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Exotic Higgs Interactions and Z–Factories

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Abstract

We discuss some consequences of tree-level $H^{\pm}W^{\mp}Z$ interactions in a model with triplet Higgs bosons whose vacuum expectation values can potentially contribute to the W-and Z-masses. It is shown that such interactions can make the model confront crucial tests in Z-factories and constrain its parameter space from the current data.

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The scalar sector of the standard electroweak theory [1] may well turn out to be a Trojan horse. On one hand, the single Higgs doublet which is required in the minimal model for spontaneous symmetry breaking is yet to show up. On the other, it might be too naive to envision just one scalar doublet in a scenario whose particle content has otherwise proved to be so full of varieties. Furthermore, it is possible [2] to include Higgs scalars belonging to representations of $SU(2)$ other than doublets without enlarging the gauge group in any manner. One such possibility is to incorporate scalar triplets in the standard model.

In this paper, we concentrate on the kind of model that was first proposed by Georgi and his collaborators [3]. Among its interesting features, the triplet(s) and the doublet are both free to contribute to the masses of the W and the Z. One can do this while still retaining $\rho = 1$ at tree-level (where $\rho = M_W^2/M_Z^2 \cos^2\theta_W$) provided that there is one complex ($Y = 2$) and one real ($Y = 0$) triplet of scalars. An equality of the vacuum expectation values (vev) of the neutral members of the triplets (in technical language, a custodial $SU(2)$ symmetry among them) is also required for this purpose. The feasibility of constructing a scalar potential whose self-interactions respect this equality has been demonstrated [4], although the deeper question of naturally preserving $\rho = 1$ to all orders is not answered yet. Here we take a phenomenological stance and focus on the observable consequences, if any, of a triplet scenario that could survive difficulties of the above nature.

If the $SU(2)$ triplet scalars have to be so arranged that their combined contributions lead to $\rho = 1$ at the tree-level, then an immediate consequence [2] is a non-zero coupling involving a charged scalar, the W and the Z. Such a coupling does not exist [5] in models with an arbitrary number of Higgs doublets and singlets. It can, therefore, be regarded as a distinguishing feature of a model where triplet vevs can be conceived of as contributing to the masses of the weak vector bosons. In what follows we shall investigate the bearing of this H^+W^-Z (and its conjugate) vertex on results coming from Z-factories.

We consider the case [6] where the doublet and the triplet Higgs fields are expressed respectively as

$$\Phi = \begin{pmatrix} \phi^+ & \phi^{0*} \\ \phi^0 & \phi^- \end{pmatrix} \tag{1}$$

and

$$\Psi = \begin{pmatrix} \chi^{++} & \xi^+ & \chi^0 \\ \chi^+ & \xi^0 & \chi^- \\ \chi^{0*} & \xi^- & \chi^{--} \end{pmatrix} \tag{2}$$

Here Φ is the standard complex doublet with $Y = 1$, while Ψ consists of a complex triplet with $Y = 2$ and a real triplet with $Y = 0$. The vacuum expectation values of the neutral fields are given by $< \phi_0 >= a/\sqrt{2}$ and $< \chi_0 >=< \xi_0 >= b$. The masses of the weak vector bosons are given by

$$M_W^2 = M_Z^2 \cos^2\theta_W = \frac{g^2}{4}\left(a^2 + 8b^2\right) \tag{3}$$

Two more parameters of practical interest in this connection are the cosine and the sine of the mixing angle between the doublet and the triplets:

$$C_H = \frac{a}{\sqrt{a^2+8b^2}} \quad , \quad S_H = \frac{2\sqrt{2}b}{\sqrt{a^2+8b^2}} \tag{4}$$

From above, a large S_H means that more contribution to the vector boson masses comes from the vev of the neutral triplets. After the absorption of the Goldstone fields, the remaining physical states can be classified according to their behavior under the custodial $SU(2)$. There is a 5-plet, $H_5^{++,+,0,-,--}$, a 3-plet, $H_5^{+,0,-}$ and two singlets, H_1^0 and $H_1^{\prime 0}$. If the Higgs potential is so chosen as to preserve the custodial $SU(2)$, then the H_5 and the H_3 fields have no mixing between them.

A detailed account of the various couplings of these fields and many of their consequences can be found in reference [6]. Let us just mention here that barring scalar interactions, the members of the H_3-plet interact only with fermions, while the H_5-plet has interactions with the gauge bosons only. An exception is the possibility of H_5^{++}-lepton-lepton coupling which leads to Majorana masses for the Neutrinos. We ignore such a possibility here.

