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THE EFFECT OF A LIGHT NEUTRAL HIGGS BOSON TO THE Z-LINESHAPE

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Abstract

The cross-sections and branching-ratios for $e^+e^- \rightarrow Hq\bar{q}$ and $e^+e^- \rightarrow Hf\bar{f}$ in the vicinity of the Z boson peak are calculated with the parameters reported by the ALEPH Collaboration at LEP. We find that the light neutral Higgs boson in the mass range below 2 GeV can be determined clearly by Z-lineshape provided the event number of $Z \rightarrow$ hadrons or charged leptons is enhanced to 10^6 or more. To fit the present ALEPH data, the current mass of top quark in the standard model should be above $m_Z/2$.

I. Introduction

The neutral Higgs boson, which plays an essential role in the electroweak gauge theory of Glashow, Weinberg, and Salam, has not been seen. A series of searches using the processes $Z \rightarrow H\ell\bar{\ell}$ and $Z \rightarrow Hq\bar{q}$ is performed on data collected by the ALEPH detector in the vicinity of the Z resonance, and the Higgs boson has been excluded in the mass range from 32 MeV to 24 GeV at 95% C. L.^[1,2] There have been many other searches, such as from the muonic X-ray, and the decay of nuclei, π, K, B, Υ , etc.^[3] However, the limitation in experiments to detect precisely the final products and the uncertainty in theory, e.g. the proposed decay models or QCD calculations, cause some of these searches unsatisfactory, especially for light Higgs roughly near the mass of the π .

We shall calculate $e^+e^- \rightarrow Hq\bar{q}$ and $e^+e^- \rightarrow Hf\bar{f}$ mediated by Z in the standard model. It has the merit that the theoretical uncertainty here is quite small since the ZZH and Zff vertices are electroweak gauge ones which are well known. On the other hand, summing over the final $q\bar{q}$ and $f\bar{f}$ can be assumed to correspond to detecting all the final hadrons or charged leptons, and the concrete final particles do not need to distinguish. This will reduce the experimental uncertainty very much. Furthermore, the light neutral Higgs boson signal in our methods is quite characteristic and can not be wiped out by other factors which also affect the Z-lineshape, e.g. the changes of the parameters of the Z peak.

Using the parameters recently presented by the ALEPH Collaboration^[4], we fit the measured Z-lineshape for $e^+e^- \rightarrow$ hadrons as function of LEP energy first, and find that the top quark mass should be approximately above $m_Z/2$, i.e. Z can not decay into $t\bar{t}$. We subsequently give the cross-sections of $e^+e^- \rightarrow Hq\bar{q}$ and $e^+e^- \rightarrow Hf\bar{f}$ as well as the branching-ratios of theirs in $e^+e^- \rightarrow q\bar{q}$ and $e^+e^- \rightarrow f\bar{f}$. The values of the branching-ratios are about 1% when the neutral Higgs boson mass is below 2 GeV, and its existence can be determined if the Z events are accumulated to 10^6 or

more.

II. The Cross-Sections and Branching-Ratios of Born Approximation

The basic processes mediated by real and virtual neutral gauge bosons are

$$e^+e^- \longrightarrow Z \longrightarrow f\bar{f}, \quad (1)$$

$$e^+e^- \longrightarrow \gamma \longrightarrow f\bar{f}, \quad (2)$$

as well as

$$e^+e^- \longrightarrow Z \longrightarrow HZ \longrightarrow Hf\bar{f}, \quad (3)$$

which are illustrated in Fig.1. The corresponding interaction lagrangians are $\mathcal{L}_{Zff} = \bar{\psi}_f \gamma^\mu (g_V - g_A \gamma_5) \psi_f Z_\mu$, $\mathcal{L}_{\gamma ff} = Q_e \bar{\psi}_f \gamma^\mu \psi_f A_\mu$ and $\mathcal{L}_{ZZH} = g_H Z^\mu Z_\mu H$. Here $g_H = 2e m_Z / \sin 2\theta_w$, and we define $C_+ = g_V^2 + g_A^2$, $C_- = g_A^2 - g_V^2$. The coefficients Q , g_V and g_A are shown in Table 1.

