SOME RESULTS ON THE BESS MODEL AT FUTURE COLLIDERS*

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1 Introduction

We present some results on the usefulness of upgraded Tevatron, LHC proton proton collider and linear $e^+e^-$ colliders in the TeV range to test the idea of a strongly interacting sector as responsible for the electroweak symmetry breaking.

The calculations are performed within an effective lagrangian description, called the BESS model, which provides for a rather general frame based on the standing point of custodial symmetry and gauge invariance, without specifying any dynamical scheme.

We are interested in studying a spontaneous symmetry breaking avoiding physical scalar particles, i.e. in a non linear rather than in a linear way. An effective lagrangian describing in an unified way mass terms and interactions of the standard electroweak gauge bosons has been derived \[1\] as a gauged non linear $\sigma$-model.

Using extensively the fact that any non linear $\sigma$-model is gauge equivalent to theories with additional hidden local symmetry \[2\], we can build up new vector resonances, similar to ordinary $\rho$ vector mesons or to the techni-$\rho$ particle of technicolor theories, as the gauge bosons associated to the hidden symmetry group of $SU(2)$ type. Under the assumption they are dynamical, we will get the $SU(2)$ BESS lagrangian \[1\] (BESS standing for Breaking Electroweak Symmetry Strongly).

Therefore the minimal BESS model is described by a Yang Mills lagrangian whose gauge group is $SU(2)_L \otimes U(1)_Y \otimes SU(2)_V$

\[
\mathcal{L}_{\text{BESS}} = -\frac{v^2}{4} \left[ \text{Tr}(W - B)^2 + \alpha \text{Tr}(W + B - V)^2 \right] + \frac{1}{2g^2} \text{Tr} \left( F_{\mu\nu}(W) F^{\mu\nu}(W) \right) + \frac{1}{2g'^2} \text{Tr} \left( B_{\mu\nu} B^{\mu\nu} \right) + \frac{2}{g'^2} \text{Tr} \left( F_{\mu\nu}(V) F^{\mu\nu}(V) \right) \tag{1.1}
\]

with $F_{\mu\nu}(V) = \partial_\mu V_\nu - \partial_\nu V_\mu + [V_\mu, V_\nu]$ where $V_\mu = ig''_a \tau^a V^a_\mu, \ (a = 1, 2, 3)$, $\alpha$ is an arbitrary parameter and $g''$ the new gauge coupling constant. The first term within brackets is the usual mass term appearing in the Standard Model (hereafter denoted as SM).

The theory is invariant under $U(1)$ electromagnetic and $SU(2)$ custodial symmetry. The additional parameters it contains are the mass $M_V$ (which depends on $\alpha$) of the new bosons forming a degenerate triplet and their gauge coupling constant $g''$.

The new particles are naturally coupled to fermions through mixing between $\hat{W}$ and $\hat{V}$, although a direct coupling, specified by a new parameter $b$, is possible. The SM is recovered in the limit $g'' \to \infty$ and $b = 0$. Mixings of the ordinary gauge bosons to the $V$’s are of the order of $O(g/g'')$. Due to these mixings, $V$ bosons are coupled to fermions even for $b = 0$. Furthermore these couplings are still present in the limit $M_V \to \infty$, and therefore the new gauge bosons effects do not decouple in the large mass limit.

In the vector dominance approximation the BESS model corresponds to a technicolor model \[3\] with a single technidoublet. If a non zero direct coupling of $V$ to fermions exists it corresponds to an extended technicolor. The model can also incorporate axial vector
resonances by enlarging the additional gauge group from $SU(2)_V$ to $SU(2)_L \otimes SU(2)_R$ local.

In what follows we will restrict ourselves to new vector bosons. Their existence will indirectly manifest at LEP through deviations from SM expectations \[4\]. For this purpose a low energy effective theory valid for heavy resonances recently derived \[5\] is useful.

## 2 Present limitations

The analysis of LEP data, concerning the total width, the hadronic and the leptonic width, the leptonic and bottom forward-backward asymmetries, the $\tau$-polarization together with the cesium atomic parity violation and the ratio $M_W/M_Z$, uses available full one loop radiative correction programs. We assume for the BESS model the same one-loop radiative corrections as for the SM in which the Higgs mass is used as a cut-off $\Lambda$, this brings in a dependence on $\alpha_s$, $m_{\text{top}}$ and $\Lambda$. We will rewrite the observable quantities in terms of the parameters $\varepsilon_i$ \[6\].

