TWO-HIGGS-DOUBLET MODELS
AND THE YUKAWA PROCESS AT LEP1*

J. Kalinowski and Maria Krawczyk

Insitute of Theoretical Physics
Warsaw University
ul. Hoża 69, 00 681 Warsaw, Poland

Dedicated to Wojciech Królikowski in honour of his 70th birthday

We investigate the production of Higgs bosons A/h via the Yukawa process $Z \to f\bar{f} \to f\bar{f}A/h$ taking into account QCD corrections and fermion mass effects. We estimate the discovery reach of this process and/or bounds on the parameter space of two-Higgs doublet models which can be derived from the analysis of $b\bar{b}\tau^+\tau^-$ events at LEP1. These limits have important consequences for extended models of electroweak interactions and their experimental verification/improvement are welcome.

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1. Introduction

Experimental searches at LEP1 for the neutral Higgs bosons in the context of extended models of electroweak interactions have been performed in the Bjorken $(Z \to Z^*h)$ and pair production $(Z \to Ah)$ processes. However, the Yukawa process $(Z \to f\bar{f} \to f\bar{f}A/h)$, in which the Higgs boson is radiated off the final fermion, provides an alternative Higgs production mechanism. Although the possible importance of this process in the context of two-Higgs doublet models, both in supersymmetric and non-supersymmetric versions, has been pointed out long time ago [1–3], experimentally it has not been looked for so far.

Recently there has been a renewed interest in the Yukawa process in the context of attempts to explain experimental measurements of R_b, the

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branching ratio for Z decays to $b\bar{b}$ [4, 5]. In particular, in the paper [4] it has been argued, based on (among others) a bound on parameter space $\tan\beta - M_A$ derived from the Yukawa process $Z \to b\bar{b}A$ followed by $A \to b\bar{b}$ [3], that problem of R_b in the supersymmetric model could be explained only for $\tan\beta \sim 1$. This bound has been obtained from the simple assumption that if 20–30 $b\bar{b}A$ events had been produced at LEP1 it is likely to have been noticed because the QCD background from $Z \to 4b$ is small. However, the analyses of $4b$-jet events, for example in $Z \to hA \to 4b$ searches [6], show that the background from $Z \to b\bar{b}gg$ due to misidentification of b-quark jets is much more important. Although the Yukawa process has a different topology, similar background problems may appear in its experimental analysis and a definite conclusion can be drawn after a dedicated experimental analysis in $4b$ channel will have been performed. On the other hand, the $b\bar{b}\tau^+\tau^-$ channel is almost background free and therefore it can be exploited to estimate limits on the parameters of the extension of the Standard Model.

In this paper we estimate the parameter bounds and/or discovery reach of the Yukawa process using the $b\bar{b}\tau^+\tau^-$ channel. To this end we provide the simple formulae including all fermion mass terms for the matrix element for process $e^+e^- \to f\bar{f}\phi$ for both $\phi = h$ and $\phi = A$. They may prove useful in constructing Monte Carlo programs in order to include experimental constraints, efficiencies etc.

In the numerical analysis we also include QCD corrections which turn out to be very important. Assuming that no signal events are found we obtain weaker bounds on $\tan\beta - M_\phi$ than in [4]. Nevertheless our results demonstrate the physics potential of the Yukawa process: even if the Higgs boson is not found in this process, the exclusion plot derived from negative search will have interesting consequences for extensions of the Standard Model.

2. Higgs particle production at LEP1

In the minimal extensions of the Standard Model (SM), either supersymmetric (MSSM) or non-supersymmetric (2HDM), two Higgs doublets are employed [7]. In this paper we consider 2HDM of type II in which, like in the MSSM, one of the Higgs doublets couples to up-type, and the other to down-type fermions. After the symmetry breakdown there are five physical Higgs particles: two CP-even neutral scalar Higgs bosons denoted by h and H (we assume that $M_h \leq M_H$), a CP-odd neutral — A (usually called a pseudoscalar), and a pair of charged particles $H^\pm$. Their experimental discovery and measurement of their couplings provides one of the major motivations for and constitues a primary physics goal to be achieved at present and future colliders.