The coupling in which we are interested in this paper is

$$\mathcal{L}_{H^\pm W^\mp Z} = \frac{-ig\, M_W S_H}{\cos\theta_W} g_{\mu\nu} W^\mu Z^\nu H_5^+ + h.c. \tag{5}$$

which has no analogue in the minimal standard model (or its extensions in terms of Higgs doublets). It can be read off from above that the higher is the contribution of the triplet vev to the W- and Z-masses, the $H_5^\pm W^\mp Z$ interaction is also stronger. It can thus serve as a very important test of whether the weak gauge bosons are deriving any substantial contribution to their masses from scalar triplets.

According to the model, there exists a degeneracy in mass among the members of the 5-plet, and also one among those of the 3-plet. Although some recent results [7] from Mark II claim to have ruled out any doubly charged scalar particle in the mass range between 6.5 GeV and 36.5 GeV, assumptions about the lepton-lepton decay channel is implicit in that analysis. In the absence (or extreme suppression) of that channel the bounds disappear. Also, the announced lower limits [8] of 35 GeV on the mass of a singly charged Higgs is applicable for the $H_3^\pm$ but becomes dubious for the $H_5^\pm$. This is because the $H_5^\pm$ have no tree-level coupling with fermions. Of course, their one-loop decays into fermions and antifermions may prevail [6], but it is not obvious that in such cases the heaviest allowed fermions will dominate in the final state, as has been assumed in the currently available analysis of experimental data. As regards the $H_5^\pm$, therefore, the supposed limit, if not altogether lost, is at least weakened. Thus, at present there is little evidence that can impose any stringent restriction on the masses of the H_5-plet unless specific assumptions are made about the Higgs potential, relating to the masses of the 5-plet and the 3-plet.

The $H_5^{\pm}W^{\mp}Z$ vertex can lead to the decay of the Z-boson through the mode $Z \rightarrow H_5^+W^{-*} \rightarrow H_5^+\ell^-\bar{\nu}_\ell$ (and its conjugate process). The H_5^+ will subsequently decay mainly into a fermion and an antifermion through one-loop processes. The signal (if we concentrate on the leptonic modes) in such cases will consist of two charged leptons along with missing transverse momenta. There is no background of the same order to this signal in the minimal standard model. For $M_{H_5} < M_Z/2$, $Z \rightarrow H_5^+H_5^-$ will also contribute to this signal. The relative importance of this decay mode and the one coming via the $H_5^{\pm}W^{\mp}Z$ interaction has to be assessed in this region of the parameter space.

The decay width for $Z \rightarrow H_5^+W^{-*} \rightarrow H_5^+\ell^-\bar{\nu}_\ell$ can be written (neglecting the lepton masses) as

$$\Gamma = \frac{1}{(2\pi)^3.12M_Z}\left(\frac{g\,S_H\,M_W}{\cos\theta_W}\right)^2 \int_0^{M_Z-M_H} dE_1 \int_{\omega-E_1}^{M_Z-M_H-E_1} dE_2\,\frac{(T_1+T_2)}{(T_3+T_4)^2} \qquad (6)$$

where $\omega = \frac{M_Z^2-M_H^2}{2M_Z}$, $T_1 = \frac{M_H^2-M_Z^2}{2}$, $T_2 = 2E_1E_2 + M_Z(E_1+E_2)$, $T_3 = M_H^2 - M_Z^2 - M_W^2$ and $T_4 = 2M_Z(E_1+E_2)$. M_H is the mass of the $H_5^{\pm}$.

Obviously the width depends on the parameter S_H. Constraints on this parameter can be obtained by considering its effects on rare weak processes. Here we use the $B^0 - \bar{B}^0$ mixing data [9] to constrain S_H. The charged scalars $H_3^{\pm}$ will contribute to such mixing through box diagrams [10], the contributions being controlled by the quantity S_H/C_H. Assuming that $m_t \geq 90$ GeV and using different values of the factor $f_B^2B_B$ and the Kobayashi-Maskawa matrix elements, we have checked that $S_H \lesssim 0.9$ is commensurate with the experimental data for all values of the H_3-mass within allowed limits.

Figure 1 shows a plot of the branching ratio for $Z \rightarrow H_5^+\ell^-\bar{\nu}_\ell$ against M_H for different values of S_H. Even for moderately large S_H, so long as $M_H \lesssim$ 55-60 GeV, the signals can be expected to override the standard model backgrounds (via $Z \to W^{+*}W^{-*}$) and the branching ratios are above the threshold of detection at the LEP. For a more massive H_5^+, the event rate will be smaller; the signals will cease to be detectable under the presently attained luminosity at $M_H \geq 65$ GeV. On the other hand, for $M_H \lesssim$ 45 GeV the rates can be quite high. As mentioned before, the mode $Z \to H_5^+ H_5^-$ will also have to be considered in this range. The branching ratio for this decay is plotted against M_H in figure 2. However, as is evident from a comparison with figure 1, the signal from the $H_5^+ W^- Z$ vertex is still likely to dominate so long as S_H is large. This can be ascribed to a greater availability of phase space during Z-decay. Thus the process involving a virtual W in such cases could be more useful in eliminating the existence of $H_5^\pm$ with a mass less than $M_Z/2$ as well.

