SIGNATURES of DYNAMICAL SYMMETRY BREAKING at TEVATRON UPGRADE and LHC

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We study the phenomenology of a strongly interacting electroweak symmetry breaking sector in which the physics is dominated by spin one resonances. Specifically we will consider an effective description of dynamical symmetry breaking based on a particular model which passes all the low-energy precision tests and gives clear signals at LHC but also at Tevatron Upgrade.

1 Introduction

We present some results on the usefulness of upgraded Tevatron and LHC hadron colliders 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\(^1\) (BESS standing for Breaking Electroweak Symmetry Strongly), 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. An effective lagrangian describing in an unified way mass terms and interactions of the standard electroweak gauge bosons can be derived 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 introduce 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 $SU(2)$ minimal BESS model\(^3\) described by a Yang Mills lagrangian whose gauge group is $SU(2)_L \otimes U(1)_Y \otimes SU(2)_V$. The parameters it contains, besides the standard model (hereafter denoted as SM) ones, are the mass $M_V$ of the new bosons forming a degenerate $SU(2)$ triplet and their gauge coupling constant $g''$. The new particles are naturally coupled to fermions through mixing between $W$, $Y$ and $V$, although a direct coupling, specified by a new parameter $b$, is possible. The SM is recovered in the limit $g'' \rightarrow \infty$ and $b = 0$. Mixings of the ordinary gauge bosons to the $V$'s are $O(g/g'')$. Due to these mixings, the $V$ 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 boson effects do not decouple in the large mass limit.

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. Also in this case the Goldstone bosons associated to the breaking of the gauge group to the $U(1)_{em}$ are absorbed by the vector and the axial-vector bosons and by the standard $W$ and $Z$. In this extension of the model we have two additional parameters: the mass $M_A$ of the axial-vector resonances and $z$ the ratio of the mixings of $V$ and $A$ bosons to the $W$.

The detailed study of the symmetries of the effective theory shows however that in special cases the resulting symmetry can be larger than the one requested by the construction. For the particular choice $M_V = M_A$ and $z = 1$ a maximal symmetry $[SU(2) \otimes SU(2)]^3$ is realized for the low energy effective lagrangian. This case is called degenerate BESS model and it turns out to be very useful in relation to schemes of strong electroweak breaking.

We stress immediately its main property and what makes it so attractive: in degenerate BESS all deviations in the low energy parameters from their standard model values are strongly suppressed. This would make it possible that a strong electroweak sector at relatively low energies exists within the precision of electroweak tests, such that it may be accessible with existing accelerators (Tevatron) or with accelerators projected for the near future (LHC). In fact one can show that the lagrangian of degenerate BESS becomes identical to that of the standard model (except for the Higgs sector) for sufficiently large mass of the degenerate vector and axial-vector mesons. In other words, different from the minimal BESS, where such a high mass decoupling is not satisfied, the decoupling occurs in degenerate BESS.

The phenomenological implications of the degenerate BESS will be a substantial part of our discussion below.

**2 Degenerate BESS model**

In general, the existence of new vector and axial-vector bosons indirectly manifests at LEP through deviations from SM expectations. For this purpose a low energy effective theory valid for heavy resonances is useful.

As well known, in the low energy limit, one can parameterize the modifications due to a heavy sector in terms of three independent parameters: $\Delta \tau_W$, $\Delta k$, $\Delta \rho$, or equivalently $\epsilon_1$, $\epsilon_2$, $\epsilon_3$. In the minimal BESS model neglecting terms $O(M_Z^2/M_V^2)$ one gets: $\epsilon_1 = \epsilon_2 = 0$ while $\epsilon_3 = (g/g'')^2 - b/2$ is the sum of two contributions: one given by the mixing and the other by the direct coupling of $V$ bosons to fermions. By comparing with the experimental value
of the $\epsilon_3$ parameter as obtained by a global fit to all the available experimental data (especially from LEP) we find that the present bounds on the minimal BESS model are quite stringent and, unless one considers a sort of fine tuning between the two parameters, very small values of $b$ and $g/g''$ are still allowed (of the order of few per cent). A question is natural: is it possible to think of a model of strongly interacting symmetry breaking sector which avoids the restrictive bounds from LEP?