The BESS contribution reads:

\[
\varepsilon_1 = \varepsilon_2 = 0 \\
\varepsilon_3 = \left(\frac{g}{g''}\right)^2 - \frac{b}{2} \quad (2.1)
\]

This shows explicitly that through LEP data we are only sensitive to one combination of BESS parameters i.e. $\varepsilon_3$. The allowed region at 90% CL in the $(b, g/g'')$ plane is shown in Fig. 1 for a top mass value of $174 \pm 17$ GeV and in the limit $M_V >> M_W$. The chosen experimental value \[7\]

\[
\varepsilon_3^{\text{exp}} = (3.9 \pm 1.7) \times 10^{-3} \quad (2.2)
\]

corresponds to the latest LEP1 data combined with UA2/CDF/D0 ones presented at the Glasgow conference, and we have added to (2.1) the contribution coming from the radiative corrections \[8\] for $M_H = \Lambda = 1$ TeV and $m_{\text{top}} = 174 \pm 17$ GeV, which is

\[
\varepsilon_3^{\text{rad. corr.}} = (6.39^{+0.14}_{-0.20}) \times 10^{-3}.
\]

We further observe that, within the BESS model, we can explain the two standard deviations from SM expectation for the $Z$ partial width in $b\bar{b}$ by assuming a sizeable non zero direct coupling $b'$ only for the heaviest generation (as expected from one loop BESS radiative corrections proportional to $m_f$). After adding the SM expectation for $m_{\text{top}} = 170$ GeV to the BESS model contribution $\varepsilon_b = -b'/2$, we get at 90% CL

\[
-2.7 \times 10^{-2} \leq b' \leq 0.32 \times 10^{-3} \quad (2.3)
\]

from $\varepsilon_b^{\text{exp}} = (0.2 \pm 4.0) \times 10^{-3}$. 

\[2\]
Fig. 1 - 90% C.L. contour in the plane $(b,g/g'')$ from the measurement of $\varepsilon_3$. The solid (dashed) line is for $m_{\text{top}}(\text{GeV}) = 191(157)$, $\Lambda = 1\text{ TeV}$ and $\alpha_s = 0.118$.

3 BESS at LHC

At hadron colliders, as far as detection of a signal from a strongly interacting symmetry breaking sector is concerned, vector boson pair production is particularly relevant. In the BESS model there are two main processes which compete for the production of a pair of ordinary gauge bosons at a $pp$ collider: $q\bar{q}$ annihilation and ordinary gauge boson fusion. In the first mechanism a quark-antiquark pair annihilates into a $V$ vector boson, which then decays into a pair of ordinary gauge vector bosons. We stress the fact that this process is always operating in BESS independently of the existence of a direct coupling of $V$ to fermions, because of the mixing.

We further observe that for masses of $V$ in the $\text{TeV}$ range, the $V$ decay is dominated by the $WW$ and $WZ$ channels due to the large coupling of the $V$ to the longitudinal components of the standard gauge bosons. For this reason, in the computation of the width $\Gamma_V$ we have ignored the contribution from the fermionic channels since it turns out to be completely negligible.

The second mechanism to produce $W/Z$ pairs is the rescattering of a pair of ordinary gauge bosons, each being initially emitted from a quark or antiquark leg. In BESS the rescattering process is naturally strong. In fact the scattering of two longitudinally polarized $W/Z$'s proceeds via the exchange of a $V$ vector boson with large couplings at each vertex. This process has been evaluated by using the effective-$W$ approximation for the initial $W/Z$ and using the equivalence theorem for the rescattering amplitudes.

It turns out that the $pp \rightarrow W^\pm Z + X$ reaction is the most interesting one in the framework of the BESS model. The process $pp \rightarrow W^+W^- + X$ is expected to suffer from a very severe background coming from $pp \rightarrow t\bar{t} + X$, with $t$ and $\bar{t}$ both decaying into $W$. Final leptonic configurations from $t\bar{t}$ production might also simulate configurations from $W^\pm Z$, but the $Z$ mass reconstruction and lepton isolation requirements should protect
from such a background [8]. The ZZ mode has not been considered because it does not proceed via an s-channel contribution in BESS.

