Triple Pseudoscalar Decay Mode of the Z Boson

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We analyze the production of triple pseudoscalar Higgs bosons in the decay channel of $Z \to AAA$ for light pseudoscalar bosons when the corresponding scalar boson is too heavy to be produced by Z decay. Analytic results are obtained both at the tree level and at the one-loop level. The branching fraction can be as large as 10^{-5}, which should be detectable at the CERN e^+e^- collider LEP. [S0031-9007(96)01476-7]

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There is essentially no stringent and model-independent limit on the mass of a pseudoscalar Higgs boson, generically denoted by A in this Letter. Such a pseudoscalar boson always exists in the extended Higgs sector beyond the standard model (SM). An identical pair of pseudoscalar bosons cannot be produced in pairs in the Z decay, as it is forbidden by Bose statistics. The potential limit on the mass of a pseudoscalar Higgs boson comes from LEP experiments. However, in all the analyses [1–3], the pseudoscalar bosons are assumed to be produced by the decay of a physical scalar boson h. For the case when the scalar boson is heavy (such as $m_h > m_Z$), no limit on m_A has been extracted yet. If the scalar partner h is heavy enough, the mode $Z \to hA$ will not be allowed by kinematics. Nevertheless, the channel $Z \to AAZ^* \to AAl^+l^-$ is allowed if A is light enough. However, its branching fraction was shown [4] to be typically about 10^{-8}, too small to be detectable for LEP. A pseudoscalar Higgs boson lighter than a b quark can be ruled out by $b \to sA$ [5]; however, the conclusion will be very much model dependent. (Therefore, it is still worthwhile to make a direct search at LEP even if the pseudoscalar mass is in this light range.) In any case, for a pseudoscalar boson whose mass is heavier than the b quark and whose companion scalar boson is too heavy for the decay $Z \to hA$, the current model independent bound on its mass is very weak.

In this Letter, we look into another potential discovery channel $Z \to AAA$ for the pseudoscalar boson which may be detectable among the rare Z decays. The channel is particularly interesting when the lightest scalar is heavier than the lightest pseudoscalar boson which can also be an axion. Experimentally, the AAA final states were searched for by LEP detectors [1] assuming that two A's are the decay product of a physical scalar boson h. A lot of that analysis can probably be borrowed immediately to the case when h is off shell.

In the popular minimal supersymmetric standard model (MSSM), at tree level the Higgs masses obey relations [5] $m_h < m_Z < m_H$, $m_h < m_A < m_H$, and $m_{H^\pm} > m_W$, where m_h is defined to be the lighter one of the two scalar bosons. These relationships are modified when one-loop corrections, due to top quark, are taken into account. m_h in this case no longer has to be lighter than m_Z. However, it is still constrained to be lighter than about 140 GeV (for $\tan\beta > 1$) [6]. With the radiative corrections, it is also possible [3] that $m_A < \frac{1}{2}m_h$. In this sense, our analysis is also very much relevant to the MSSM in addition to the more general models.

The one-loop amplitude for $Z \to AAA$ via the virtual top quark was roughly estimated by Li [7]. Here we study in detail both the tree-level process due to a virtual scalar Higgs boson, and the one-loop process due to the top-quark loop.

In Fig. 1, we illustrate with one of the Feynman diagrams that the triple pseudoscalar decay mode $Z \to AAA$ occurs through the gauge vertex $Z \to Ah^*$, followed by $h^* \to AA$ [3]. Phenomenologically, one can describe the interaction among the scalar and the pseudoscalar Higgs bosons by an effective Lagrangian,

$$\mathcal{L} = \lambda\langle V\rangle hAA\,. \tag{1}$$

The coefficient $\lambda\langle V\rangle$ is related to the vacuum expectation value of the Higgs field, the quartic bosonic couplings, and also some mixing angles. Its value is about the scale of the electroweak interaction.

