PSEUDO GOLDSTONES AT FUTURE COLLIDERS FROM THE EXTENDED BESS MODEL

R. Casalbuoni, S. De Curtis and D. Dominici
Dipartimento di Fisica, Univ. di Firenze
I.N.F.N., Sezione di Firenze

P. Chiappetta
Centre Physique Théorique, CNRS Luminy, Marseille

A. Deandrea and R. Gatto
Département de Physique Théorique, Univ. de Genève

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ABSTRACT

We consider the production of the lightest pseudo-Goldstone bosons at future colliders through the vector resonances predicted by the extended BESS model, which consists of an effective lagrangian parametrization with dynamical symmetry breaking, describing scalar, vector and axial-vector bound states in a rather general framework. We find that the detection of pseudo-Goldstone pairs at LHC requires a careful evaluation of backgrounds. For $e^+e^-$ collisions in the TeV range the backgrounds can be easily reduced and the detection of pseudo-Goldstone pairs is generally easier.
1 Introduction

The possibility of a new strong-interaction sector as responsible for electroweak symmetry breaking, although difficult to formulate in a quantitatively comprehensive scheme, is still considered as a possible alternative to the theoretically unsatisfactory present formulation in terms of elementary scalars. The earliest suggestion in this sense was technicolor [1]. The one-family technicolor model [2] is based on four techniquark doublets, 3 with colours plus one leptonic, and has thus a flavour symmetry $SU(8) \otimes SU(8) \otimes U(1)$. Anomaly cancellation occurs similarly as for the ordinary quark-lepton families. Condensation of technifermions brings down to the diagonal flavour $SU(8) \otimes U(1)$ group, giving a total of 63 Goldstone bosons. Three of them provide for the longitudinal degrees of freedom of $W$ and $Z$. While ordinary fermions remain massless at this stage, an extension of the theory, called extended technicolor, generates fermion masses. At the same time however it leads to difficulties related to the experimental limits on flavour-changing neutral currents. Recently, thoughts have been devoted to this difficult problem, with proposals referred to as walking technicolor [3].

Theories of dynamical symmetry breaking, avoiding the introduction of fundamental scalar fields, generally lead to the prediction of pseudo-Goldstone bosons, due to the breaking of a large initial global symmetry group $G$. We have considered the production of the lightest pseudo-Goldstone bosons (PGB’s) at future colliders through the vector resonances predicted by the extended BESS model with $SU(8) \otimes SU(8)$ symmetry. This model [4] consists of an effective lagrangian parametrization which describes scalar, vector and axial-vector bound states in quite a general framework. For example, the effective low energy phenomenology of ordinary technicolor would correspond to a specialization of the extended BESS picture.

In the absence of a specific definite theory of the strong electroweak sector, one would like to remain as general as possible, avoiding specific dynamical assumptions. The BESS model (BESS = breaking electroweak symmetry strongly) was essentially developed to provide for such a general frame [5]. The basic ingredients for the construction were custodial symmetry and gauge invariance.

The original BESS was based on a minimal chiral structure $G = SU(2)_L \otimes SU(2)_R$. To discuss physics related to possible pseudo-Goldstones one has to use an extension of the model to a larger $SU(N)_L \otimes SU(N)_R$ chiral structure. The extended BESS will contain explicit vector and axial vector resonances and a number of pseudo-Goldstones. Through their mixing with $W$, $Z$ and gluons, some of the spin-one resonances will couple to quarks and leptons, and thus they will be produced at proton-proton and electron-positron colliders at high energy.

Extended BESS can be taken for $N = 8$, and, more particularly, specialized to reproduce the low energy phenomenology of the “historical” $N = 8$ technicolor. The main new features brought by extended BESS into lower energy phenomenology are a number of low mass pseudo-Goldstones and the appearance of an additional singlet vector resonance, in addition to the vector triplet of vector resonances typical of the original BESS model.

We recall that, in dynamical schemes for electroweak symmetry breaking, an initial global invariance group $G$ is subsequently spontaneously broken into a subgroup $H$ by the symmetry breaking dynamical mechanism. As long as additional interactions (such as gauge interactions and others), which break $G$, are neglected, the Goldstone bosons, which
correspond to the generators belonging to the quotient \( G/H \), remain exactly massless. Among those interactions are the standard model gauge interactions of the local group \( SU(3) \otimes SU(2)_L \otimes U(1)_Y \), which in general break the symmetry \( G \). The resulting effective interactions will break the degeneracy among the initial vacua, or, saying it differently, induce an orientation within such vacua.

The initially massless Goldstone bosons, which correspond to oscillations along the directions connecting different vacua, will not remain all massless, due to the induced vacuum orientation. Such massive scalars are the pseudo-Goldstone bosons (PGB) (see Weinberg in [1]). Among the interactions responsible for the induction of the vacuum orientation are the local gauge interaction of the color electroweak group. They contribute to the pseudo-Goldstone masses, and studies of their properties, within a class of models, have been carried out [6].

However, in any dynamical symmetry scheme, this will not be the only source of pseudo-Goldstone masses. In fact suitable terms must be present, responsible for the masses of quarks and leptons themselves. For instance, in extended technicolor, one introduces gauge interactions which connect ordinary fermions to technifermions. The chiral symmetry \( G \), which is only related to the technifermion sector, is broken, and one expects this to be a source of pseudo-Goldstone masses.

The fact that these interactions are essentially the source of the fermion masses leads one to expect that the induced pseudo-Goldstone masses from those interactions could in some way be related to the fermion masses. This point was quantitatively examined [7] and we shall refer to such a study for a choice of the pseudo-Goldstone mass spectrum adopted in the present work.