We recall that the very small experimental value of the $\epsilon_3$ parameter, which measures the amount of isospin-conserving virtual contributions to the vector boson self-energies, strongly disadvantages the ordinary technicolor schemes, for which the contribution to $\epsilon_3$ is large and positive. This problem could be attributed to the vector dominance in the dispersion relation satisfied by the $\epsilon_3$ parameter:

$$\epsilon_3 = -\frac{g^2}{4\pi} \int_0^\infty \frac{ds}{s^2} \left[ Im\Pi_{VV}(s) - Im\Pi_{AA}(s) \right]$$

(1)

where $\Pi_{VV(AA)}$ is the correlator between two vector (axial-vector) currents. If the vector and axial-vector spectral functions are saturated by lowest lying vector and axial-vector resonances, one has $Im\Pi_{VV(AA)}(s) = -\pi g^2_{V(A)} \delta(s - M^2_{V(A)})$ where $g_{V(A)}$ parameterizes the matrix element of the vector (axial-vector) current between the vacuum and the state $V_\mu$ ($A_\mu$), and $M_{V(A)}$ is the vector (axial-vector) mass. From the previous equation, one obtains

$$\epsilon_3 = \frac{g^2}{4} \left[ \frac{g^2_{V}}{M^4_{V}} - \frac{g^2_{A}}{M^4_{A}} \right]$$

(2)

By evaluating eq. (2) within the BESS model with also axial-vector resonances (with $b = 0$) one gets $\epsilon_3 = (g/g'')^2 (1 - z^2)$. If the underlying theory mimics the QCD behaviour, naively scaled from $f_\pi \simeq 93$ MeV to $v \simeq 246$ GeV, then $z = 1/2$ and so the deviation for the $\epsilon_3$ parameter is positive and potentially large. On the contrary, in the degenerate BESS model the approximate degeneracy among the masses of the vector and axial-vector states and their couplings makes $\epsilon_3$ vanish (in the low energy limit). In other words, by calling $M$ the common mass of the resonances (they are degenerate up to weak corrections) in the $M \to \infty$ limit, the model decouples and all the $\epsilon_i$ go to zero.

The important feature of the model under examination is that the previous results are protected by an extended vector-axial symmetry $[SU(2) \otimes SU(2)]^3$, broken at low-energy by the electroweak interactions (in fact $\epsilon_3 = 0$ follows from the $SU(2)_L \otimes SU(2)_R$ custodial symmetry).
In an expansion in $M_2^2/M^2$, we have evaluated the leading terms for the corrections to the $\epsilon$ parameters. They are given by

$$\epsilon_1 = -c^2 + s^2 X, \quad \epsilon_2 = -c^2 X, \quad \epsilon_3 = -X$$

all proportional to $X \approx 2(M_2^2/M^2)(g/g'')^2$ which contains a double suppression factor: $M_2^2/M^2$ and $(g/g'')^2$. Radiative corrections have also to be taken into account. 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 $\Lambda$. For a top mass value of 175 GeV and for $M_H = \Lambda = 1$ TeV, we can compare the sum of the SM contributions and the previous deviations with the experimental values for the $\epsilon$ parameters, determined from the available LEP data and the $M_W$ measurement from Tevatron:

$$\epsilon_1 = (3.48 \pm 1.49) \times 10^{-3}, \quad \epsilon_2 = (-5.7 \pm 4.19) \times 10^{-3}, \quad \epsilon_3 = (3.25 \pm 1.40) \times 10^{-3}.$$ 

From the combinations of these experimental results, the upper limit in the plane $(M, g/g'')$ is given in Fig. 1 (solid line). The statistical significance of the plot is that of a 95% C.L. limit in one variable, the mass, at a given value of $g/g''$. The result of this analysis shows that in the degenerate BESS relatively light resonances are compatible with the electroweak data as given by LEP and Tevatron.