Currently the best experimental limits on Higgs boson masses are obtained from LEP1 experiments performed at the Z boson peak. At the tree level the neutral Higgs bosons h and A can be produced in Z boson decays via three processes:

$$Z \to Z^* h \,, \tag{1}$$

$$Z \to Ah \,, \tag{2}$$

$$Z \to f\bar{f} \to f\bar{f}A/h \,. \tag{3}$$

In the SM the associated Higgs pair production process (2) is absent and the Yukawa process (3) is suppressed by a factor $(m_f/M_W)^2$ with respect to Higgs-strahlung process(1). Therefore the lower limit on the Higgs mass $M_{H_{\text{SM}}} > 65.2$ GeV has been derived [8] from the negative search via the process (1) at LEP1.

In the two-doublet extensions of SM the Higgs-strahlung process (1) occurs at a lower rate

$$\Gamma(Z \to hZ^*) = \Gamma_{\text{SM}}(Z \to H_{\text{SM}}Z^*) \sin^2(\beta - \alpha) \tag{4}$$

because the ZZh coupling is reduced by a factor $\sin(\beta - \alpha)$, where α and β are the mixing angles in the neutral and charged Higgs sectors, respectively. The negative search in this process results in the upper limit [9] on $\sin^2(\beta - \alpha)$ for a given M_h, for example $\sin^2(\beta - \alpha) < 0.1$ if $M_h < 50$ GeV. However, for small $\sin^2(\beta - \alpha)$ one can exploit the Higgs pair production process (2), if kinematically allowed, because it is complementary to the process (1) in the sense that

$$\Gamma(Z \to hA) = 0.5\Gamma(Z \to \bar{\nu}\nu) \cos^2(\beta - \alpha)\lambda^{3/2} \,, \tag{5}$$

where $\lambda = (1 - \kappa_h - \kappa_A)^2 - 4\kappa_h^2\kappa_A^2$, with $\kappa_i = m_i^2/M_Z^2$. Such a procedure has been adopted at LEP1. An independent contraint on the non-SM contributions to Z decay is obtained from the analysis of the Z-lineshape, where the process (2) also contributes.

In this paper we consider a scenario in which the process (1) is suppressed (small $\sin^2(\beta - \alpha)$) *and* the process (2) is closed kinematically $(m_h + m_A > m_Z)$. Then the Yukawa process (3) becomes a dominant Higgs production mechanism at LEP1. Such a scenario can easily be realized in the 2HDM where the Higgs masses and mixing angles are not constrained theoretically. On the other hand, in the MSSM, due to supersymmetry relations, the Yukawa process may become dominant only for $m_h > 50$ GeV and $\tan\beta > 10$ [2].

The number of expected events crucially depends on $h\bar{f}f$ and $A\bar{f}f$ couplings: the SM Higgs coupling $(\sqrt{2}G_F)^{1/2}m_f$ is multiplied by the factors

5 is very weak and therefore can be neglected[2]. To derive the limits on $\tan\beta - M_\phi$ (with $\phi = h, A$) we proceed as follows:

a) We perform the calculations at the Z pole for 10^7 Z's produced.

b) We consider two different final state configurations: $b\bar{b}(\tau^+\tau^-)$ and $\tau^+\tau^-(b\bar{b})$, where the first pair denotes the fermions produced in e^+e^- collisions which radiate the Higgs boson (either h or A) and the pair in the parenthesis is coming from Higgs decay.

c) As we discussed, the $b\bar{b}\tau^+\tau^-$ channel seems to be the most promising both from theoretical (negligible QCD background) and experimental (relatively good efficiency) points of view. For example, the L3 Collaboration [13] quotes the acceptance for signal events from $Z \rightarrow hA \rightarrow b\bar{b}\tau^+\tau^-$ of the order of 5%. We assume that in the analysis of the Yukawa process similar efficiency can be achieved

d) We assume no signal events and we derive the bounds corresponding to 95% CL.

Fig. 1. The $\tan\beta - M_A$ exclusion/discovery plot for the Yukawa process for A production. The region above the lines is excluded if no signal in $b\bar{b}\tau^+\tau^-$ mode is observed. The solid line represents the results when QCD corrections are accounted for by taking the running b-quark mass and the dashed line corresponds to fixed b-quark mass $m_b = 4.6$ GeV. For comparison the dotted line shows the region that can be excluded based on 20 events with b-quark jets (using the running b-quark mass).