## 2 PGB’s at future colliders

As we have mentioned in the introduction, for quantitative estimates of the pseudo-Goldstone production cross-sections, we shall employ the \( SU(8) \otimes SU(8) \) extended BESS model. For earlier studies on PGB phenomenology in technicolor theories we refer the reader to [8] and [9] and references therein. We will denote the \( SU(8) \) gauge fields as \( V^A = (V^a, \bar{V}^a, V_D, V_{8a}, V_{8a}^a, V_3, \bar{V}_3^a, \bar{V}_3^{aa}) \), where \( \mu = (0,a) \) (\( a \) being an \( SU(2) \) index), and \( i = 1,2,3 \) is a color index. An analogous notation will be used for the axial particles \( A^A \) and the Goldstone bosons \( \pi^A \). The \( SU(8) \) generators can be found in Appendix A of [1]. We shall use throughout this work the notations of ref. [1] and [7].

The production is induced by the processes

\[
f^+ + f^- \rightarrow \gamma, Z, V^3 \rightarrow P^+ P^- \tag{2.1}
\]

and

\[
f_1 + f_2 \rightarrow W^\pm, V^\pm \rightarrow P^\pm P^0 \tag{2.2}
\]

where \( P^\pm(P^0) \) denote the lightest charged (neutral) PGB’s and \( f \) denotes a light fermion. The gauge bosons \( V \) appearing in (2.1) (2.2) are the \( V^a \).

The main point of the calculations performed in ref. [7] was to work within the low energy effective theory, as characterized by the initial chiral group \( G \), its unbroken subgroup \( H \), and the color electroweak group, assuming that the information for the
fermion mass mechanism can be embodied, from the viewpoint of the low energy theory, into effective Yukawa couplings between ordinary fermions and pseudo-Goldstones.

Most of the allowed Yukawa coupling constants, for those couplings which are invariant under the color-electroweak group, are then related, within the low energy expansion, to the fermion masses. The pseudo-Goldstone mass spectrum can then be derived from the one-loop effective potential, which includes, besides the ordinary gauge interactions, also the Yukawa couplings. The resulting masses are expected in general to lie in a natural range depending on the masses of the heaviest fermions, that is the top and bottom quarks. In particular, those states, which would remain massless in absence of the Yukawa couplings, are expected to lie in a range situated around such heaviest fermions.

For the calculations performed in this work we shall adopt a possible PGB spectrum obtained in ref.\[4\]. The PGB’s have the following masses, for the choice of parameters: $\Lambda = 2\, TeV$, $\alpha_s = 0.12$ and $m_t = 150\, GeV$:

\[ M^2(\pi^a) = 0 \quad a = 1, 2, 3 \]
\[ M^2(\tilde{\pi}^\pm) = \frac{\Lambda^2}{\pi^2 v^2} (m_t^2 + m_b^2) = (388\, GeV)^2 \]
\[ M^2 \left( \frac{\tilde{\pi}^3 - \pi_D}{\sqrt{2}} \right) = \frac{2\Lambda^2}{\pi^2 v^2} m_b^2 = (18\, GeV)^2 \]
\[ M^2 \left( \frac{\tilde{\pi}^3 + \pi_D}{\sqrt{2}} \right) = \frac{2\Lambda^2}{\pi^2 v^2} m_t^2 = (548\, GeV)^2 \]
\[ M^2(\pi_s^{\alpha\pm}) = \frac{\Lambda^2}{4\pi^2 v^2} \left[ m_t^2 + m_b^2 + \frac{9}{2} v^2 g_s^2 \right] = (952\, GeV)^2 \]
\[ M^2(\pi_s^{\alpha3}) = \frac{\Lambda^2}{2\pi^2 v^2} \left( m_t^2 + \frac{9}{4} v^2 g_s^2 \right) = (974\, GeV)^2 \]
\[ M^2(\pi_s^{\alpha\pm}) = \frac{\Lambda^2}{2\pi^2 v^2} \left( m_b^2 + \frac{9}{4} v^2 g_s^2 \right) = (930\, GeV)^2 \]
\[ M^2 \left( \frac{P_3^{0i} + P_3^{3i}}{\sqrt{2}} \right) = \frac{\Lambda^2}{2\pi^2 v^2} (4m_t^2 + v^2 g_s^2 + \frac{1}{3} v^2 g'^2) = (784\, GeV)^2 \]
\[ M^2 \left( \frac{P_3^{0i} - P_3^{3i}}{\sqrt{2}} \right) = \frac{\Lambda^2}{2\pi^2 v^2} (4m_b^2 + v^2 g_s^2 + \frac{1}{3} v^2 g'^2) = (560\, GeV)^2 \]
\[ M^2 \left( P_3^{-i} \right) = \frac{\Lambda^2}{2\pi^2 v^2} (3m_t^2 + m_b^2 + v^2 g_s^2 - \frac{1}{6} v^2 g'^2) = (726\, GeV)^2 \]
\[ M^2 \left( P_3^{+i} \right) = \frac{\Lambda^2}{2\pi^2 v^2} (m_t^2 + 3m_b^2 + v^2 g_s^2 + \frac{5}{6} v^2 g'^2) = (632\, GeV)^2 \]  

where $g_s, g, g'$ are the SU(3) $\otimes$ SU(2)$_L$ $\otimes$ U(1)$_Y$ gauge couplings, and $v \simeq 246 GeV$.