The relevant backgrounds are the standard model production of $W^\pm Z$ through quark-antiquark annihilation, $\gamma W^\pm$ fusion and $W^\pm T^Z$ fusion.

In our calculation we have made use of the DFLM structure functions, for $\Lambda_{QCD} = 260 \text{ MeV}$. For the case of the fusion process as for $q\bar{q}$ annihilation we have taken an evolution scale for the structure functions equal to the square of the invariant mass of the produced gauge boson pair.

We assume LHC running at 14 TeV with a luminosity of $10^{34} \text{ cm}^{-2} \text{ sec}^{-1}$.

Concerning the cuts, a first one on the rapidity $y_{W,Z}$ of the final $W$ and $Z$, $|y_{W,Z}| \leq 2.5$ was imposed to all cases. Then we applied a lower cut in $M_{WZ}$ (the invariant mass of the $WZ$-pair), approximately corresponding to the beginning of the resonance at the left of the peak. An upper cut has been fixed once for all at $M_{WZ} = 3 \text{ TeV}$, where the resonance tail is already extinguished. Finally a cut in $p_T$ (the transverse momentum of the $Z$) has been obtained from the requirement of maximizing the statistical significance of the signal, $S/\left(S + B\right)^{1/2}$, $S$ being the signal and $B$ the background.

The calculated event rates are largely observable at the projected LHC energy and luminosity, for reasonable ranges of the BESS parameters. Detailed studies of background and statistical significance of signals versus background can be found in [9] where the $pp$ center of mass energy was assumed to be 16 TeV. The rate of the events decreases by roughly 20% if we consider the presently planned energy of 14 TeV [10].

As it is clear from the tables in ref. [9], the $q\bar{q}$ mechanism is found to be in general dominant at LHC with respect to the fusion mechanism.

![Fig. 2 - Invariant mass distribution of the $W^\pm Z$ pairs produced per year at LHC for $M_V = 1000 \text{ GeV}$, $g'' = 22$ and $b = 0$. The applied cuts are $(p_T)_Z > 360 \text{ GeV}$ and $M_{WZ} > 900 \text{ GeV}$. The lower, intermediate and higher histograms refer the background (3137 events), background plus fusion signal (3536 events) and background plus fusion signal plus $q\bar{q}$ annihilation signal (6294 events).](image)

Fig. 2 and Fig. 3 give the predictions for invariant $WZ$ mass and $p_T$ of the $Z$ distributions for $M_V = 1000 \text{ GeV}$, $g'' = 22$ and $b = 0$ to which corresponds a width $\Gamma_V = 4 \text{ GeV}$. 

4
Fig. 3 - $(p_T)_Z$ distribution of the $W^\pm Z$ pairs produced per year at LHC for $M_V = 1000 \text{ GeV}$, $g'' = 22$ and $b = 0$. The applied cuts and the number of events are the same as in Fig. 2.

Fig. 4 and Fig. 5 give the predictions for invariant $WZ$ mass and $p_T$ of the $Z$ distributions for $M_V = 1500 \text{ GeV}$, $g'' = 20$ and $b = 0.016$ to which corresponds a width $\Gamma_V = 35 \text{ GeV}$.

The vertical lines in the graphs indicate where the lower cuts in $M_{WZ}$ and $p_T$ have been put for the illustrated cases. The invariant mass distributions show a peak around the mass of the $V$, and the $p_T$ distribution is characterized by a jacobian peak, the broadness being directly related to the $V$ width.

Fig. 4 - Invariant mass distribution of the $W^\pm Z$ pairs produced per year at LHC for $M_V = 1500 \text{ GeV}$, $g'' = 20$ and $b = 0.016$. The applied cuts are $(p_T)_Z > 360 \text{ GeV}$ and $M_{WZ} > 1300 \text{ GeV}$. The lower, intermediate and higher histograms refer the background (1234 events), background plus fusion signal (1500 events) and background plus fusion signal plus $q\bar{q}$ annihilation signal (27210 events).
For both bosons decaying leptonically, which is the gold-plated signal, one has to multiply by the branching factor $B(Z \rightarrow \ell^+\ell^-) \cdot B(W^\pm \rightarrow \ell^\pm \bar{\nu}_\ell) \approx 1.5\%$, for ($\ell = e, \mu$). The figures show that, even after multiplying by the branching factor corresponding to selecting only leptonic decays of $W$ and $Z$, one is left with a statistically significant signal having quite well distinguished features both in $M_{WZ}$ and $(p_T)_Z$ distributions.