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[2] We use the program developed in Ref. [12] to calculate the Higgs decay branching ratios.
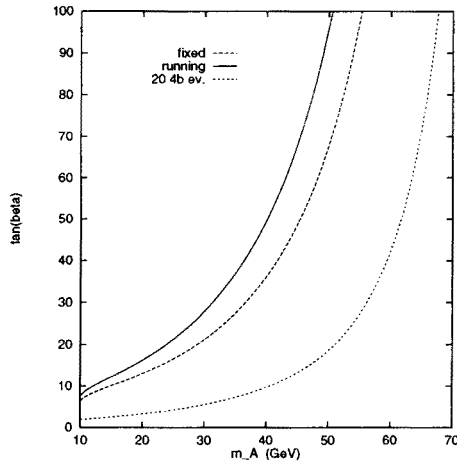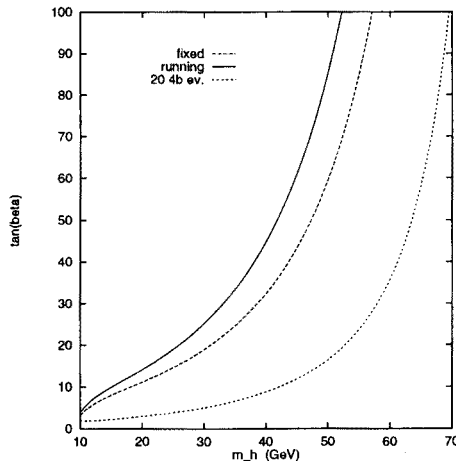
Fig. 2. The $\tan\beta - M_h$ exclusion/discovery plot for the Yukawa process for h production. The region above the lines is excluded if no signal in $b\bar{b}\tau^+\tau^-$ mode is observed. The solid line represents the results when QCD corrections are accounted for by taking the running b-quark mass and the dashed line corresponds to fixed b-quark mass $m_b = 4.6$ GeV. For comparison the dotted line shows the region that can be excluded based on 20 events with b-quark jets (using the running b-quark mass).

The results are presented in Fig. 1 for the pseudoscalar Higgs boson A and in Fig. 2 for the scalar h. Parameters above the lines are excluded. The solid lines represent the limits obtained with running b-quark mass $m_b(M_\phi)$, and the dashed lines correspond to the case of fixed b-quark mass $m_b = 4.6$ GeV, $i.e.$ neglecting QCD corrections. The QCD corrections lower the Higgs-quark coupling and consequently weaker bounds can be established. For comparison the dotted lines delineate the excluded region based on 20 $4b$-jet events expected.

Note that in the MSSM case the mass range of interest for M_h and M_A is lying above, say 50 GeV. On the other hand in the 2HDM relatively light Higgs bosons are still not excluded, for example for $\tan\beta = 20$ the Higgs masses as low as 25 GeV, and for $\tan\beta = 55$ masses of 45 GeV are not excluded.

To summarise, the Yukawa process provides interesting limits on the parameter space of 2HDM and MSSM. Both QCD and fermion mass effects influence the results considerably.

Although the first attempt to include the Yukawa process in Higgs searches at LEP1 has been made recently by L3 Collaboration [13] nevertheless this process still awaits a serious experimental investigation.

Appendix

We consider the Yukawa process

$$e^-(k_1)e^+(k_2) \to f(p_1)\bar{f}(p_2)\phi(l)$$

with $f = b$ or τ and the corresponding 4-momenta are given in brackets. The electron mass is neglected ($k_{1,2}^2 = m_e^2 = 0$) and the final state fermion (pole) mass is denoted by m ($p_{1,2}^2 = m^2$). The Higgs mass is denoted by M_ϕ and $s = (k_1 + k_2)^2$.

The differential cross section $E_1 E_2 d\sigma / d^3 p_1 \, d^3 p_2$ reads

$$E_1 E_2 \frac{d\sigma}{d^3 p_1 \, d^3 p_2} = \frac{1}{128\pi^5 s^2 x_\phi} \overline{|\mathcal{M}|}^2 \delta(x_\phi - 2 + x_1 + x_2), \qquad (A.1)$$

$$x_1 = \frac{2E_1}{\sqrt{s}}, \quad x_2 = \frac{2E_2}{\sqrt{s}}, \quad x_\phi = \frac{2E_\phi}{\sqrt{s}}, \qquad (A.2)$$

where $E_{1,2}$ and E_ϕ denote CM energies of fermions and the Higgs boson ϕ, respectively.