For the calculation we need the trilinear coupling of the $V$ to the PGB’s as derived in ref.\[4\].

\[ \mathcal{L}^{(3)} = ig_\pi \{ V_\mu^3 (\pi^- \partial^\mu \pi^+ + \pi^0 \partial^\mu \pi^0 - P_3^{-i} \partial^\mu P_3^{-i} + P_3^{+i} \partial^\mu P_3^{+i}) \]
\[ + \frac{2}{\sqrt{3}} V_D (P_3^{0i} \partial^\mu P_3^{0i} + P_3^{3i} \partial^\mu P_3^{3i} + P_3^{-i} \partial^\mu P_3^{-i} + P_3^{+i} \partial^\mu P_3^{+i}) \]
\[ + V_\mu (\partial^\mu \pi^3 \pi^+ - \pi^3 \partial^\mu \pi^+ + \partial^\mu \pi^3 \partial^\mu \pi^+ + \partial^\mu \pi^3 \partial^\mu \pi^3 + \partial^\mu P_3^{0i} P_3^{-i} - P_3^{3i} \partial^\mu P_3^{+i}) \]
\[ + h.c. \]  

(2.4)
where
\[ g_{V\pi\pi} = \frac{g'' x^2}{4 r_V} (1 - z^2) \] (2.5)

with
\[ r_V = \frac{M_W^2}{M_V^2}, \quad x = \frac{g}{g''} \] (2.6)

The coupling constant \( g'' \) is the gauge coupling of the \( V \) resonance and \( z \) is a combination of free parameters appearing in front of the BESS lagrangian (see eq.(2.33) of ref.[4]). The case \( z = 0 \) corresponds to decoupling of the axial-vector resonances.

The mixing of the new vector bosons \( V^a \) can be directly read in eq.(2.27) of ref.[4]. The elementary cross section is given by
\[ \frac{d\sigma}{dt} = \frac{1}{12} \frac{|M|^2}{16\pi s^2} \] (2.7)

For the process (2.1) we have
\[ |M|^2 = 8(ut - M_P^4)g_{V\pi\pi}^2 \left\{ (v_Z^2 + a_Z^2) \left( \frac{T_{VZ}^2}{(s - M_Z^2)^2 + M_Z^2 \Gamma_Z^2} \right) ight\} \]
\[ + v_{\gamma}^2 \frac{T_{V\gamma}^2}{s^2} \]
\[ + 2v_{\gamma} v_Z \frac{T_{VZ} T_{V\gamma}}{(s - M_Z^2)^2 + M_Z^2 \Gamma_Z^2} \left\{ \frac{(s - M_Z^2)}{s} \right\} \frac{1}{(s - M_V^2)^2 + M_V^2 \Gamma_V^2} \] (2.8)

where
\[ T_{VZ} = \frac{v^2}{4} g g'' x^2 \cos 2\theta \]
\[ T_{V\gamma} = \frac{v^2}{2} g g'' x^2 \sin \theta \] (2.9)

and \( M_P \equiv M_{P\pm} \).

The couplings of the gauge bosons \( Z \) and \( \gamma \) to the fermions are given by
\[ v_{\gamma} = eQ \quad v_Z = \frac{e}{2\sin 2\theta} (T_3 - 4Q \sin^2 \theta) \quad a_Z = \frac{e}{2\sin 2\theta} T_3 \] (2.10)

with \( T_3 = \pm 1 \).

For the process (2.2) we have
\[ |M|^2 = 8(ut - M_{P\pm}^2 M_{P\mp}^2)g_{V\pi\pi}^2 (v_W^2 + a_W^2) \left( \frac{T_{VW}^2}{(s - M_W^2)^2 + M_W^2 \Gamma_W^2} \right) \frac{1}{(s - M_V^2)^2 + M_V^2 \Gamma_V^2} \] (2.11)

where
\[ T_{VW} = \frac{v^2}{4} g g'' x^2 \] (2.12)

with
\[ v_W = a_W = \frac{e}{2\sqrt{2}\sin \theta} \] (2.13)

The resonant process is dominant, as it results for instance by comparing the non resonant cross section
\[ \sigma(e^+e^- \rightarrow P^+P^-) = \frac{1}{4} \left( 1 - \frac{4M_P^2}{s} \right)^{3/2} \sigma(e^+e^- \rightarrow \mu^+\mu^-) \] (2.14)

with the results of our calculations (remember that, at 1 TeV, \( \sigma(e^+e^- \rightarrow \mu^+\mu^-) = 87 \text{ fb} \)).
3 PGB’s at future linear $e^+e^-$ colliders

Projects of $e^+e^-$ linear colliders are being studied at present at different laboratories (among them SLAC, KEK, Novosibirsk and Serpukhov, DESY, Darmstadt, CERN, with several other groups working in various universities). For general reviews of such studies and of the physics potentialities we refer to [1] and [2].

We have already discussed the usefulness of very energetic $e^+e^-$ colliders in exploring an alternative scheme of electroweak symmetry breaking based on a strong interacting sector with new vector resonances [3]. The sensitivity of $e^+e^-$ linear colliders, for different proposed options of energies and luminosities, to the BESS model parameters, was there quantitatively examined, particularly in connection to the vector bosons $V$ that appear in the model.

The $V$’s can be produced as real resonances if their mass is below the collider energy. In a high energy collider one expects to see dominant peaks below the maximum c.m. energy corresponding to such resonances. Due to beamstrahlung and synchrotron radiation it may not become necessary to tune the beam energies in order to see such peaks.

In ref. [1] we were essentially interested in the neutral vector resonances of the strongly interacting sector as described by BESS. The description of such resonances in BESS is rather general, and, after convenient choice of parameters may also apply to a phenomenological description of the standard techni-$\rho$. Studies of the techni-$\rho$ production in $e^+e^-$ colliders have been carried out by Peskin [4], Iddir et al. [5], through study of strong final state interaction, and have also been discussed by Barklow [6] and Hikasa [7], via various methods.

A prediction of such models for the electroweak breaking, in the general case of a large initial global symmetry group, is the existence of pseudo-Goldstone bosons. Our calculations here are within extended BESS. Future $e^+e^-$ colliders are one of the best opportunities to study the production of pairs of charged pseudo-Goldstone bosons. The methods used for their detection turn out to be very similar to those used in the case of charged Higgs searches [7], but with the advantage that PGB can here be resonantly produced: $e^+e^- \rightarrow V \rightarrow P^+P^-$. From now on we shall use the following notations: $P^\pm \equiv \tilde{\pi}^\pm$, and $P^0 \equiv \frac{\tilde{\pi}^3 - \tilde{\pi}^0}{\sqrt{2}}$ for the lightest neutral PGB’s.

