LIMITS ON THE BESS MODEL AT NLC *

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1. The BESS model and the present bounds on its parameters

This contribution to the workshop contains an update of our previous work\cite{1,2} concerning the sensitivity of future $e^+e^-$ linear colliders to a strongly interacting electroweak sector. We have examined the occurrence of new effects at proposed colliders, ranging from an energy of 300 GeV to 2 TeV and of different luminosity options.

Our calculations are performed within a strongly interacting electroweak symmetry breaking model, named BESS\cite{3}. The model is an effective lagrangian parameterization of the symmetry breaking mechanism, based on a symmetry $SU(2)_L \times SU(2)_R / SU(2)_{L+R}$. New vector bosons are present and we expect new effects due to their mixing with the electroweak gauge bosons and their fermion couplings.

The parameters of the BESS model are the mass of these new bosons $M_V$, their self coupling $g''$ and a third parameter $b$ whose strength characterizes the direct couplings of the new vectors $V$ to the fermions. However due to the mixing of the $V$ bosons with $W$ and $Z$, the new particles are coupled to the fermions also when $b = 0$. The parameter $g''$ is expected to be large due to the fact that these new gauge bosons are thought as bound states from a strongly interacting electroweak sector. By taking the formal $b \to 0$ and $g'' \to \infty$ limit, the new bosons decouple and the standard model (SM) is recovered. Whereas by considering only the limit $M_V \to \infty$ they do not decouple.

* Invited talk at the “Workshop on Physics and Experiments at Linear $e^+e^-$ Colliders”, Waikoloa, Hawaii, April 26-30, 1993 (presented by D. Dominici)
In our study we have considered the sensitivity of processes involving different final states from $e^+e^-$ to the new physics predicted by the BESS model.

Future $e^+e^-$ colliders can be very useful in studying detailed properties of the vector particles predicted by the BESS model or by extra $Z'$ models, particularly after their possible discovery at future $pp$ colliders like LHC or SSC. If the energy of the collider is very close to the mass of the resonances, then they can be copiously produced and studied. Also note that, in such linear colliders, beamstrahlung will automatically provide for a spectrum of lower initial energies.

In our analysis we consider mainly indirect effects of the new particles to different observables, supposing $M_V > \sqrt{s}$. We have considered $e^+e^-$ annihilation into fermion antifermion and two gauge bosons. In this processes the main effect is the presence of the new neutral vector exchange in the $s$ channel. We have also considered the fusion channel where two gauge bosons and two leptons appear in the final state. In this process both charged and neutral vector bosons can be produced in the $s$ channel fusion.

These seem to be the most promising channels, especially the annihilation, where all the initial state energy is converted in the energy of the final state. The $WW$ annihilation channel is particularly relevant, especially if the $W$ polarization can be reconstructed, because $V$ particles are strongly coupled to longitudinally polarized $W$’s. The $W_LW_L$ channel severely constrains the parameter space of the model, already for a 500 GeV collider. The bounds improve by increasing the energy, because the deviations due to BESS increase with the energy.

The fermion channel is relevant only for energies in the range $300 - 500$ GeV and by using longitudinally polarized electron beams.

The fusion channel can be interesting for higher energies $1.5 - 2$ TeV, however an extremely high luminosity is needed.

We have not considered the $\gamma\gamma$ and the $e\gamma$ options, because the new gauge bosons are exchanged in the $t$ channel and the couplings of the $W$ to a photon as well as the fourlinear $WW\gamma\gamma$ couplings are the same as in the SM.

Finally, we have not taken into account beamstrahlung effects. However for two body final states, which are the most successful channels in our analysis, 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.

Using the following LEP data averaged on the four LEP experiments and the
CDF/UA2 measurement of the mass ratio $M_W/M_Z$ $^4$

$$M_Z = 91.187 \pm 0.007 \text{ GeV}$$
$$\Gamma_Z = 2488 \pm 7 \text{ MeV}$$

$$\Gamma_h = 1740 \pm 6 \text{ MeV}$$
$$\Gamma_\ell = 83.52 \pm 0.28 \text{ MeV}$$
$$A_{FB}^t = 0.0164 \pm 0.0021$$
$$A_{\tau}^{pol} = 0.142 \pm 0.017$$
$$A_{FB}^b = 0.098 \pm 0.009$$
$$\frac{M_W}{M_Z} = 0.8798 \pm 0.0028$$

we can derive 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 predictions of these observables for BESS are evaluated by including the same one-loop electroweak radiative corrections of the SM calculated with $M_H$ interpreted as a cut-off $\Lambda$. The bounds depend mainly on the still large range allowed for the SM parameters $m_{top}$ and $\alpha_s$. For this reason in Fig. 1 we show the total allowed region for $m_{top}$ and $\alpha_s$ within the indicated ranges.