For unpolarized beams the total cross-sections of $e^+e^- \rightarrow f\bar{f}$ and $e^+e^- \rightarrow Hf\bar{f}$ are given by

$$\sigma_B(e^+e^- \rightarrow f\bar{f}) = \frac{4\pi\alpha^2 Q^2}{3} \cdot \frac{AB}{C} + \frac{2\sqrt{2}\alpha Q g_F m_Z^2 g_V^i g_V^f}{3} \cdot \frac{AB}{C} + \frac{g_F^2 m_Z^4 C_\pm^i}{6\pi} \cdot \frac{SA}{C^2} \cdot (g_V^{f^2} B + g_A^{f^2} A^2), \quad (4)$$

$$\sigma_B(e^+e^- \rightarrow Hf\bar{f}) = \frac{g_F^2 m_Z^8}{3\sqrt{2}\pi^3} \cdot \frac{C_\pm^i}{C^2} \cdot \int_{m_H}^{(S+m_H^2-4m_f^2)/2\sqrt{S}} dE_H \cdot \frac{\sqrt{E_H^2-m_H^2} \cdot \sqrt{1-m_f^2/D}}{(D-m_Z^2)^2+m_Z^2\Gamma_t^2} \cdot \left[-3C_-^f m_f^2 + C_+^f \left(D + \frac{1}{3}E_H^2 - \frac{1}{3}m_H^2 - m_f^2 + \frac{2m_f^2(E_H^2-m_H^2)}{3D} \right) \right], \quad (5)$$

$$\begin{aligned} A &= \sqrt{1-4m_f^2/S}, \\ B &= (1+2m_f^2/S), \\ C &= \sqrt{(S-m_Z^2)^2+m_Z^2\Gamma_t^2}, \\ D &= (S+m_H^2-2\sqrt{S}E_H), \end{aligned}$$

where equation (5) has avoided the infrared divergence at $m_H = 0$ ^[5]. Here the upper indices i and f represent the initial and final states, α is the electromagnetic coupling constant, G_F is the Fermi coupling constant, m_f is the mass of the final-state fermion, m_Z and m_H are the masses of Z boson and Higgs boson, s is the square of the center-of-mass energy of the colliding beam, E_H is the energy of the Higgs boson, and Γ_i is the total width of Z decay. In the standard model, the width of $Z \rightarrow f\bar{f}$ is

$$\Gamma_B(Z \rightarrow f\bar{f}) = \frac{G_F m_Z^3}{6\sqrt{2}\pi} \cdot \sqrt{1 - 4m_f^2/m_Z^2} \cdot [C_+^f(1 - m_f^2/m_Z^2) - 3C_-^f m_f^2/m_Z^2] \quad (6)$$

Now we define the branching-ratio:

$$B_R(e^+e^- \rightarrow H f\bar{f}) = \sigma'_B(e^+e^- \rightarrow H f\bar{f}) / \sigma_B(e^+e^- \rightarrow f\bar{f}). \quad (7)$$

III. The Radiative Corrections

In e^+e^- annihilation the proper treatment of the electromagnetic radiation in initial-state is required. Here we adopt the structure function approach introduced by Kuraev and Fadin which can calculate this correction to 0.1% accuracy^[6,7]. The corrected cross-section is formulated by

$$\sigma(s) = \int_{x_{\min}}^{x_{\max}} dx \sigma_B(s(1-x)) F_{\text{QED}}(x, s), \quad (8)$$

where $\sigma_B(s)$ is the cross-section of Born Approximation, and

$$F_{\text{QED}}(x, s) = \kappa \beta x^{\beta-1} \left[1 + \frac{3}{4}\beta - \frac{\beta^2}{24} \left(\frac{1}{3} \ln \frac{s}{m_e^2} + 2\pi^2 - 37/4 \right) \right. \\ \left. - \beta(1-x) + \frac{1}{8}\beta^2 \left[4(2-x) \ln \frac{1}{x} - \frac{1+3(1-x)^2}{x} \{ \ln(1-x) - 6 + x \} \right] \right]. \quad (9)$$

Here $\beta = \frac{2}{\pi}(\ln \frac{s}{m_e^2} - 1)$ and $\kappa = 1 + \frac{\pi}{4}(\frac{\pi^2}{3} - \frac{1}{2})$ for vector coupling and $1 + \frac{\alpha\pi}{3}$ for axial vector coupling^[8].

In the expression of $F_{QED}(x, s)$, the first term is the soft photon contribution, while the second and third terms are the hard photon contributions, and they are truncated to β^2 order.