Besides studying the virtual effects we shall also discuss the direct production of the heavy resonances. Data from the Fermilab Tevatron Collider, collected by the CDF collaboration, establish limits on the model parameter space. Their search was done through the decay $W' \to e\nu$, assuming standard couplings of the $W'$ to the fermions. Their result can be easily translated into a limit for the degenerate BESS model parameter space. In Fig. 1 these limits are shown (dashed line). The excluded region is above the curve. The figure was obtained using the CDF 95% C.L. limit on the $W'$ cross-section times the branching ratio at $\sqrt{s} = 1.8$ TeV and an integrated luminosity of 19.7 $pb^{-1}$, and comparing this limit with the predictions of our model at fixed $g/g''$, thus giving a limit for $M$. This procedure was then iterated for various values of $g/g''$. The limit from CDF is more restrictive for low resonance masses, while LEP limit is more restrictive for higher mass values. Since in the running period just completed at Tevatron the integrated luminosity was more than 100 $pb^{-1}$, by waiting for the analysis of these data, we have considered an extrapolation of the CDF limit in the electron channel. This extrapolation is based on the simple principle that when background is present the cross-section limit scale inversely with the square root of the luminosity. The result is given by the dotted line in Fig. 1.

We have also studied the sensitivity of degenerate BESS at LEP2 by comparing cross-sections and asymmetries in the fermionic pair channels and $WW$. 

\[ \text{(3)} \]
channel between the model and SM. The general conclusion is that the bounds on the model would not be much stronger than those from LEP and Tevatron.

We conclude this section with some remarks about the decay of the vector mesons $L_\mu$ and $R_\mu$ ($L_\mu = (V_\mu - A_\mu)/2$, $R_\mu = (V_\mu + A_\mu)/2$). A feature of degenerate BESS, as compared to BESS with only vector resonances, comes from the absence of direct coupling of the new resonances to the would-be Goldstone bosons which provide the longitudinal degrees of freedom to the $W$’s, then their partial width into longitudinal $W$’s will be suppressed. As a consequence the width into a $W$ pair is of the same order of the fermionic width. Unlike other schemes of strong electroweak breaking (as the minimal BESS model), the $W_LW_L$ channel is not enhanced. On the contrary we expect very good signatures from the degenerate BESS in the di-lepton channels.

3 Degenerate BESS at Tevatron Upgrade and LHC

We have considered the detection of a signal from strong electroweak sector at a possible upgrading of the Fermilab Tevatron. The option we have chosen, is the so called TeV-33 with a c.m. energy of the collider of 2 $TeV$ and an integrated luminosity of 10 $fb^{-1}$. We have analyzed the production of the charged resonances $L^{\pm}$ of the degenerate BESS in the leptonic channel. The choice of this channel is due to the clean signature and the large cross-section.
The events where simulated using Pythia Montecarlo. A rough simulation of the detector was also performed. The energy of the leptons was smeared according to $\Delta E/E = 15\%$ and the error in the 3-momentum determination was assumed of 5%. Only Drell-Yan mechanism for production was considered and the signal events are compared with the background from SM di-lepton production. For example, in Fig. 2 we show the differential distribution of events of $p\bar{p} \rightarrow L^\pm, W^\pm \rightarrow \mu\nu$ in the transverse momentum of the muon for $M_{L^\pm} = 500$ GeV and $g/g'' = 0.2$. Even if the cuts applied are not optimized (see Table 1), the Jacobian peak is very well visible over the SM background.

We have examined various cases with different choices of $M$, and $g/g''$ (taken inside the physical region shown in Fig. 1) to give an estimate of the sensitivity of the model to this option for the upgrading of the Tevatron (see Table 1). For each case we have applied optimal cuts to maximize the statistical significance of the signal (last column in Table 1). We see that the number of signal events decreases for increasing mass of the resonance. The conclusion is that Tevatron with the high luminosity option could be enough to discover a strong electroweak resonant sector as described by the degenerate BESS model for masses up to 1 TeV.