**Fig. 1 - 90% C.L. contour in the plane $(b, g/g'')$ for $M_V = 600 \text{ GeV}$, from LEP and CDF/UA2 data $(130 \leq m_{top}(\text{GeV}) \leq 180, 0.11 \leq \alpha_s \leq 0.13, \text{ and } \Lambda = 1 \text{ TeV}$).**

The bounds become stronger for increasing $\alpha_s$ and $m_{top}$, while they are almost independent of the mass of the new resonances $V$ and of the choice of the cut-off.

LEP 200 is expected to increase only marginally the sensitivity over LEP. The relevant modification will be brought by the more accurate determination of $M_W$. 
2. Annihilation channels

Our analysis, in the fermion channels, is based on the following observables: the total hadronic and muonic cross sections, their ratio, the forward-backward asymmetries in muons and $\bar{b}b$ and, assuming a longitudinal polarization $P_e$ of the electron beam, the left-right asymmetries in muons, $\bar{b}b$ and hadrons

$$
\begin{align*}
\sigma^\mu, \sigma^h, \quad R = \sigma^h/\sigma^\mu \\
A_{FB}^{e^+e^-\rightarrow\mu^+\mu^-}, \quad A_{FB}^{e^+e^-\rightarrow\bar{b}b} \\
A_{LR}^{e^+e^-\rightarrow\mu^+\mu^-}, \quad A_{LR}^{e^+e^-\rightarrow\bar{b}b}, \quad A_{LR}^{e^+e^-\rightarrow\text{had}}
\end{align*}
$$

(2.1)

We assume a systematic error in luminosity $\delta \mathcal{L}/\mathcal{L} = 1\%$ and $\delta \epsilon_{\text{had}/\epsilon_{\text{had}}} = 1\%$ (which is perhaps an optimistic choice due to the problems connected with the $b$-jet reconstruction), $\delta \epsilon_{\mu}/\epsilon_{\mu} = 0.5\%$, where $\epsilon$ denote the selection efficiencies.

Concerning the $WW$ channel, we study the following observables:

$$
\frac{d\sigma}{d\cos\theta}(e^+e^-\rightarrow W^+W^-), \quad A_{LR}^{e^+e^-\rightarrow W^+W^-}
$$

(2.2)

where $\theta$ is the center of mass scattering angle. We have also considered the possibility to measure the final $W$ polarization by using the $W$ decay distributions, and we have added to our observables the longitudinal and transverse polarized $W$ differential cross sections and asymmetries.

In order to get a clear signal to reconstruct the polarization of the $W$’s we study the channel for one $W$ decaying leptonically and the other hadronically. We have assumed an effective branching ratio $B = 0.1$ to take into account the loss of luminosity from beamstrahlung.$^5$

The analysis has been performed by taking 19 bins in the angular region restricted by $|\cos\theta| < 0.95$ and assuming systematic errors $\delta B/B = 0.005$.$^{1,2}$ and $1\%$ for the acceptance.

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 considered observables from the SM predictions are within the experimental errors. Here we assume $\sqrt{s} = 300 \text{ GeV}$ with an integrated luminosity of $L = 20 \text{ fb}^{-1}$ and $M_V = 600 \text{ GeV}$ (all the following results are obtained for $m_{\text{top}} = 150 \text{ GeV}$ and $\Lambda = 1 \text{ TeV}$).

By comparing with the present bounds given in Fig. 1 we see that the combination of all the observables provides for an efficient test at a collider with $\sqrt{s} = 300 \text{ GeV}$.
Fig. 2 - 90% C.L. contours in the plane \((b,g/g'')\) for \(\sqrt{s} = 300 \text{ GeV}\) and \(M_V = 600 \text{ GeV}\) from the unpolarized \(WW\) differential cross section (solid line), from the \(WLWL\) differential cross section (dashed line), from all the differential cross sections for \(WLWL\), \(WTWL\), \(WTWT\) combined with the \(WW\) left-right asymmetries (dotted line) and from all the \(WW\) and fermion observables with \(P_e = 0.5\) (dash-dotted line). The allowed regions are the internal ones.

Fig. 3 - 90% C.L. contours in the plane \((M_V,g/g'')\) for \(\sqrt{s} = 0.3, 0.5, 1 \text{ TeV}\), \(L = 20 \text{ fb}^{-1}\) 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 \(WLWL\), \(WTWL\), \(WTWT\) combined with the \(WW\) left-right asymmetries. The lines give 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 fermion observables by considering \(\sqrt{s} = 1 \text{ TeV}\) and \(L = 80 \text{ fb}^{-1}\).