The amplitude for $Z(p_Z, \varepsilon_Z) \to A(p_1) + A(p_2) + A(p_3)$ can be written in terms of the form factors as

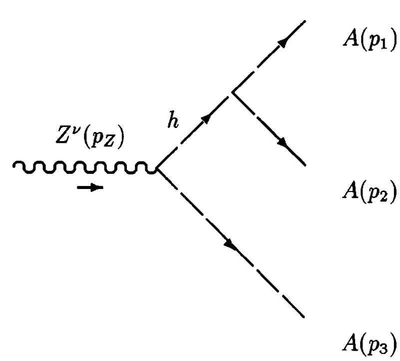

Fig. 1. One of the tree-level Feynman diagrams for the process $Z \to AAA$ via the scalar h Higgs boson. Two other diagrams are obtained by permuting the momenta.

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$$\mathcal{M} = [F^h(p_2,p_3)p_1^\nu + F^h(p_1,p_3)p_2^\nu + F^h(p_1,p_2)p_3^\nu](\varepsilon_Z)_\nu\,, \tag{2}$$

where

$$F^h(p_2,p_3) = \frac{g\lambda\langle V\rangle}{\cos\theta_W}\,\frac{2}{(p_2+p_3)^2 - M_h^2}\,. \tag{3}$$

We simplified our picture by assuming that the contribution of the lightest scalar Higgs boson dominates. The analysis is parametrized model independently such that it would be straightforward to adapt our study to a specific model.

From Eq. (2), we obtain the spin-summed amplitude squared as follows:

$$\sum|\mathcal{M}|^2 = \frac{4\pi\alpha\lambda^2\langle V\rangle^2}{x_W(1-x_W)M_Z^2}\left[\frac{2xy - 4(1-z-a)}{(1-x+a-h)(1-y+a-h)} + \frac{z^2-4a}{(1-z+a-h)^2}\right] + 2 \text{ other permutations of } x,y,z\,. \tag{4}$$

Here $a = M_A^2/M_Z^2$, $h = M_h^2/M_Z^2$, and $x = 2p_1\cdot p_Z/M_Z^2$, $y = 2p_2\cdot p_Z/M_Z^2$, $z = 2p_3\cdot p_Z/M_Z^2$, with $x+y+z=2$. The allowed x and y ranges are

$$2\sqrt{a} \le x \le 1-3a\,,$$
$$1 - \tfrac{1}{2}(x+d) \le y \le 1 - \tfrac{1}{2}(x-d)\,, \tag{5}$$

with $d = (x^2-4a)^{1/2}[1 - 4a/(1-x+a)]^{1/2}$. (6)

The partial width for the channel $Z \to AAA$ is

$$d\Gamma = (Z\to AAA) = \frac{M_Z}{256\pi^3}\left(\frac{1}{3}\sum|\mathcal{M}|^2\right)\frac{dx\,dy}{3!}\,. \tag{7}$$

In Fig. 2, we demonstrate the branching fractions of the process $Z\to AAA$ for different scenarios, (a) $M_h = 90$ GeV (dashed line), (b) $M_h = 100$ GeV (solid line), and (c) $M_h = 110$ GeV (dot-dashed line), for the case $\lambda\langle V\rangle = 100$ GeV. We find that the size of the branching fraction can be as large as 10^{-5} for lighter h.

Next, we look at the induced amplitude at the one-loop level. This is potentially significant when M_h is very large so that the tree-level amplitude is not important. It is also interesting because it depends only on the coupling of the pseudoscalar boson with the top quark, and independent of the details of the Higgs self-couplings. We shall parametrize the Yukawa coupling of the top quark to the light pseudoscalar boson (A) in the following model independent form:

$$\mathcal{L}_{\text{Yukawa}} = g_t\bar{t}i\gamma_5 tA\,. \tag{8}$$

The coupling between the top quark and the Z gauge boson is given in the standard model,

$$g_Z^t = \frac{e}{4\sin\theta_W\cos\theta_W}\,.$$

For the top-induced amplitude of the process $Z(p_Z)\to A(p_1)A(p_2)A(p_3)$, there are six Feynman diagrams. Under charge conjugation, they pair up into three sets,

$$\mathcal{M} = 3\,\frac{2g_t^3g_Z^tm_t}{96\pi^2}\iiint 3!\,d\alpha\,d\beta\,d\gamma \times\left(\frac{\mathcal{N}_{123}^\nu}{(\mu_{123}^2)^2} + \frac{\mathcal{N}_{132}^\nu}{(\mu_{132}^2)^2} + \frac{\mathcal{N}_{213}^\nu}{(\mu_{213}^2)^2}\right)(\varepsilon_Z)_\nu\,, \tag{9}$$