The peak cross section is

$$\sigma(M_V^2) = 12\pi \frac{\Gamma_V^e \Gamma_V^P}{M_V^2(\Gamma_{TOT})^2}$$

with

$$\Gamma_V^e = \frac{4}{3} \alpha_{em} M_V (v_e^2 + a_e^2)$$

where we have used the couplings of the $V$ to the fermions [4]

$$v_f = \frac{1}{2 \sin 2\theta} (CT_3 + 4DQ) \quad a_f = \frac{1}{2 \sin 2\theta} CT_3$$

with

$$C = -\frac{\cos 2\theta}{\cos \theta} \frac{g}{g''} \quad D = -\frac{\sin^2 \theta}{\cos \theta} \frac{g}{g''}$$

$$\Gamma_{TOT} = \Gamma_V^e + \Gamma_V^P + \Gamma_{TOT}^e + \Gamma_{TOT}^P$$
The decay width of $V^3$ in $P^+ P^-$ is given by

$$\Gamma^P_V = \frac{1}{48\pi} g^2_{V\pi\pi} M_V (1 - 4 \frac{M^2_P}{M^2_V})^{3/2}$$

In computing $\Gamma_V^{TOT}$ we have neglected the fermion contribution.

We present in the following table the results for the total cross section for $M_V = 1$ TeV and $g/g'' = 0.05$ (this value is compatible with the present limitations coming from LEP1 [18]). The assumed spectrum for the PGB’s is that of eq.(2.4).

| $z$  | $\sigma$(pb) | $\Gamma^W_V$ | $\Gamma^P_V$(GeV) | $\Gamma^V_V$(GeV) | $\sigma_{WW}$(pb) | $\sigma_{ZZ}$(pb) | $\sigma_{tt}$(pb) |
|------|--------------|---------------|-------------------|------------------|------------------|------------------|------------------|
| 0    | 1.6          | 10.3          | 2.7               | 13               | 2.7+6.1          | 0.21             | 0.20             |
| 0.5  | 2.8          | 5.8           | 1.5               | 7.3              | 2.1+1.5          | 0.16             | 0.14             |
| 0.7  | 6.1          | 2.7           | 0.7               | 3.4              | 1.4+0.2          | 0.12             | 0.10             |

Notice that the peak cross sections do not depend on $g/g''$, and they increase with $z$ as $1/(1-z^2)^2$. The large cross sections that we have found are due to the relatively small $V$ mass assumed, and to the large branching ratio of $V \rightarrow P^+ P^-$. In the following table we exhibit the sensitivity to the $V$ mass (assuming the worst case, $z = 0$). The cross section decreases very rapidly when $V$ becomes heavier.

| $\sqrt{s} = M_V$ (TeV) | $\sigma$(pb) | $\Gamma^W_V$ | $\Gamma^P_V$(GeV) | $\Gamma^V_V$(GeV) | $\sigma_{WW}$(pb) | $\sigma_{ZZ}$(pb) | $\sigma_{tt}$(pb) |
|------------------------|--------------|---------------|-------------------|------------------|------------------|------------------|------------------|
| 1.0                    | 1.6          | 10.3          | 2.7               | 13               | 2.7+6.1          | 0.21             | 0.20             |
| 1.2                    | 0.69         | 25.9          | 11.8              | 37.7             | 2.1+1.5          | 0.16             | 0.14             |
| 1.5                    | 0.11         | 79.7          | 50.8              | 172.4            | 1.4+0.2          | 0.12             | 0.10             |
| 1.7                    | 0.03         | 149.6         | 106.8             | 456.5            | 1.2+0.04         | 0.10             | 0.08             |

The background processes in the above table are $e^+ e^- \rightarrow t\bar{t}$, $e^+ e^- \rightarrow W^+ W^-$, $e^+ e^- \rightarrow ZZ$. With respect to the standard model we have for $\sigma_{WW}$ an enhancement (given in the sixth column of the table as the second number) due to the production of a couple of $W$’s from the $V$ resonance, while for $\sigma_{ZZ}$ the numerical value is that of the standard model as the coupling $V^3 ZZ$ is zero. For $\sigma_{tt}$ the numerical value is again very close to that of the standard model, as, excluding a direct coupling of $V$ to fermions, the extra contributions with respect to the standard model are suppressed by the small mixing factor $g/g''$.

Concerning the decay of the PGB’s we have

$$\Gamma(P^+ \rightarrow t\bar{b}) = \frac{1}{8\pi} \frac{m_t^2}{v^2} M_P \sqrt{1 - \frac{m_t^2}{M_P^2}}$$

Therefore we have to consider the following final state

$$P^+ P^- \rightarrow t\bar{b} b \rightarrow WbW\bar{b} \rightarrow jjbb\nu \bar{b}$$

These backgrounds have already been considered for the charged Higgs boson production at future $e^+ e^-$ colliders [19]. We are a priori in a more favorable situation since the PGB we have studied are resonantly produced. A detailed analysis of these processes requires full knowledge of the experimental set-up and is beyond the scope of this work.
Nevertheless in our case the signal cross-section is, even in the case $z=0$, of the same order of magnitude and in some cases even larger than the background, thus favoring in principle signal detection.

The background process $e^+e^- \rightarrow W^+W^-$ can be easily reduced below 1% of its initial value by requiring the tagging of one $b$ in the final state. This can be easily understood, since the branching ratio of $W \rightarrow b + \text{u-type quark}$ is very low due to either a small Kobayashi-Maskawa matrix element or phase-space suppression.

In principle also invariant mass and $p_T$ cuts may be useful, but in order to reconstruct a PGB mass or $p_T$ it is necessary to face a many-jet problem, i.e. jet-combinatorics and isolation. Moreover not only the signal, but also $WW$ production, is a high $p_T$ process, thus reducing considerably the efficiency of a $p_T$ cut.