By increasing the energy of the collider, the allowed region of Fig. 2 shrinks\(^2\) and the fermions observables become irrelevant. This can be seen in Figs. 3, 4. It is due to the fact that in BESS the vector resonances are strongly coupled to the longitudinal vector bosons and this interaction destroys the cancellation among the \(\gamma-Z\) exchange and the neutrino contribution occurring in the SM. From these figures it also appears the relevance of final \(W\)'s polarization reconstruction.

3. Fusion subprocesses

The fusion subprocesses are interesting as they allow for study of a wide range of mass for the \(V\) resonance for a given \(e^+e^-\) c.m. energy.

We have studied the production of \(W^+W^-\) pairs by the fusion mechanism of a pair of ordinary gauge bosons, each being initially emitted from an electron or a positron. In the so called effective-\(W\) approximation the initial \(W, Z, \gamma\) are assumed to be real and the cross section for producing a \(W^+W^-\) pair is obtained by a convolution of the fusion subprocess with the luminosities of the initial \(W, Z, \gamma\) inside the electrons and positrons.

We expect big deviations in the invariant mass differential cross section \(d\sigma/dM_{WW}\) in all the processes mediated by the exchange of the \(V\) resonance in the \(s\) channel. However since the \(V\) bosons are strongly coupled to longitudinal \(W\)'s, unless one imposes suitable cuts in the \(\cos \theta_W\) variable for the unpolarized differential cross section\(^6\), the deviations will be clearly visible only in the final \(WLWL\) channel.
To see the order of magnitude of the effect, we have considered the process $e^+e^- \rightarrow W^+_L W^-_L \bar{\nu}\nu$, even if it is perhaps unlikely that the experiments will allow to reconstruct such a distribution. We have only applied a minor cut in the transverse momentum of the outgoing $W$'s: $p_T \geq 10$ GeV.

The results for two options of $\sqrt{s}$ and $M_V$ are shown in Table 1. The number of events are compared with the corresponding SM predictions, obtained with $M_H = 100$ GeV. No branching ratio and selection efficiency has been applied to these numbers.

| $\sqrt{s}$ (TeV) | $M_V$ (TeV) | $(M_{WW})_{\text{win.}}$ (TeV) | # evts. | # evts. | $S/\sqrt{B}$ |
|----------------|------------|-------------------------------|--------|--------|-------------|
| 1.5            | 1          | 0.9 - 1.1                     | 7.7    | 30.1   | 11.5        |
| 2              | 1.5        | 1.3 - 1.6                     | 4.6    | 15.3   | 5.0         |

Table 1 - Fusion process $e^+e^- \rightarrow W^+_L W^-_L \bar{\nu}\nu$ for $L = 80$ fb$^{-1}$ and $\sqrt{s}$ = 1.5, 2 TeV. $\Gamma_V$ is the width of the $V$ resonance; in the third column we give the window for the integration of $d\sigma(LL)/dM_{WW}$ on $dM_{WW}$. The last column shows the statistical significance.

The two cases quoted in Table 1, corresponds to $g/g'' = 0.08$, $b = 0.02$ (the first one) and $g/g'' = 0.05$, $b = 0.01$ (the second one).

The statistical significance looks good, but we must notice that it gets reduced when including the branching ratio and selection efficiency for the final $W$’s (which is $\simeq 0.25$ for the decay in two jets). Therefore an even larger luminosity is in general necessary to investigate the fusion channel.

Our conclusion is that, to test the SM against a possible electroweak strong sector, as described here through the BESS model, at these colliders, the annihilation channels are by far the most important.

Even if the mass of the $V$ resonance is bigger than the c.m. energy of the collider, the process of $W$ pair production will allow for strong restrictions on the parameter space of the BESS model, especially so if the $W$ polarizations can be reconstructed from their decay distributions.

If no deviation from the SM prediction is found, already at $\sqrt{s} = 500$ GeV and integrated luminosity $L = 20$ fb$^{-1}$, the BESS model parameters $g''$ and $b$ can be severely restricted and we find significant improvement with respect to LEP. With higher energy colliders the parameter space contracts and at $b = 0$ we get an upper bound on $g/g''$ which for $M_V > \sqrt{s}$ is almost independent on $M_V$. 
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$s^{1/2}$(TeV) = 0.3

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

$s^{1/2}$(TeV) = 1.0
$g/g''$

$s^{1/2}$(GeV)