The sensitivity increases if $WZ$ reconstruction can be done using the $l\nu, jj$ final state [11]. We can infer that a mass discovery limit for charged vector resonances around 2 TeV can be achieved at LHC for a large domain of the BESS parameter space. Nevertheless there are still some parameter values which lead, even for light $M_V$ masses, to too small number of events to be discovered.

![Fig. 5](image)

**Fig. 5** - $(p_T)_Z$ distribution of the $W^\pm Z$ pairs produced per year at LHC for $M_V = 1500$ GeV, $g'' = 20$ and $b = 0.016$. The applied cuts and the number of events are the same as in Fig. 4.

## 4 Tevatron upgrade

We have also considered the detection of a signal from strong electroweak sector at a possible upgrade of the Fermilab Tevatron. The option, we have chosen, is the one with the doubling of the c.m. energy of the collider to 4 TeV with an integrated luminosity of 10 $fb^{-1}$. In this case we do not consider the second mechanism of production (the fusion), because its contribution, due to the lower energy of the collider with respect to LHC, is negligible.

We have studied some examples with different choices of $M_V$, $b$ and $g''$ to give an estimate of the sensitivity of this option for the upgrading of the Tevatron.

Fig. 6 and Fig. 7 give the predictions for invariant $W^+Z$ mass and $p_T$ of the $Z$ distributions for $M_V = 600$ GeV, $g'' = 13$ and $b = 0.01$ to which corresponds a width $\Gamma_V = 0.9$ GeV.
The signal is doubled by adding the $W^{-}Z$ channel final state. Even after multiplying by the appropriate branching ratio one is left with a statistical significant signal.

As shown by Fig. 8 and Fig. 9, results are depending significantly on the values of BESS parameters $b$ and $g''$. For the same $V$ mass the case corresponding to the choice $g'' = 20$ and $b = 0.016$ leads to roughly five times more events. Increasing the mass to $800 \text{ GeV}$ reduces the signal by roughly a factor of five. In a definite region of the parameters $(b, g/g'')$, the discovery limit of the Tevatron Upgrade can reach masses $M_V \sim 1 \text{ TeV}$. 
Fig. 8 - Invariant mass distribution of the $W^+Z$ pairs produced per year at Tevatron Upgrade for $M_V = 600$ GeV, $g'' = 20$ and $b = 0.016$. The applied cuts are $(p_T)_Z > 120$ GeV and $M_{WZ} > 500$ GeV. The lower, higher histograms refer the background (606 events), background plus $q\bar{q}$ annihilation signal (4142 events).

Fig. 9 - $(p_T)_Z$ distribution of the $W^+Z$ pairs produced per year at Tevatron for $M_V = 600$ GeV, $g'' = 20$ and $b = 0.016$. The applied cuts and the number of events are the same as in Fig. 8.

5 $e^+e^-$ colliders

Future $e^+e^-$ colliders are sensitive to the neutral $V^0$ resonance if the mass $M_V$ of the new boson multiplet lies not far from the maximum machine energy, or if it is lower, such a resonant contribution would be quite manifest. The result of our analysis [12] is that also virtual effects are important. It appears that annihilation into a fermion pair in such machines, at the considered luminosities, would marginally improve on existing limits if polarized beams are available and left-right asymmetries are measured. On the other hand, the process of $W$-pair production by $e^+e^-$ annihilation would allow for sensitive tests of the strong sector, especially if the $W$ polarizations are reconstructed from their decay distributions, and the more so the higher the energy of the machine. This is because
BESS modifies the standard couplings in such a way that the typical cancellations present in the SM do not happen anymore and the amplitude is growing with $s$.

If the masses of the $V$ bosons are higher than the maximum c.m. energy, they give rise to indirect effects in the $e^+ e^- \to f^+ f^-$ and $e^+ e^- \to W^+ W^-$ cross sections.

