using the following LEP data and the CDF/UA2 measurement of the mass ratio
we obtain bounds on the BESS model, that we express as 90% C.L. contours in the plane \((b, g/g'')\) for given \(M_V\) (see Fig. 1). The bounds depend mainly on the large range allowed at present for the SM parameters \(m_{t_{\text{top}}}\) and \(\alpha_s\). For this reason we show in Fig. 1 the total allowed region for \(m_{t_{\text{top}}}\) and \(\alpha_s\) within the indicated ranges.

The latest data given at the Marseille Conference [3] do not improve significantly the restrictions on the parameter space of the BESS model shown in Fig. 1. LEP 200 is expected to increase only marginally the sensitivity over LEP. The relevant modification will be brought by more accurate determination of \(M_W\).

In order to compare with a standard techni-\(\rho\), one has to take \(b = 0\), and

\[
\frac{g}{g''} = \sqrt{2} \frac{M_W}{M_{\rho_T}} \tag{1.2}
\]

and identify \(M_{\rho_T}\) with \(M_V\) [4].

### 2. THE FERMIONIC CHANNEL

The fermionic channel \(e^+e^- \rightarrow f^+f^-\) at linear \(e^+e^-\) colliders improves the existing limits on BESS from LEP1 and UA2/CDF only for energies in the range \(300 - 500\) \(GeV\) and using longitudinally polarized electron beams. Our analysis is based on the observables:

\[
\sigma^\mu, \quad R = \sigma^h / \sigma^\mu, \\
A_{FB}^{e^+e^- \rightarrow \mu^+\mu^-}, \quad A_{FB}^{e^+e^- \rightarrow \bar{b}b} \\
A_{LR}^{e^+e^- \rightarrow \mu^+\mu^-}, \quad A_{LR}^{e^+e^- \rightarrow \bar{b}b}, \quad A_{LR}^{e^+e^- \rightarrow had} \tag{2.1}
\]
where $A_{FB}$ and $A_{LR}$ are the forward-backward and left-right asymmetries, and $\sigma^{h(\mu)}$ is the total hadronic (muonic) cross section. The relevant formulas for this study have been reported in [5].

In the numerical analysis, following the existing studies of 500 GeV $e^+e^-$ linear colliders [6], we assume a relative systematic error in luminosity of $\delta L/L = 1\%$ and $\delta \epsilon_{\text{hadr}}/\epsilon_{\text{hadr}} = 1\%$ (which is perhaps an optimistic choice due to the problems connected with the $b$-jet reconstruction), $\delta \epsilon_{\mu}/\epsilon_{\mu} = 0.5\%$, where $\epsilon_{\text{hadr,\mu}}$ denote the selection efficiencies. We shall also assume the same systematic errors for the 1 and 2 TeV machines. Finally we have considered an integrated luminosity $L = 20$ fb$^{-1}$. This integrated luminosity would correspond to about one year ($10^7$ sec.) of running. One should of course take into account beamstrahlung effects. However for two body final states, as we consider here, the practical effect is a reduction of the luminosity. This means that with the assumed nominal luminosity one has to run for a correspondingly longer period.

In the case the mass of the resonance could not be reached we can get restrictions on the parameter space by combining the observables of eq. (2.1). Throughout this paper we assume $m_{\text{top}} = 150$ GeV and $\Lambda = 1$ TeV. Our results are shown in Fig. 2. Unfortunately the most sensitive observables are the left-right asymmetries, which means that, if the beams are not polarized, one gets practically no advantage over LEP1 from this channel.

The contours shown in Fig. 2 correspond to the regions which are allowed at 90% C.L. in the plane $(b,g/g'')$, assuming that the BESS deviations for the observables of eq. (2.1) from the SM predictions are within the experimental errors. The results are obtained assuming a longitudinal polarization of the electron $P_e = 0.5$ (solid line) and $P_e = 0$ (dashed line). We assume $\sqrt{s} = 500$ GeV and $M_V = 600$ GeV.

![Fig. 2 - 90% C.L. contours in the plane $(b,g/g'')$ for $\sqrt{s} = 500$ GeV and $M_V = 600$ GeV from the fermionic channel (we assume $m_{\text{top}} = 150$ GeV, $\alpha_s = 0.12$, $\Lambda = 1000$ GeV). The solid line corresponds to polarization $P_e = 0.5$ while the dashed line is for unpolarized electron beams. The allowed regions are the internal ones.](image)

As it is clear there is no big improvement with respect to the already existing bounds from LEP1. Increasing the energy of the machine does not drastically change the results. We have also explored the sensitivity with respect to $M_V$, by choosing $b = 0$. We find that, even for polarized electron beams, the bounds improve only for $M_V$ close to the value of the energy of the machine.