Similar considerations apply to the $e^+e^- \rightarrow ZZ$ background. In this case the tagging of one $b$ is less efficient in reducing the background, but the cross-section is already more than one order of magnitude smaller than the preceeding one.

The background $e^+e^- \rightarrow t\bar{t}$ is more difficult to weed out. The study of charged Higgs boson discovery potential has shown that a microvertex detector is crucial for establishing the signal over the $e^+e^- \rightarrow t\bar{t}$ background [19].

We will assume $B = 0.20$ for the product of the branching ratios $W \rightarrow \text{hadrons}$ and $W \rightarrow \text{leptons}$, and a $b$-tagging efficiency $\epsilon_b = 0.5$. Assuming an integrated luminosity of $80 \text{ fb}^{-1}$, after multiplication of the number of events of the Table by the branching ratios and $b$-tagging efficiencies, a still large number of events is left when $M_V = 1 \text{ TeV}$. When $M_V$ is higher than $1.2 \text{ TeV}$ and $z = 0$, the signal becomes smaller than background and deserves careful study of background rejection.

To conclude this section we mention the suggestion, originally due to Ginzburg et al. [21], of the possibility of obtaining an energetic photon beam by colliding electron bunches with a laser beam in the visible spectrum. This technique should allow keeping a high luminosity for the photon beam from the back scattered laser, and it should allow for a photonic spectrum mostly concentrated at the highest energies, not much lower than the electron energy. Such a behaviour is quite different from that of the expected beamstrahlung photons concentrated at the lower energies, and from that of the bremsstrahlung photons. This technical possibility would thus allow for energetic photon-photon and electron-photon collisions. For the purpose of the present paper, where we are interested in a possible strong electroweak sector, $\gamma\gamma$ collisions would appear of interest if resonant behaviours are present in states of zero angular momentum which can couple to two real photons. These states may be pseudo-Goldstone states, when one considers the effective interaction due to the Adler-Bell-Jackiw anomaly. Also interesting will be the production of pairs of such pseudos from $\gamma\gamma$ (both real or virtual). If energetically reachable, however, the resonant behaviours we have discussed will be more prominent signals.

4 PGB’s at LHC

Much work has been devoted in recent years to study of physical implications of a possible strong electroweak sector in view of future hadronic colliders [22].
We have considered the PGB production at LHC via the charged $V$ resonance. Also in this case the methods used for PGB detection are similar to those used in the case of charged Higgs [7], but with the advantage that the PGB are produced from a charged $V$ resonance. We have evaluated the quark-antiquark annihilation (Drell-Yan type) contribution to the differential cross section both in terms of the invariant mass of the pair of PGB’s and in terms of the transverse momentum $p_T$ of the PGB for the process

$$pp \rightarrow W^\pm \rightarrow V^\pm \rightarrow P^\pm P^0 + X$$

(4.1)

Its expression follows directly from the partonic cross section given in eq.(2.2). The partial width of the decay $V^\pm \rightarrow P^\pm P^0$ is

$$\Gamma_{V^\pm} = \frac{1}{96\pi} g_{V^\pm}^2 M_V \left[ 1 - \frac{(M_{P^\pm} + M_{P^0})^2}{M_V^2} \right] \left[ 1 - 2 \frac{M_{P^\pm}^2 + M_{P^0}^2}{M_V^2} \right]$$

(4.2)

We have then added the fusion contribution coming from the process

$$pp \rightarrow W^\pm Z \rightarrow V^\pm \rightarrow P^\pm P^0$$

(4.3)

The fusion amplitudes have been computed using the equivalence theorem [20].

To compute $W^+Z \rightarrow P^+P^0$ we need $L_{\pi\pi\pi\pi}$ [4]:

$$L_{\pi\pi\pi\pi} = -\frac{1}{6} \frac{1}{v^2} \left[ (1 - \frac{3}{4} \alpha) \right] \left[ -\partial_\mu \pi^+ \partial^\mu \pi^- (\pi^-)^2 + \partial_\mu \pi^+ \partial^\mu \pi^- \pi^+ \pi^- \\
+ \partial_\mu \pi^- \partial^\mu \pi^+ \pi^- - 2 \partial_\mu \pi^- \partial^\mu \pi^- \pi^+ \pi^- + \partial_\mu \pi^- \partial^\mu \pi^- (\pi^-)^2 \right]$$

(4.4)

The fusion amplitude for the process $W^+Z \rightarrow P^+P^0$ is given by

$$A(W^+Z \rightarrow P^+P^0) = \frac{1}{\sqrt{2}} \left[ (1 - \frac{3}{4} \alpha) \frac{t}{v^2} + \frac{\alpha M_V^2}{4 v^2} \left( \frac{u - t}{s - M_V^2} + \frac{s - t}{u - M_V^2} \right) \right]$$

(4.5)

We have also evaluated the amplitude $W^+Z \rightarrow W^+Z$ through the equivalence theorem, using the trilinear coupling, given in eq.(2.5), the quadrilinear coupling being given by [4]

$$L_{\pi\pi\pi\pi} = -\frac{1}{6} \frac{1}{v^2} \left[ (1 - \frac{3}{4} \alpha) \right] \left[ -\partial_\mu \pi^+ \partial^\mu \pi^- (\pi^-)^2 \right. \\
+ \partial_\mu \pi^+ \partial^\mu \pi^- \pi^+ \pi^- + \partial_\mu \pi^- \partial^\mu \pi^- \pi^+ \pi^- \\
- 2 \partial_\mu \pi^- \partial^\mu \pi^- \pi^+ \pi^- + \partial_\mu \pi^- \partial^\mu \pi^- (\pi^-)^2 + h.c.]$$

(4.6)

where

$$\alpha = \frac{x^2}{r_V} (1 - z^2)^2$$

(4.7)
The result, to be compared with our previous work based on $SU(2) \otimes SU(2)$, is

$$A(W^+ Z \rightarrow W^+ Z) = i \left[ \left(1 - \frac{3}{4} \alpha \right) \frac{t}{v^2} + \frac{\alpha M_V^2}{4 v^2} \left( \frac{u-t}{s-M_V^2} + \frac{s-t}{u-M_V^2} \right) \right]$$  \hspace{1cm} (4.8)$$

In Fig. 1 (Fig. 2) we plot the invariant mass ($p_T$) distribution for the set of parameters $M_V = 1000$ GeV, $g'' = 13$ and $z = 0$; we have added the events of the $P^+ P^0$ channel with the events of the $P^- P^0$ one. We have plotted in Fig. 3 and 4 the same distributions with $M_V = 1200$ GeV, $g'' = 6.9$ and $z = 0.5$.