The matrix element, averaged over the initial and summed over final fermion polarizations, can be cast in the following form

$$\overline{|\mathcal{M}|}^2 = 64\pi^2 \alpha_{el}^2 N_c \frac{G_F}{\sqrt{2}} g_{\phi f \bar{f}}^2 m_f^2 s$$

$$\times \left\{ Q_e^2 Q_f^2 \frac{\gamma^2}{s^2} + \frac{(a_e^2 + v_e^2)[v_f^2 \gamma^2 + a_f^2 \zeta^2] + 2a_e v_e a_f v_f \chi}{(s - M_Z^2)^2 + M_Z^2 \Gamma_Z^2} \right.$$

$$\left. + Q_e Q_f \frac{(2v_e v_f \gamma^2 + a_e a_f \chi)(s - M_Z^2)}{s((s - M_Z^2)^2 + M_Z^2 \Gamma_Z^2)} \right\}, \qquad (A.3)$$

The color factor is $N_c = 3$ for $f = b$ and $N_c = 1$ for $f = \tau$. We distinguish the fermion mass which enters the coupling, m_f, from the pole mass m. In the case of the τ lepton we take $m_f = m = m_\tau$. However, in the case of the b-quark, we include QCD corrections by taking the running quark mass $m_f = m_b(M_\phi)$. Q_e, Q_f are electric charges of electrons and fermions, respectively (in units of e) whereas $a_e(a_f), v_e(v_e)$ correspond to axial and vector couplings of electron (fermion f) to Z-boson with $a = I_{3L}/2\sin\theta_W \cos\theta_W$ and $v = (I_{3L} - 2Q\sin^2\theta_W)/2\sin\theta_W \cos\theta_W$.

The contributions of the photon, Z-boson exchange and the $\gamma - Z$ interference are denoted by γ^2, ζ^2 and χ, respectively, and can be written as follows:

a) *Pseudoscalar*

In the case of the pseudoscalar production, $\phi = A$, we have $g^2_{Af\bar{f}} = \tan^2\beta$, $M_\phi = M_A$ and

$$
\gamma^2 = \frac{1}{\xi_1^2 \xi_2^2} \frac{M_A^2}{s} \left[x_A^2 \frac{-2m^2 - s}{s} + x_A(\Pi_1 \xi_2 + \Pi_2 \xi_1) \right]
$$
$$
+ \frac{1}{\xi_1 \xi_2} \left[x_A^2 - 2\left(\frac{M_A^2}{s} + 1 \right) x_T^2 \right]
$$
$$
\zeta^2 = \frac{1}{\xi_1^2 \xi_2^2} \frac{M_A^2}{s} \left[x_{21}^2 \frac{2m^2 - s}{s} - x_{21}(\Pi_1 \xi_2 - \Pi_2 \xi_1) \right]
$$
$$
+ \frac{1}{\xi_1 \xi_2} \left[x_{21}^2 + x_{21}\Pi_- + 2\left(\frac{M_A^2 - 4m^2}{s} + 1 - x_A \right) x_T^2 \right]
$$
$$
\chi = \frac{1}{\xi_1^2 \xi_2^2} \frac{M_A^2}{s} [\Xi_1 \xi_2^2 - \Xi_2 \xi_1^2] - \frac{1}{\xi_1 \xi_2} [(\Xi_1 \xi_2 - \Xi_2 \xi_1) - x_A \Delta\Pi]. \quad (A.4)
$$

b) *Scalar*

For the scalar, $\phi = h$, we have $g^2_{hf\bar{f}} = (\cos\alpha / \sin\beta)^2$, $M\phi = M_h$ and