3. THE $WW$ CHANNEL
In this section we consider the channel \( e^+ e^- \rightarrow W^+ W^- \), which is expected to be more sensitive, at high energy, than the \( f \bar{f} \) channel to effects coming from a strongly interacting electroweak symmetry breaking sector. In the case of a vector resonance this is due to the strong coupling between the longitudinal \( W \) bosons and the resonance. Furthermore this interaction, in general, destroys the fine cancellation among the \( \gamma - Z \) exchange and the neutrino contribution occurring in the SM. This effect gives rise, in the case of the BESS model, to a differential cross-section increasing linearly with \( s \). However one can show that the leading term in \( s \) is suppressed by a factor \((g/g'')^4\). Therefore the effective deviation at the energies considered here is given only by the constant term, which is of the order \((g/g'')^2\).

We consider one \( W \) decaying leptonically and the other hadronically. The main reason is that in this way we get a clear signal useful to reconstruct the polarization of the \( W \)s [7]. Let us consider the observables:

\[
\frac{d\sigma}{d\cos\theta}(e^+ e^- \rightarrow W^+ W^-) = \left(\frac{d\sigma}{d\cos\theta}(P_e = +P) - \frac{d\sigma}{d\cos\theta}(P_e = -P)\right) / \frac{d\sigma}{d\cos\theta} \tag{3.1}
\]

where \( \theta \) is the \( e^+ e^- \) center of mass scattering angle. Assuming that the final \( W \) polarization can be reconstructed by using the \( W \) decay distributions, we examine the cross sections for \( W_L W_L \), \( W_T W_L \), and \( W_T W_T \). The relevant formulas have been given in [5]. In the case of the \( WW \) channel we assume \( \delta B/B = 0.005 \) [8], where \( B \) denotes the product of the branching ratio for \( W \rightarrow \text{hadrons} \) and that for \( W \rightarrow \text{leptons} \), and we assume 1\% for the acceptance.

To discuss the restrictions on the parameter space for masses of the resonance a little higher than the available c.m. energy we have taken into account the experimental efficiency. We have assumed an overall detection efficiency of 10\% including the branching ratio \( B = 0.29 \) and the loss of luminosity from beamstrahlung [7]. This gives an effective branching ratio of about 0.1.

For a collider at \( \sqrt{s} = 500 \text{ GeV} \) the results are illustrated in Fig. 3. The contours have been obtained by taking 18 bins in the angular region restricted by \( |\cos\theta| < 0.95 \). This figure illustrates the 90\% C.L. allowed regions for \( M_V = 600 \text{ GeV} \) obtained by considering the unpolarized \( WW \) differential cross-section (dotted line), the \( W_L W_L \) cross section (dashed line), and the combination of the left-right asymmetry with all the differential cross-sections for the different final \( W \) polarizations (solid line). We see that already at the level of the unpolarized cross-section we get important restrictions with respect to LEP1.

**Fig. 3 -** 90\% C.L. contours in the plane \((b, g/g'')\) for \( \sqrt{s} = 500 \text{ GeV} \) and \( M_V = \)
600 GeV from the unpolarized WW differential cross section (dotted line), from the \( W_L W_L \) differential cross section (dashed line) and from all the differential cross sections for \( W_L W_L, W_T W_L, W_T W_T \) combined with the WW left-right asymmetries (solid line). The allowed regions are the internal ones.

Fixing now \( b = 0 \) we can see in Fig. 4 the restrictions in the plane \((M_V, g/g'')\) for three different choices of the collider energy, assuming an integrated luminosity of 20\( fb^{-1} \).

**Fig. 4** - 90% C.L. contours in the plane \((M_V, g/g'')\) for \( \sqrt{s} = 0.3, 0.5, 1 \) TeV, \( L = 20 \) \( fb^{-1} \) and \( b = 0 \). The solid line corresponds to the bound from the unpolarized WW differential cross section, the dashed line to the bound from all the polarized differential cross sections \( W_L W_L, W_T W_L, W_T W_T \) combined with the WW left-right asymmetries. The lines give the upper bounds on \( g/g'' \).