Commonly, $X_{max} < 1$, and it should be determined with the experimental conditions. Here we take $X_{max} = 0.999$, and the integration can be checked insensitive to 0.999 or 0.99. We take $X_{min} = 0$. When $x \rightarrow 0$ the soft photon term is the dominant contribution, and $F_{QED}(x, s)$ can be approximately shown by

$$F_{QED}(x, s) \Big|_{x \rightarrow 0} \doteq b \, d x^\beta / d x. \quad (10)$$

Here we define $b = \kappa[1 + \frac{3}{4}\beta - \frac{\beta^2}{24}(\frac{1}{3}\ln \frac{s}{m_e^2} + 2\pi^2 - \frac{37}{4})]$.

We take the small quantity $\epsilon = 0.001$ (It does not matter whether $\epsilon = 0.005$ or 0.0001 within the required accuracy 0.1%), and transform equation (8) into

$$\begin{aligned} \sigma(s) &\doteq \int_0^\epsilon dx \, \sigma_B(s(1-x)) F_{QED}(x, s) \Big|_{x \rightarrow 0} + \int_\epsilon^{0.999} dx \, \sigma_B(s(1-x)) F_{QED}(x, s) \\ &\doteq b \epsilon^\beta \sigma_B(s) + \int_\epsilon^{0.999} dx \, \sigma_B(s(1-x)) F_{QED}(x, s). \end{aligned} \quad (11)$$

In the equation above, we have made the integrant singularity free.

Similarly, the branching-ratio is corrected by

$$B_T(s) \doteq b \epsilon^\beta B_{TB}(s) + \int_\epsilon^{0.999} dx \, B_{TB}(s(1-x)) F_{QED}(x, s). \quad (12)$$

Also important for strongly interacting final states are the final-state QCD radia-

tive correction^[9],

$$\sigma(s) = N_c \sigma_B(s) F_{QCD}, \quad (13)$$

$$B_T(s) = N_c B_{TB}(s) F_{QCD}, \quad (14)$$

$$\Gamma = N_c \Gamma_B F_{QCD}, \quad (15)$$

where $N_c = 1$ for leptons and 3 for colour-triplet quarks. To a very good approximation, F_{QCD} is given to leading order in α_s by

$$F_{QCD} \doteq 1 + \alpha_s / \pi, \quad (16)$$

here α_s is the strong coupling constant.

IV. Results and Discussions

Some parameters reported by the ALEPH Collaboration are listed in Table 2. Using these parameters we can perform our calculations above in computers and give some physics results.

(i) First of all, we perform the total width of $Z \rightarrow f\bar{f}$ as function of top quark mass through equations (6) and (15). The results are illustrated in Fig.2(a). We find that m_t approaches $m_Z/2$ when $\Gamma(Z \rightarrow f\bar{f})$ does the experimental value 2.541 ± 0.056 GeV. Since $\Gamma(Z \rightarrow t\bar{t}) \rightarrow 0$ if $m_t \rightarrow m_Z/2$, we can conclude that $t\bar{t}$ does not occur in the decay of $Z \rightarrow$ hadrons, i.e. the mass of top quark is beyond $m_Z/2$.

This conclusion can be proved by another way, calculating the cross-section peak of $e^+e^- \rightarrow$ hadrons as function of m_t through equation (4), (11) and (13) (see Fig.2(b)). In order to fit the measured $\sigma_{had}^{peak} = 41.4 \pm 0.8$ nb, m_t should be taken about $m_Z/2$ or much larger. So we believe $m_t > m_Z/2$.

The result agrees with the mass limit of top quark reported by ALEPH Collaboration in the direct search for Z decays into pairs of possible new heavy quarks (t

and b')^[10].

(ii) We show the cross-sections and branching-ratios of $e^+e^- \rightarrow Hq\bar{q}$ and $e^+e^- \rightarrow Hf\bar{f}$ where f is a charged lepton or quark in Fig.3 and Fig.4 as functions of $\sqrt{s}$ through equations (5), (7), (11), (12), (13) and (14). For light neutral Higgs boson ($m_H < 2 \text{ GeV}$), the branching-ratios are about 1%, but they fall down considerably when $m_H > 10 \text{ GeV}$. In the performance, we find that a light neutral Higgs boson makes the lineshape shift to the higher energy side and it cannot be wiped out by changes of the parameters of Z peak such as m_Z , Γ_Z and α , etc. Therefore, it is clear that the Z-lineshape can be used to search for the light neutral Higgs boson in the mass range below 2 GeV.