The same analysis performed at the LHC collider gives very clear signatures. We have considered a configuration of LHC with a c.m. energy $\sqrt{s} = 14$ TeV, a luminosity of $10^{34} cm^{-2}s^{-1}$ and one year run ($10^7$ s). Such
Table 1: Degenerate BESS at Tevatron Upgrade. For all the cases we have also applied a cut $|p_{\mu}^{miss}|_c = |p_{\mu}^c|_c$. Here $#B(S)$=number of background(signal) events.

| $g/g''$ | $M_{L\pm}$ (GeV) | $\Gamma_{L\pm}$ (GeV) | $|p_{L\pm}^c|_c$ (GeV) | $(E_{miss}^{\mu\nu})_c$ (GeV) | $\#B$ | $\#S$ | $\frac{S}{\sqrt{S+B}}$ |
|---------|------------------|-------------------|------------------|-----------------|------|------|------------------|
| 0.12    | 400              | 0.4               | 100              | 150             | 1271 | 1135 | 23.1             |
| 0.20    | 500              | 1.4               | 150              | 200             | 223  | 870  | 26.3             |
| 0.20    | 600              | 1.6               | 200              | 100             | 69   | 282  | 15.0             |
| 0.30    | 800              | 4.9               | 250              | 100             | 19   | 83   | 8.2              |
| 0.40    | 1000             | 10.9              | 250              | 100             | 17   | 21   | 3.4              |

A machine will be able either to discover the new resonances or to constrain the physical region left unconstrained by previous data. In Fig. 3 we show the differential distribution of events at LHC of $pp \to L^{\pm}, W^{\pm} \to \mu\nu$ in the transverse momentum of the muon for a spectacular case corresponding to $M_{L\pm} = 500$ GeV and $g/g'' = 0.15$. The total $L^{\pm}$ width is $\Gamma_{L\pm} = 0.9$ GeV, with the corresponding $B(L^+ \to \mu\nu) = 8.5 \times 10^{-2}$. The number of signal events per year is approximately 128000, the corresponding background consists of 51500 events. Also for higher masses of the resonances we have a very large number of events in the LHC configuration. Clearly these results are a little bit optimistic. In fact the reconstruction of resonance mass will require a careful study of the experimental setup, due to the smallness of the resonance width. Anyway we think that since the signal to background ratio is extremely good there would not be problems for detectability.

Finally, we have considered the possibility that no new resonances are discovered at LHC. In this case limits can be imposed on the parameter space of the model. We have calculated the total cross-section $pp \to L^{\pm}, W^{\pm} \to \ell\nu$ and, and compared with the SM background. The result is that the new resonances of the model can be discovered directly for a wide range of values of the parameter space of the model. The discovery limit in the mass of the resonance depends on the value of $g/g''$. For example if $g/g'' = 0.1$, the resonance is visible over the background at least up to 2 TeV, in the channel $pp \to \mu\nu$.

In this preliminary study we did not consider the production and decay of the corresponding neutral resonances of the model. Another subject under study is the hadronic decay channel which could give much more informations especially at Tevatron Upgrade.

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Figure 3: \((p_\mu)\_\mu\) distribution of \(pp \rightarrow L^\pm, W^\pm \rightarrow \mu\nu\) events at LHC, for \(M_{L^\pm} = 500\) GeV, \(g/g'' = 0.15\). The following cuts have been applied: \(|p_\mu|, |p_{\text{miss}}| > 150\) GeV. The continuous line represents the Standard Model background while the dashed one is the degenerate BESS model expectation.

4 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 Tevatron Upgrade and by LHC, to test for strong electroweak breaking. In particular the calculations are performed within the degenerate BESS, a model which, due to its decoupling properties, passes all the low energy precision tests. We have studied the direct production at hadron colliders of the new charged resonances decaying leptonically. By comparing with the SM background, within suitable cuts and detection limits we conclude that Tevatron with the high luminosity option could be enough to discover a strong electroweak resonant sector as described by the degenerate BESS for masses up to 1 TeV. The same analysis performed at LHC gives very spectacular signatures. On the other hand, if no resonances will be discovered at LHC the parameter region of the degenerate BESS will practically close.

The degenerate BESS model is comparatively much more evident than ordinary BESS, and probably than any other strong electroweak model not sharing its peculiar symmetry properties.
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