In Fig. 5 the upper bounds on \( g/g'' \) for \( M_V = 1.5 \) TeV and \( b = 0 \) are shown as a function of the center of mass energy of the \( e^+e^- \) collider in the case no deviation from the SM is found. The relevance of final W polarization reconstruction over the unpolarized cross section (solid line) is apparent in the whole energy range considered.

A higher luminosity option is shown for the case \( \sqrt{s} = 1 \) TeV and \( L = 80 \) \( fb^{-1} \) (black dots).

**Fig. 5** - 90% C.L. contours in the plane \((\sqrt{s}, g/g'')\) for \( M_V = 1.5 \) TeV, \( b = 0 \) and \( L = 20 \) \( fb^{-1} \). The lines correspond to the unpolarized WW differential cross section (solid line), the \( W_L W_L \) differential cross section (dashed line), and all the differential cross sections for \( W_L W_L, W_T W_L, W_T W_T \) combined with the WW left-right asymmetries (dotted line) and from all the WW and fermionic observables with \( \bar{P}_e = 0.5 \) (dash-dotted line) and represent the upper bounds on \( g/g'' \). The black dots are the bounds for the unpolarized WW differential cross section and from all the WW and fermionic observables at \( \sqrt{s} = 1 \) TeV and \( L = 80 \) \( fb^{-1} \).

### 4. FUSION PROCESSES

\( W^+W^- \) pairs can also be produced through the fusion of a pair of ordinary gauge bosons, each of them emitted from an electron or a positron. In the effective-W approximation the initial \( W, Z, \gamma \) are assumed to be real particles and the cross section for producing a \( W^+W^- \) pair is obtained by means of a convolution of the fusion subprocess with the luminosities of the initial \( W, Z, \gamma \) inside electrons and positrons. There are two fusion subprocesses which contribute to produce \( W^+W^- \) pairs. The first one is \( e^+e^- \rightarrow W^+_L W^+_L, e^+e^- \). It is mediated by \( W^\pm \) and \( V^\pm \) exchanges in the \( t \) and \( u \) channels. The second fusion subprocess we consider is \( e^+e^- \rightarrow W^+_L W^+_L, e^- \). It is mediated by \( \gamma, Z \) and \( V^0 \) exchanges in the \( s \) and \( t \) channels. We have included in the computation contributions both from the gauge boson trilinear and quadrilinear couplings.
The fusion processes may be relevant because they allow to study a wide range of masses for the V resonance from one given $e^+e^-$ c.m. energy. In the $e^+e^-$ center-of-mass frame the invariant mass distribution $d\sigma/dM_{WW}$ is

$$
\frac{d\sigma}{dM_{WW}} = \frac{1}{4\pi s M_{WW}^2} \sum_{i,j} \sum_{l_1,l_2} \int_{(p_T^2)_{min}}^{M_{WW}^2/4} dp_T^2 \int_{-\log\sqrt{\tau}}^{-\log\sqrt{\tau}} dy \ f_{i1} (\sqrt{\tau} e^y) f_{j2} (\sqrt{\tau} e^{-y})
$$

where $p_T$ is the transverse momentum of the outgoing $W$, $\tau = M_{WW}^2/s$, $p$ and $p'$ are the absolute values of the three momenta for incoming and outgoing pairs of vector bosons: $p = (E_1^2 - M_1^2)^{1/2} = (E_2^2 - M_2^2)^{1/2}$ and $p' = (\sqrt{M_{WW}/2})(1 - 4M_1^2/M_{WW}^2)^{1/2}$ where $E_i$ the fraction of the electron (or positron) energy carried by the vector boson $V_i$ with mass $M_i$ and helicity $l_i$. The structure functions $f$ appearing in formula (4.1) are given by:

$$
f^+(x) = \frac{\alpha_{em}}{4\pi} \frac{[(v/a)^2 + (1-x)^2(v-a)^2]}{x} \log \frac{s}{M^2}
$$

$$
f^-(x) = \frac{\alpha_{em}}{4\pi} \frac{[(v-a)^2 + (1-x)^2(v+a)^2]}{x} \log \frac{s}{M^2}
$$

$$
f^0(x) = \frac{\alpha_{em}}{\pi} (v^2 + a^2) \frac{1-x}{x}
$$

and represent the probability of finding inside the electron a vector boson of mass $M$ with fraction $x$ of the electron energy. In eq. (4.2) $v$ and $a$ are the vector and axial-vector couplings of the gauge bosons to fermions. For the detailed formulas for amplitudes and couplings see [5]. We do not find significant differences between the SM and the BESS model differential cross section in the case of the process $e^+e^- \rightarrow W^+W^-e^+e^-$. This is due, on one hand, to the absence of the $s$ channel exchange of the $V$ resonance and on the other hand, to the dominance of the $\gamma\gamma$ fusion contribution, and to the the fact that in BESS the couplings of the photon to the fermions and to $W^+W^-$ are the same as those of the SM.