$$
\gamma^2 = \frac{1}{\xi_1^2 \xi_2^2} \frac{M_h^2 - 4m^2}{s} \left[x_h^2 \frac{-2m^2 - s}{s} + x_h(\Pi_1 \xi_2 + \Pi_2 \xi_1) \right]
$$
$$
+ \frac{1}{\xi_1 \xi_2} \left[x_h^2 - 2(\frac{M_h^2 - 4m^2}{s} + 1)x_T^2 \right]
$$
$$
\zeta^2 = \frac{1}{\xi_1^2 \xi_2^2} \left\{ \frac{M_h^2}{s} \left[x_{21}^2 \frac{2m^2 - s}{s} - x_{21}(\Pi_1 \xi_2 - \Pi_2 \xi_1) \right] \right.
$$
$$
\left. - \frac{4m^2}{s} \left[x_h^2 \frac{2m^2 - s}{s} + x_h(\Pi_1 \xi_2 + \Pi_2 \xi_1) \right] \right\}
$$
$$
+ \frac{1}{\xi_1 \xi_2} \left[x_{21}^2 + x_{21}\Pi_- - 16\frac{m^2}{s}\left(x_h - \frac{M_h^2}{s} \right) + 2\left(\frac{M_h^2}{s} + 1 - x_h \right) x_T^2 \right]
$$
$$
\chi = \frac{1}{\xi_1^2 \xi_2^2} \left[\frac{M_h^2}{s}(\Xi_1 \xi_2^2 - \Xi_2 \xi_1^2) - \frac{4m^2}{s} x_h(\Xi_1 \xi_2 - \Xi_2 \xi_1) \right]
$$
$$
- \frac{1}{\xi_1 \xi_2} \left[(\Xi_1 \xi_2 - \Xi_2 \xi_1) - x_h \Delta\Pi \right] \quad (A.5)
$$

where the following variables are introduced

$$x_{21} = x_2 - x_1 \tag{A.6}$$

$$\xi_1 = 1 - x_1, \quad \xi_2 = 1 - x_2 \tag{A.7}$$

$$x_T^2 = \frac{4(p_1 + p_2) \cdot k_1 \, (p_1 + p_2) \cdot k_2}{s^2} - 1 + x_h - \frac{M_\phi^2}{s} \tag{A.8}$$

$$\Pi_1 = 8\frac{p_1 \cdot k_1 \, p_1 \cdot k_2}{s^2}, \quad \Pi_2 = 8\frac{p_2 \cdot k_1 \, p_2 \cdot k_2}{s^2} \tag{A.9}$$

$$\Pi_- = \Pi_1 - \Pi_2 \tag{A.10}$$

$$\Xi_1 = \frac{4p_1 \cdot (k_1 - k_2)}{s}, \quad \Xi_2 = \frac{4p_2 \cdot (k_1 - k_2)}{s} \tag{A.11}$$

$$\Delta\Pi = 8\frac{p_1 \cdot k_1 \, p_2 \cdot k_2 - p_1 \cdot k_2 \, p_2 \cdot k_1}{s^2} \tag{A.12}$$

REFERENCES

[1] E. Carlson, S. Glashow, U. Sarid, *Nucl. Phys.* **B309**, 598 (1988); J. Kalinowski, S. Pokorski, *Phys. Lett.* **B219**, 116 (1989).
[2] J. Kalinowski, H.P. Nilles, *Phys. Lett.* **B255**, 134 (1991); J. Kalinowski, in Proc. Int. Symposium on Elementary Particle Physics, Kazimierz, (1991).
[3] A. Djouadi, P.M. Zerwas, J. Zunft, *Phys. Lett.* **B259**, 175 (1991).
[4] J.D. Wells, G.L. Kane, preprint hep-ph/9510372.
[5] E. Ma, D. Ng, Proc. Int. Symposium on Vector Boson Self-Interactions, UCLA (1995); E. Ma, D. Ng, preprint hep-ph/9508338; A.K. Grant, *Phys. Rev.* **D51**, 207 (1995).
[6] ALEPH Collab., Note EPS0415 (July 1995), submitted to the EPS and Lepton-Photon Conferences.
[7] J.F. Gunion, H.E. Haber, G.L. Kane, S. Dawson, *The Higgs Hunter's Guide*, Addison–Wesley, Reading 1990.
[8] J.-F. Grivaz, talk at Int. EPS Conference on High Energy Physics, Brussels (July 1995).
[9] L3 Collab., Internal Note 1800 (July 1995), submitted to the EPS and Lepton-Photon Conferences.
[10] J. Kalinowski, M. Krawczyk, in preparation.
[11] J. Kalinowski, M. Krawczyk, *Phys. Lett.* **B361**, 66 (1995).
[12] A. Djouadi, J. Kalinowski, P. Zerwas, preprint DESY 95-211.
[13] L3 Collab., Internal Note 1801 (July 1995), submitted to the EPS and Lepton-Photon Conferences.