It has been pointed out in reference [6] that in the mass range we are concerned with, hadronic colliders are not expected to be particularly useful for the signature of the H_5-plet. In the case of more massive scalars belonging to this multiplet, information may be available at the SSC [11] and at LEP II (where $e^+e^- \to Z^* \to H_5^+ W^-$ will be feasible).

To conclude, the $H_5^\pm W^\mp Z$ interaction proves to be of paramount importance for the detection of a low-mass 5-plet. About a year of run at the LEP can serve either to unveil the signature of the $H_5^\pm$ or to rule it out over a considerable region of the $S_H - M_H$ plane.

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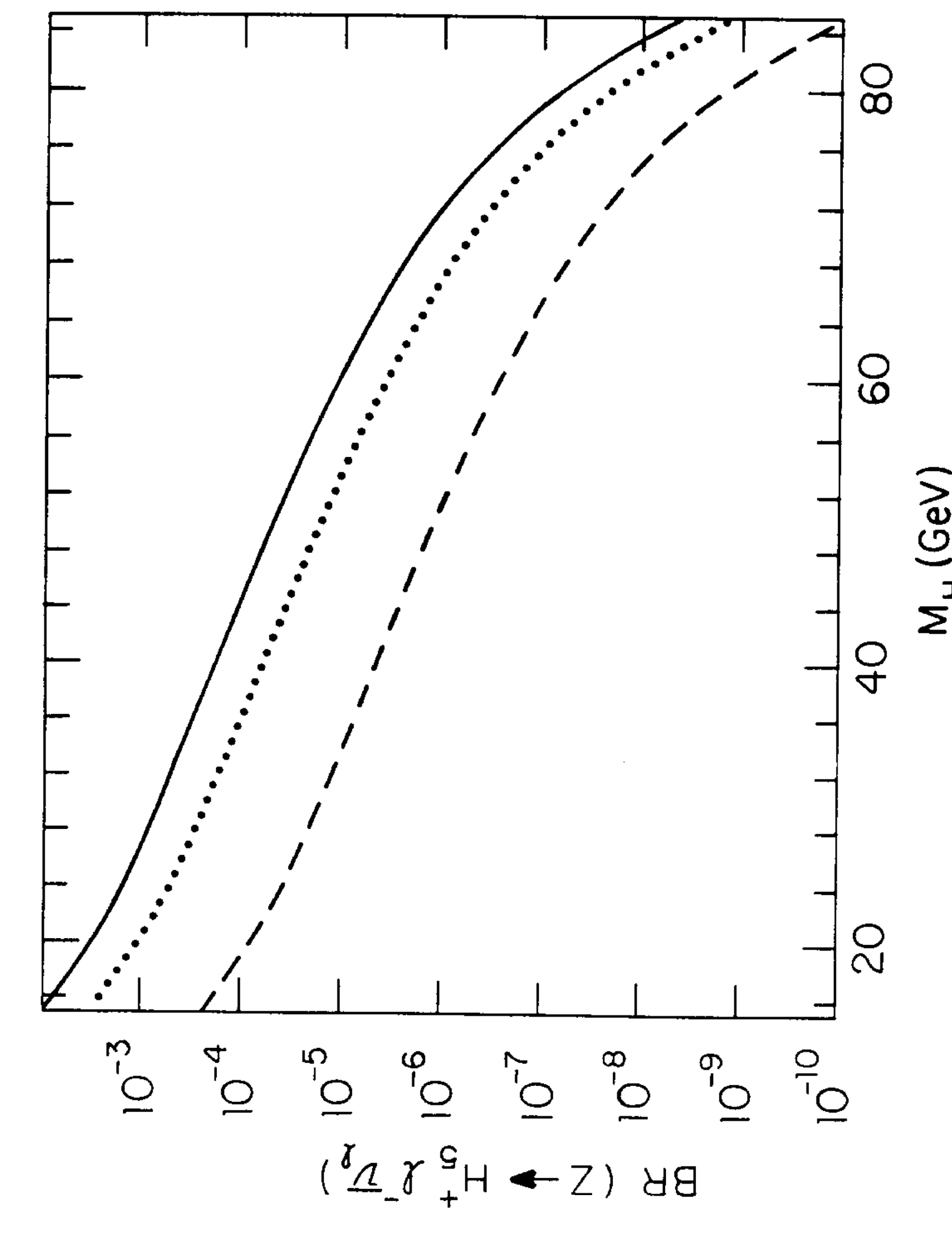
Figure Captions

Fig. 1: $BR(Z \to H_5^+ \ell^- \bar{\nu}_\ell)$ versus the H_5-mass for different values of S_H. The solid, dotted and dashed lines correspond respectively to $S_H = 0.95$, 0.55 and 0.15.