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. The fusion subprocess gives a small contribution (less than roughly 10%).

We can perform the same analysis also for the neutral channel:

$$pp \rightarrow Z, \gamma \rightarrow V^3 \rightarrow P^+ P^- + X$$  \hspace{1cm} (4.9)$$

In this case, the fusion amplitudes are given by

$$A(W^+W^- \rightarrow P^+ P^-) = i \left[ \left(1 - \frac{3}{4} \alpha \right) \frac{u}{v^2} + \frac{\alpha M_V^2}{4 v^2} \left( \frac{t-u}{s-M_V^2} + \frac{s-u}{t-M_V^2} \right) \right]$$  \hspace{1cm} (4.10)$$

and

$$A(ZZ \rightarrow P^+ P^-) = i \left[ \left(1 - \frac{3}{4} \alpha \right) \frac{-s}{v^2} + \frac{\alpha M_V^2}{4 v^2} \left( \frac{s-u}{t-M_V^2} + \frac{s-t}{u-M_V^2} \right) \right]$$  \hspace{1cm} (4.11)$$

Notice that in the $t$ channel of the amplitude (4.10) and in the $t$ and $u$ channels of (4.11) we have to consider the exchange of the triplet $\tilde{V}$, which however in BESS is practically degenerate in mass with the triplet of the $V$. As shown in Fig. 5 and 6 for $M_V = 1000$ GeV, $g'' = 13$ and $z = 0$, the total number of events is depressed by roughly one order of magnitude compared to the other case, since the Drell-Yan type subprocess is very small. Therefore the fusion subprocess becomes important (roughly 30%). Concerning the final state, the decay widths $P^+$ are given in eq.(3.6), while the partial decay width of $P^0$ in $\bar{b}b$ is given by

$$\Gamma(P^0 \rightarrow \bar{b}b) = \frac{1}{8\pi} \frac{m_{b}^2}{v^2} M_P \sqrt{1 - \frac{4 m_{b}^2}{M_P^2}}$$  \hspace{1cm} (4.12)$$

to be compared with the $P^0$ decay to two gluons $[9]$

$$\Gamma(P^0 \rightarrow gg) = \frac{\alpha_s^2 N_{TC}^2}{8\pi^3} \frac{M_P^3}{6v^2}$$  \hspace{1cm} (4.13)$$

where $N_{TC}$ is the number of technicolor. For masses of $P^0$ in the considered range this decay is less important. The $P^0$ decay in two photons is depressed by a factor $(\frac{\alpha_s}{\alpha})^2$.

Therefore the expected signals for $P^\pm P^0$ are $\bar{t}b\bar{b}$ or $\bar{t}bqq$, and $\bar{t}b\bar{b}$ for $P^+ P^-$. These final states have to be studied and compared with the background.
For instance, the $t\bar{t}b\bar{b}$ background comes from the following processes

$$
\begin{align*}
  gg & \rightarrow t\bar{t}b\bar{b} \\
  gg & \rightarrow t\bar{t}Z \rightarrow t\bar{t}b\bar{b} \\
  gg & \rightarrow t\bar{t} + jets
\end{align*}
$$

(4.14)

where the last jets are misidentified as $b$ jets. These background have been studied for charged Higgs boson discovery from $tb$ decays at LHC using SDC detector. In order to disentangle signal from background, reasonably efficient and pure $b$ tagging is mandatory. We recall that the energy of LHC is now taken to be at 14 TeV. The following procedures have been applied in ref. [17]. A lepton with high momentum ($p_T > 20$ GeV), coming from the $t$ decays (via $W$) is used as trigger and the missing momentum $p_T > 50$ GeV required. The second $W$ coming from the second $t$ is assumed to decay hadronically. The invariant mass of each pair of jets (not containing tagged $b$ quarks) is required to satisfy

$$
M_{W} - \Delta M_{W} < M_{jj} < M_{W} + \Delta M_{W}
$$

(4.15)

Then for each pair satisfying the previous criterion one computes a three jet invariant mass $M_{b\bar{b}jj}$, by combining $M_{jj}$ with a tagged $b$ jet, and requires that

$$
m_{t} - \frac{\Delta m_{t}}{2} < M_{b\bar{b}jj} < m_{t} + \frac{\Delta m_{t}}{2}
$$

(4.16)

Using this cuts one can reduce the background. Finally one can compute $M_{b\bar{b}jj}$ and make a plot of the $M_{b\bar{b}jj}$ invariant mass distribution. Clear signal peaks appear except when $M_{H^+} \sim m_{t}$.

Our case deserves careful study along the previous procedure, since the expected number of signal events is not large. A similar analysis has also to be performed for the $t\bar{b}bb$ and $t\bar{b}gg$ final states. We plan to do this in the next future in collaboration with experimentalists involved in LHC. Notice that it will be crucial to know if $b$ tagging can be performed with the planned huge luminosity of $10^{34} cm^{-2}s^{-1}$.