$$\hat{p}_{123} = \gamma p_1 - \delta p_3 - \tfrac{1}{2}(\alpha+\gamma-\beta-\delta)p_Z\,, \tag{10}$$

$$\mu_{123}^2 = \hat{p}_{123}^2 - \tfrac{1}{4}M_Z^2 - (\gamma+\delta)m_A^2 + m_t^2 + (\delta p_3 + \gamma p_1)\cdot p_Z\,, \tag{11}$$

$$\mathcal{N}_{123}^\nu = p_2^\nu(M_Z^2 - 4m_t^2 - 8\mu_{123}^2 + 4\hat{p}_{123}^2) + 4[(p_3-p_1)^\nu p_Z - 2p_1^\nu p_3 + 2p_3^\nu p_1]\cdot\hat{p}_{123}\,. \tag{12}$$

The Feynman parameters satisfy $\alpha+\beta+\gamma+\delta=1$ and $0\le\alpha,\beta,\gamma,\delta\le 1$. In Fig. 3, we carefully show the choice of the momentum flow and the corresponding Feynman parameters. Our results can be easily produced following such convention. A color factor 3 has been explicitly included in Eq. (9). It is straightforward to generalize expressions (10)–(12) to other cases 132 and 213 by permutations. The charge conjugated diagrams give equal contributions as one can easily check that $\mathcal{N}_{123} = \mathcal{N}_{321}$, etc. To arrange this one-loop amplitude in a similar form as (2), we introduce the form factors $F^t(p_i,p_j)$ in parallel with F^h,

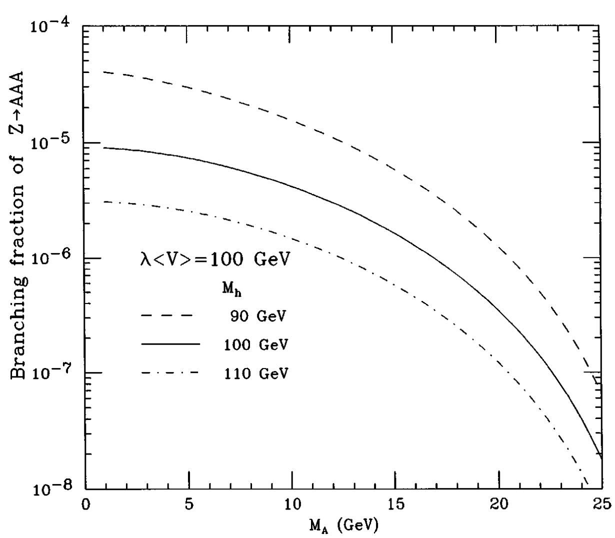

FIG. 2. Predicted branching fractions of the tree-level process $Z\to AAA$ for different scenarios, (a) $M_h = 90$ GeV (dashed line), (b) $M_h = 100$ GeV (solid line), and (c) $M_h = 110$ GeV (dot-dashed line). We have set $\lambda\langle V\rangle = 100$ GeV.

$$F^t(p_1, p_3) = 3\,\frac{2g_t^3 g_Z^t m_t}{96\pi^2} \iiint 3!\, d\alpha\, d\beta\, d\gamma \Bigg[\frac{(4p_Z + 8p_1)\cdot \hat{p}_{123}}{(\mu_{132}^2)^2} + \frac{(4p_Z + 8p_3)\cdot \hat{p}_{312}}{(\mu_{312}^2)^2} + \frac{M_Z^2 - 4m_t^2 - 8\mu_{123}^2 + 4\hat{p}_{123}^2}{(\mu_{123}^2)^2} \Bigg]. \tag{13}$$

The above formulas are ready for numerical integrations. However, for the purpose of illustration we extract only the leading contribution in the large m_t limit even though the correction can be of order of $M_Z^2/m_t^2 \approx 0.25$. We also remove irrelevant constant terms from F^t. Such constant terms cannot contribute to the overall amplitude for a physical polarization ε of the Z boson. We obtain

$$F^t(p_1, p_3) \approx 3\,\frac{g_t^3 g_Z^t (p_1 \cdot p_3)}{8\pi^2 m_t^3}. \tag{14}$$

Unfortunately, such a top-loop induced amplitude is so small that it produces, by itself, a negligible branching fraction for $Z \to AAA$ below 10^{-10}, even if we assume a SM coupling $g_t = (\sqrt{2}\,G_F)^{1/2} m_t$. This is much smaller than the previous rough estimate [7] by many orders of magnitude. More likely, the signal of $Z \to AAA$ comes from the Higgs mediated process.