We have analyzed cross-sections and asymmetries for the channel $e^+ e^- \to f^+ f^-$ and $e^+ e^- \to W^+ W^-$. For the purposes of our calculation we have also assumed that it will be possible to separate $e^+ e^- \to W_L^+ W_L^-$, $e^+ e^- \to W_R^+ W_R^-$, and $e^+ e^- \to W_T^+ W_T^-$. The distribution of the $W$ decay angle in its c.m. frame depends indeed in a very distinct way from its helicity, being peaked forward (backward) with respect to the production direction for positive (negative) helicity or at 90° for zero helicity.

We consider the $WW$ channel, for one $W$ decaying leptonically and the other hadronically. To discuss the restrictions on the parameter space for masses of the resonance a little higher than the available energy we have taken into account the experimental efficiency. We have assumed an overall detection efficiency of 10% including account the branching ratio $B = 0.29$ and the loss of luminosity from beamstrahlung.

For a collider at $\sqrt{s} = 500$ GeV with an integrated luminosity of 20 $fb^{-1}$ the results are illustrated in Fig. 10. 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 $M_V = 600$ 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.

For colliders with $\sqrt{s} = 1, 2$ TeV and for $M_V = 1.2$ and 2.5 TeV respectively, the allowed region, combining all the observables, reduces in practice to a line. Therefore, even the unpolarized WW differential cross section measurements can improve the bounds.
6 Conclusions

We have used the BESS model, as a rather general frame based on custodial symmetry and gauge invariance, to examine the possibilities offered by the upgraded Tevatron, by LHC, and by $e^+e^-$ colliders in the $TeV$ range, to test for strong electroweak breaking. We have first presented the existing limits on the BESS parameters from the latest LEP data, atomic parity violation, and from the ratio of $W$ to $Z$ mass. We have then summarized the projections for observables in $WZ$ production at LHC within present BESS limitations, and compared them with the standard model backgrounds, within suitable cuts and detection limits. We have then examined the corresponding observables at the upgraded Tevatron. Finally we have discussed the sensitivity to BESS parameters of $TeV$ $e^+e^-$ colliders for annihilation into fermions or into $W$ pairs, considering cross-sections and asymmetries. Our study shows the interest of these future facilities in relation to a possible strong electroweak breaking.

References

[1] R. Casalbuoni, S. De Curtis, D. Dominici and R. Gatto, Phys. Lett. B155 (1985) 95; and Nucl. Phys. B282 (1987) 235

[2] M. Bando, T. Kugo, S. Uehara, K. Yamawaki and T. Yanagida, Phys. Rev. Lett. 54 (1985) 1215; A.P. Balachandran, A. Stern and G. Trahern, Phys. Rev. D19 (1979) 2416.

[3] For a review see E. Fahri and L. Susskind, Phys. Rep. 74 (1981) 277.

[4] R. Casalbuoni, S. De Curtis, D. Dominici, F. Feruglio and R. Gatto, Phys. Lett. B258 (1991) 161.

[5] L. Anichini, R. Casalbuoni, S. De Curtis, Univ. di Firenze Preprint, DFF-210/10/1994.

[6] G. Altarelli and R. Barbieri, Phys. Lett. B253 (1991) 161; G. Altarelli, R. Barbieri and S. Jadach, Nucl. Phys. B369 (1992) 3; D.C. Kennedy and P. Langacker, Phys. Rev. D44 (1991) 1591.

[7] G. Altarelli, CERN preprint, CERN-TH 7464/94 October 1994.

[8] I. Josa, T. Rodrigo and F. Pauss, CERN 90-10, volume II, p. 796, Proceedings of Large Hadron Collider Workshop, Aachen, 4-9 October 1990, Eds. G. Jarlskog and D. Rein.

[9] R. Casalbuoni, P. Chiappetta, S. De Curtis, F. Feruglio, R. Gatto, B. Mele and J. Terron, Phys. Lett. B249 (1991) 130.

[10] R. Casalbuoni, P. Chiappetta, A. Deandrea, S. De Curtis, D. Dominici and R. Gatto, Zeit. für Phys., C65 (1995) 327.

[11] C.P. Yuan, in Perspectives in Higgs Physics, Ed. G. Kane, World Scientific, 1993.

[12] R. Casalbuoni, P. Chiappetta, A. Deandrea, S. De Curtis, D. Dominici Zeit. für Phys., C60 (1993) 315.