Finally we have computed also the $WZ$ production which has been shown to allow for identification of a charged $V$ at LHC up to $2$ TeV masses within the $SU(2) \otimes SU(2)$ model. Since new channels for $V^\pm$ decays are open, the signal will be reduced. Three contributions coming from Drell-Yan type, fusion, and SM background are summed up. In order to allow for a direct comparison with previous minimal BESS [23] we have taken an LHC energy of $16$ TeV. The rate of events decreases by roughly 20% if we consider the presently planned energy of $14$ TeV.

Fig. 7 and Fig. 8 (resp. Fig. 9 and Fig. 10) give the prediction for invariant $WZ$ mass and $p_T$ of the $Z$ for $M_V = 1000$ GeV, $g'' = 13$ and $z = 0$ for BESS $SU(2)$ (respectively for BESS $SU(8)$). Although the signal is reduced by 20% the identification will be very easy. For higher masses, since the width increases and the cross section for the production of PGB decreases, the discovery potential is reduced down to $1.5$ TeV, as shown in Fig. 11 and Fig. 12. In particular the shape of the jacobian peak does not differ from the background, the signal leading only to an excess of events.

Since only leptonic decays of electroweak gauge bosons have been taken into account, the situation may be less pessimistic, if identification through hadronic $W$ decay and leptonic $Z$ decay, which has been previously shown to be crucial for removing top background, is possible. Within the ability to perform $b$ tagging with good efficiency and purity, one may hope to disentangle $t\bar{t}$ background from $W$ pair production which is enhanced by $V^3$ resonance in our case.
5 Conclusion

We have investigated the production of the lightest pseudo-Goldstone bosons at future colliders through the resonances of the extended BESS model, which is an effective lagrangian parametrization to describe the low energy phenomenology of a general class of theories with dynamical symmetry breaking. The existence of pseudo-Goldstone bosons is in fact a quite common and interesting prediction of such theories.

Detection at LHC of a charged vector resonance through its decay into $WZ$ pairs is possible in the framework of the extended BESS model for a significant domain of its parameter space. Production of pairs of pseudo-Goldstone bosons $P^\pm P^0$ is also important, but discovery via $t\bar{b}b\bar{b}$ or $ttgg$ decays needs a careful evaluation of backgrounds in the LHC environment.

A more promising preview is instead obtained for production of charged pseudo-Goldstones at the $V$ resonance in $e^+e^-$ collisions in the TeV range. In fact the largest background, namely $WW$ production, can be easily reduced to a very low level by requiring the tagging of one $b$ in the final state. Other backgrounds, such as $ZZ$ and $tt$ production, have smaller cross-sections as compared with signal cross-section, at least in a range of the parameter space of the model. For increasing values of the $M_V$ mass and decreasing values of the $z$ parameter (we have examined in detail the worst case $z = 0$) the signal cross-section becomes smaller than background and deserves a detailed study of background rejection.
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**Figure Captions**

**Fig. 1** Invariant mass distribution of the $P^+P^0 + P^-P^0$ produced per year at LHC for $M_V = 1000 \ GeV$, $g'' = 13$ and $z = 0$, with a luminosity of 100 $fb^{-1}$. The applied cuts are: $|y_P| < 2.5$, $(p_T)_{P0} > 300 \ GeV$. The lower (higher) histogram refers to the fusion signal (fusion signal plus $q\bar{q}$ annihilation signal).

**Fig. 2** $(p_T)_{P0}$ distribution of the $P^+P^0 + P^-P^0$ produced per year at LHC for $M_V = 1000 \ GeV$, $g'' = 13$ and $z = 0$, with a luminosity of 100 $fb^{-1}$. The applied cuts are: $|y_P| < 2.5$, $M_{PP} > 500 \ GeV$. The lower (higher) histogram refers to the fusion signal (fusion signal plus $q\bar{q}$ annihilation signal).

**Fig. 3** Invariant mass distribution of the $P^+P^0 + P^-P^0$ produced per year at LHC for $M_V = 1200 \ GeV$, $g'' = 6.9$ and $z = 0.5$, with a luminosity of 100 $fb^{-1}$. The applied cuts are: $|y_P| < 2.5$, $(p_T)_{P0} > 300 \ GeV$. The lower (higher) histogram refers to the fusion signal (fusion signal plus $q\bar{q}$ annihilation signal).

**Fig. 4** $(p_T)_{P0}$ distribution of the $P^+P^0 + P^-P^0$ produced per year at LHC for $M_V = 1200 \ GeV$, $g'' = 6.9$ and $z = 0.5$, with a luminosity of 100 $fb^{-1}$. The applied cuts are: $|y_P| < 2.5$, $M_{PP} > 500 \ GeV$. The lower (higher) histogram refers to the fusion signal (fusion signal plus $q\bar{q}$ annihilation signal).

**Fig. 5** Invariant mass distribution of the $P^+P^-$ produced per year at LHC for $M_V = 1000 \ GeV$, $g'' = 13$ and $z = 0$, with a luminosity of 100 $fb^{-1}$. The applied cuts are: $|y_P| < 2.5$, $(p_T)_{P0} > 300 \ GeV$. The lower (higher) histogram refers to the fusion signal (fusion signal plus $q\bar{q}$ annihilation signal).

**Fig. 6** $(p_T)_{P0}$ distribution of the $P^+P^-$ produced per year at LHC for $M_V = 1000 \ GeV$, $g'' = 13$ and $z = 0$, with a luminosity of 100 $fb^{-1}$. The applied cuts are: $|y_P| < 2.5$, $M_{PP} > 500 \ GeV$. The lower (higher) histogram refers to the fusion signal (fusion signal plus $q\bar{q}$ annihilation signal).