Fig. 2: $BR(Z \to H_5^+ H_5^-)$ versus the H_5-mass.



BR (Z → $H_5^+ \ell^- \bar{\nu}_\ell$)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
20
40
60
80
M_H (GeV)

Fig. 1

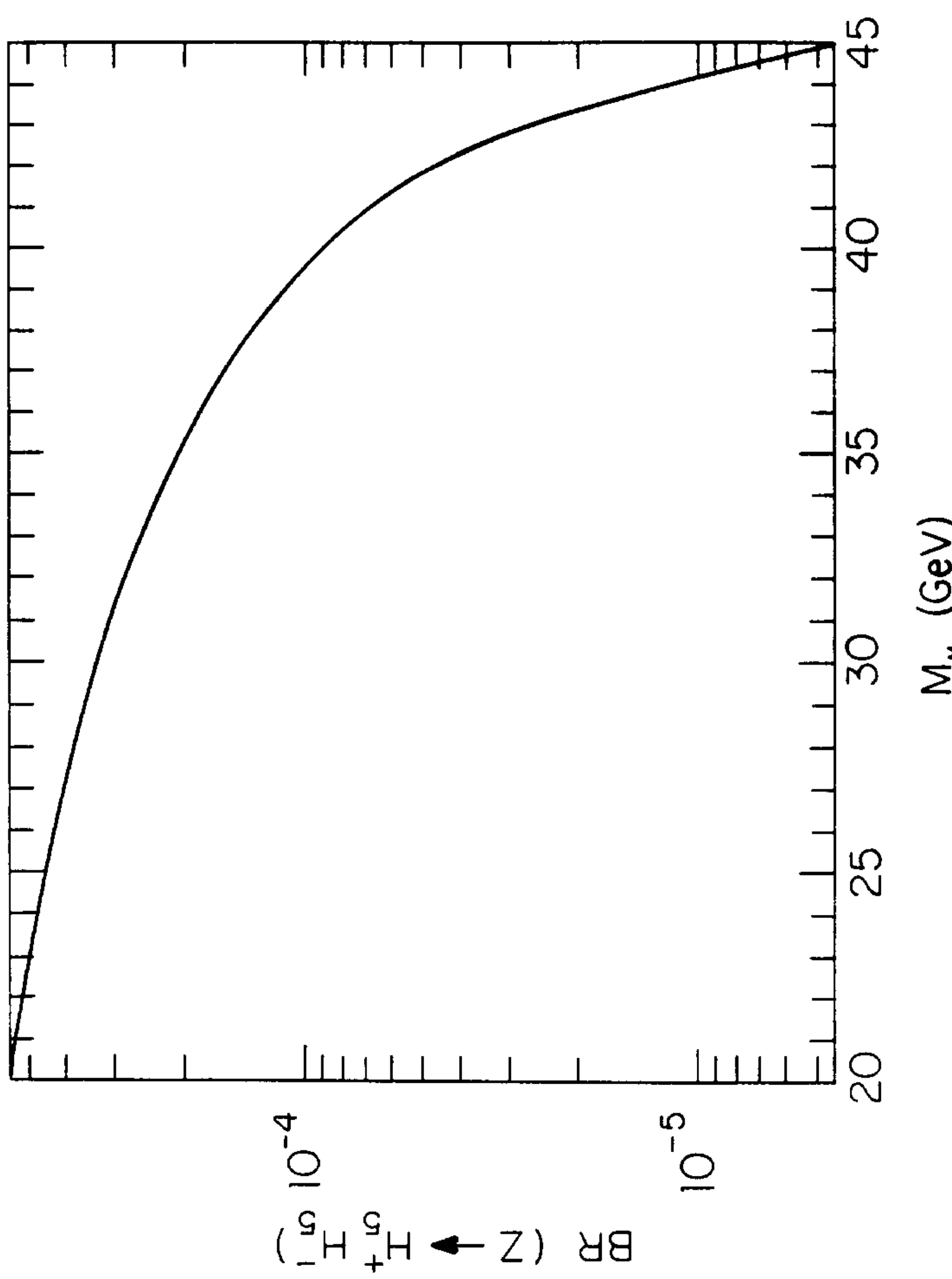


Fig. 2