Since one requires the scalar boson h to be light enough (such as 90 GeV) in order to get a large branching ratio, one may also consider the alternative production of $e^+e^- \to Z^* \to hA \to AAA$. This possibility is already covered in some of the Higgs search analysis [1,2].

As the accumulated events of $Z \to$ *hadrons* among the four LEP groups have reached 10^7, a branching ratio of 10^{-5} is potentially detectable. The main difficulty seems to be finding a clear signal with high efficiency for such events. If the pseudoscalar boson is heavier than $2m_b \approx$ 10 GeV, then presumably it will decay dominantly into six b quarks. In MSSM [8], for $\tan\beta > 1$, the scalar and pseudoscalar bosons decay into $b\overline{b}$ about 90% of the time and about (6–8)% into $\tau^+\tau^-$.

For the case 10 GeV $\approx 2m_b > m_A > 2m_\tau \approx 3.5$ GeV, the A boson can decay dominantly into six τ leptons or six charm quarks. The two modes are competitive with each other. One can search for $\tau^+\tau^-$ plus four jets or $\tau^+\tau^-\tau^+\tau^-$ plus two jets or $\tau^+\tau^-\tau^+\tau^-\tau^+\tau^-$ all together to maximize detection efficiencies. The answer will depend on the relative fraction between $\tau^+\tau^-$ and $c\overline{c}$ final states.

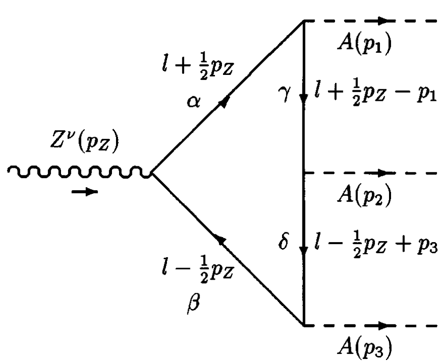

FIG. 3. One of the one-loop Feynman diagrams for the process $Z \to AAA$ via the virtual top quark. The choice of momentum flow and the Feynman parameters are clearly labeled. Two other diagrams are obtained by permuting the momenta.

For the channel $Z \to AAA \to b\overline{b}b\overline{b}b\overline{b}$, the clear signal can be a number of b-tagged jets. A similar signal was searched before in the previous Higgs search analysis [1] for lighter on-shell scalar boson h using the same AAA final state. It was concluded [1] that the current limit of this branching ratio is at about a 10^{-4} level. With more recent data, this limit may be improved by a factor of 3 or more with improved statistics. To improve this further, one probably has to increase the efficiency in the identification of six jets from the three A bosons and the efficiency in b tagging. Typically a prize [of about (20–30)%] has to be paid to impose a tight cut to reject three, four, or five jet events. The efficiency will be higher for lighter pseudoscalar. In addition, one has to pay a prize for b tagging. The current b-tagging efficiency of LEP detectors is roughly about 20% per jet for over 90% purity. Even if one tags only three out of six jets, the prize is already quite severe (about 10%). These two effects combine to give (3–5)% efficiency of identifying $Z \to AAA$. (OPAL [1] quoted (6–11)%, but with a rather high background.)

In a general multidoublet extension of the standard model, it is possible that the pseudoscalar decays into τ leptons or b quarks with a similar branching fraction; in that case, the best modes to discover pseudoscalar boson may be $b\overline{b}\tau^+\tau^-\tau^+\tau^-$ or $b\overline{b}b\overline{b}\tau^+\tau^-$ final states [9]. So far these modes have not been seriously searched for by LEP yet.

Our analysis indicates that there is a good chance that one can detect a signal of pseudoscalar boson in Z decay with a branching ratio of about 10^{-5}. It is certainly far from trivial; however, the reward is that the pseudoscalar boson may be already there in the data waiting to be uncovered.

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