**Fig. 7** Invariant mass distribution of the $W^+Z + W^-Z$ pairs produced per year at LHC ($\sqrt{s} = 16 \ TeV$) for $M_V = 1000 \ GeV$, $g'' = 13$ and $z = 0$ within BESS $SU(2) \otimes SU(2)$, with a luminosity of 100 $fb^{-1}$. The applied cuts are: $|y_{W,Z}| < 2.5$, $(p_T)_{Z} > 360 \ GeV$ and $M_{WZ} > 850 \ GeV$. The lower, intermediate and higher histograms refer to the background, background plus fusion signal and background plus fusion signal plus $q\bar{q}$ annihilation signal, respectively.

**Fig. 8** $(p_T)_{Z}$ distribution of the $W^+Z + W^-Z$ pairs produced per year at LHC ($\sqrt{s} = 16 \ TeV$) for $M_V = 1000 \ GeV$, $g'' = 13$ and $z = 0$ within BESS $SU(2) \otimes SU(2)$, with a luminosity of 100 $fb^{-1}$. The applied cuts are: $|y_{W,Z}| < 2.5$, $(p_T)_{Z} > 360 \ GeV$ and $M_{WZ} > 850 \ GeV$. The lower, intermediate and higher histograms refer to the background, background plus fusion signal and background plus fusion signal plus $q\bar{q}$ annihilation signal, respectively.

**Fig. 9** Invariant mass distribution of the $W^+Z + W^-Z$ pairs produced per year at LHC ($\sqrt{s} = 16 \ TeV$) for $M_V = 1000 \ GeV$, $g'' = 13$ and $z = 0$ within BESS $SU(8) \otimes SU(8)$, with a luminosity of 100 $fb^{-1}$. The applied cuts are: $|y_{W,Z}| < 2.5$, $(p_T)_{Z} > 360 \ GeV$ and $M_{WZ} > 850 \ GeV$. The lower, intermediate and higher histograms...
refer to the background, background plus fusion signal and background plus fusion signal plus $q\bar{q}$ annihilation signal, respectively.

**Fig. 10** $(p_T)_Z$ distribution of the $W^+Z+W^-Z$ pairs produced per year at LHC ($\sqrt{s} = 16$ TeV) for $M_V = 1000$ GeV, $g'' = 13$ and $z = 0$, within BESS $SU(8) \otimes SU(8)$, with a luminosity of 100 $fb^{-1}$. The applied cuts are: $|y_{W,Z}| < 2.5$, $(p_T)_Z > 360$ GeV and $M_{WZ} > 850$ GeV. The lower, intermediate and higher histograms refer to the background, background plus fusion signal and background plus fusion signal plus $q\bar{q}$ annihilation signal, respectively.

**Fig. 11** Invariant mass distribution of the $W^+Z+W^-Z$ pairs produced per year at LHC ($\sqrt{s} = 16$ TeV) for $M_V = 1500$ GeV, $g'' = 13$ and $z = 0$ within BESS $SU(8) \otimes SU(8)$, with a luminosity of 100 $fb^{-1}$. The applied cuts are: $|y_{W,Z}| < 2.5$, $(p_T)_Z > 480$ GeV and $M_{WZ} > 1100$ GeV. The lower, intermediate and higher histograms refer to the background, background plus fusion signal and background plus fusion signal plus $q\bar{q}$ annihilation signal, respectively.

**Fig. 12** $(p_T)_Z$ distribution of the $W^+Z+W^-Z$ pairs produced per year at LHC ($\sqrt{s} = 16$ TeV) for $M_V = 1500$ GeV, $g'' = 13$ and $z = 0$, within BESS $SU(8) \otimes SU(8)$, with a luminosity of 100 $fb^{-1}$. The applied cuts are: $|y_{W,Z}| < 2.5$, $(p_T)_Z > 450$ GeV and $M_{WZ} > 1100$ GeV. The lower, intermediate and higher histograms refer to the background, background plus fusion signal and background plus fusion signal plus $q\bar{q}$ annihilation signal, respectively.
This figure "fig1-1.png" is available in "png" format from:

http://arxiv.org/ps/hep-ph/9403305v1
# $P^+/- P^0$ Events/year

![Figure 1](image-url)
This figure "fig2-1.png" is available in "png" format from:

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This figure "fig3-1.png" is available in "png" format from:

http://arxiv.org/ps/hep-ph/9403305v1
This figure "fig1-2.png" is available in "png" format from:

http://arxiv.org/ps/hep-ph/9403305v1
This figure "fig2-2.png" is available in "png" format from:

http://arxiv.org/ps/hep-ph/9403305v1
Fig. 2

# $P^+/P^0$ Events/year

$p_T$(GeV)
This figure "fig3-2.png" is available in "png" format from:

http://arxiv.org/ps/hep-ph/9403305v1
This figure "fig1-3.png" is available in "png" format from:

   http://arxiv.org/ps/hep-ph/9403305v1
This figure "fig3-3.png" is available in "png" format from:

http://arxiv.org/ps/hep-ph/9403305v1
Fig. 3

# $P^+/- P^0$ Events/year

$M_{PP}(\text{GeV})$
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http://arxiv.org/ps/hep-ph/9403305v1
This figure "fig3-4.png" is available in "png" format from:

http://arxiv.org/ps/hep-ph/9403305v1
Fig. 4

# $\text{P}^{\pm}/\text{P}^0$ Events/year vs. $p_T$(GeV)
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Fig. 5
This figure "fig1-6.png" is available in "png" format from:

http://arxiv.org/ps/hep-ph/9403305v1
Fig. 6

$\# \, P^+ \, P^- \, \text{Events/year}$

$M_{PP} \, (\text{GeV})$
# WZ Events/year

Fig. 7
# WZ Events/year

Fig. 8
# WZ Events/year

![Graph showing the distribution of WZ events per year against M_{WZ} (GeV)](image)

Fig. 9
Fig. 10

# WZ Events/year

$p_T\text{(GeV)}$
# WZ Events/year

![Graph showing # WZ Events/year vs. MWZ(GeV)](image)

**Fig. 11**
Fig. 12

# WZ Events/year

$p_T$(GeV)