So far, there are about 25000 events of $Z \rightarrow \text{hadrons}$ in Z factory at LEP and the statistical errors exceed 1% in the vicinity of Z resonance. Moreover, the systematic errors are about 1% (exactly, they are 1.3% for the luminosity measurement, 0.6% for the Z events of each selection and 0.4% for the corresponding error in the combined cross-section.)^[4]. All these errors have shaded the processes with Higgs boson.

Our suggestion is the detector should be improved continuously to suppress the systematic errors (especially the errors of selecting the Z events.) to about 0.1%, and the Z events should be collected largely to 10^6 or more.

If the systematic and statistical problems are solved, we can fit the experimental data on the basis of equations (4), (11) and (13) instead of the Breit-Wigner form near the Z resonance, in order to find the possible influence from $e^+e^- \rightarrow Hq\bar{q}$ or $e^+e^- \rightarrow Hf\bar{f}$. Then we can give a determination for the possibility of the existence of light neutral Higgs boson.

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Table 1

The coupling constants of the Feynman diagram in Fig.1.

$f\bar{f}$	Q	g_V	g_A
$\nu_e \bar{\nu}_e, \nu_\mu \bar{\nu}_\mu, \nu_\tau \bar{\nu}_\tau$	1	$\frac{1}{2}$	$\frac{1}{2}$
$e^- e^+, \mu^- \mu^+, \tau^- \tau^+$	1	$2 \sin^2 \theta_W - \frac{1}{2}$	$-\frac{1}{2}$
$u \bar{u}, c \bar{c}, t \bar{t}$	$\frac{2}{3}$	$\frac{4}{3} \sin^2 \theta_W - \frac{1}{2}$	$-\frac{1}{2}$
$d \bar{d}, s \bar{s}, b \bar{b}$	$-\frac{1}{3}$	$\frac{2}{3} \sin^2 \theta_W - \frac{1}{2}$	$-\frac{1}{2}$

Table 2

Some parameters of Z peak reported by the ALEPH Collaboration in Ref.[4].

m_Z (GeV)	91.182 ± 0.026 (exp.) ± 0.030 (beam)
Γ_Z (GeV)	2.541 ± 0.056
σ_{had}^{peak} (nb)	41.4 ± 0.8
$\sin^2 \theta_W (m_Z)$	0.231 ± 0.008
N_ν	3.01 ± 0.15 (exp.) ± 0.05 (theor.)
$\alpha_s (m_Z)$	0.22 ± 0.10

Figure Captions

Fig.1 Feynman diagrams for (a) $e^+e^- \rightarrow Z \rightarrow f\bar{f}$ and $e^+e^- \rightarrow \gamma \rightarrow f\bar{f}$, (b) $e^+e^- \rightarrow Z \rightarrow Z H \rightarrow H f\bar{f}$.

In our performance, we take the masses of leptons and quarks as $m_f(\nu_e, \nu_\mu, \nu_\tau, e, \mu, \tau; u, d, s, c, b) = 0.0, 0.0, 0.0, 0.0, 0.1, 1.8; 0.0, 0.0, 0.2, 1.5, 5.0$ GeV, and $\alpha = \frac{1}{128}$. We also take the measured parameters of Z resonance as $m_Z = 91.182$ GeV, $\Gamma_Z = 2.523$ GeV, $\sin^2\theta_w = 0.230$, $N_\nu = 3$, $\alpha_s = 0.22$, and all these values are within the given experimental errors.

Fig.2 (a) The total width of $Z \rightarrow f\bar{f}$ where f is a fermion as function of the top quark mass, (b) The uncorrected cross-section peak of $e^+e^- \rightarrow$ hadrons as function of the top quark mass. They both give $m_t \gtrsim m_Z/2$.

Fig.3 The cross-sections of (a) $e^+e^- \rightarrow Hq\bar{q}$ (b) $e^+e^- \rightarrow Hf\bar{f}$ as functions of the center-of-mass energy.

Fig.4 The branching-ratios of (a) $e^+e^- \rightarrow Hq\bar{q}$ and (b) $e^+e^- \rightarrow Hf\bar{f}$ as functions of the center-of-mass energy.

Fig.1(a)

Fig.1(b)

Fig.2(a)

Fig.2(b)

Fig.3(a)

Fig.3(b)

Fig.4(a)

Fig.4(b)