Let us now consider the process $e^+e^- \rightarrow W^+W^-\nu\bar{\nu}$. We have computed the differential cross sections $d\sigma/dM_{WW}$ both for the SM with $M_H = 100 \text{ GeV}$ and for the BESS model. The only interesting channel is the one corresponding to longitudinally polarized final $W$'s. The results are illustrated in Fig. 6 where we compare $d\sigma/M_{WW}(LL)$ for the SM (dashed line) and for the BESS model (solid line) for $\sqrt{s} = 1.5 \text{ TeV}$, $b = 0.01$, $g'' = 13$ and $M_V = 1 \text{ TeV}$. We apply only a cut for $(p_T)_{min} = 10 \text{ GeV}$.

**Fig. 6** - Longitudinally polarized differential cross-section $d\sigma/dM_{WW}(e^+e^- \rightarrow W_L^+W_L^-\nu\bar{\nu})$
(in fb/GeV) versus $M_{WW}$ for the SM (dash line) and BESS model (solid line) corresponding to $\sqrt{s} = 1500$ GeV, $M_V = 1000$ GeV, $b = 0.01$, and $g'' = 13$.

Integrating the differential cross section for $500 < M_{WW}(GeV) < 1500$ and even considering a high integrated luminosity of $80 fb^{-1}$ we obtain 127 $W_L$ pairs for the SM and 158 for the BESS model (with $M_V = 1 TeV$, $g'' = 13$ and $b = 0.01$) corresponding to a statistical significance of only 2.75. This result is quite discouraging as we have still not included the branching ratio. The situation does not improve significantly even when considering a wider resonance, varying the BESS parameters, or considering $\sqrt{s} = 2 TeV$ in the region allowed by the present bounds (see Fig. 1).

The fusion process in the charged channel $e^+e^- \rightarrow W_{L,T}^+Z_{L,T}e^-$ is even less encouraging. In this case in fact, the SM cross section is bigger, being dominated by the $\gamma W \rightarrow WZ$ fusion process, while the BESS effect $WZ \rightarrow V \rightarrow WZ$ is of the same order of magnitude and we expect a worse signal to background ratio.
5. CONCLUSIONS

The result of our study is that the annihilation channels are by far the most important ones in order to distinguish between the SM and the strong electroweak sector as described through the BESS model at $e^+e^-$ colliders for the considered energy range. In particular the process of $W$-pair production by $e^+e^-$ annihilation allows for sensitive tests of the strong sector, especially if the $W$ polarizations are reconstructed. Fusion processes may become more relevant at higher energies or luminosities, but are still of minor interest at the energies and luminosities considered in this work.

The study performed for the case of an $e^+e^-$ accelerator is complementary to those performed for $pp$ colliders. In fact proton colliders offer the possibility of studying the $V^\pm$ resonances through the $W^\pm Z$ decay [9], while the $V^0 \rightarrow W^+W^-$ channel is difficult to study due to background problems. On the contrary $e^+e^-$ colliders give the possibility of detecting new neutral vector bosons. This can be relevant in order to distinguish among BESS and other models.

Even in the case of a mass of the $V^0$ resonance higher than the c.m. energy of the collider, the process of $W$ pair production will allow to restrict the parameter space of BESS, especially if the $W$ polarizations can be reconstructed.

Already at $\sqrt{s} = 500 \text{ GeV}$ and integrated luminosity $L = 20 \text{ fb}^{-1}$, if no deviation from the SM prediction is found, the BESS model parameters $g''$ and $b$ can be severely restricted. If higher energy colliders are available ($\sqrt{s} = 1, 2 \text{ TeV}$ and $L = 20, 80 \text{ fb}^{-1}$), it is possible to get an upper bound on $g/g''$ of the order of 0.02 at $b = 0$, for any given value of $M_V$.

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$g/g''$

$M_V$ (GeV)

$s^{1/2}$ (TeV) = 0.3

$s^{1/2}$ (TeV) = 0.5

$s^{1/2}$ (TeV) = 1.0
\frac{d\sigma}{d M_{WW}} (LL) (fb/GeV)