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Radion effects on the production of an intermediate-mass scalar and Z at LEP II

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Abstract

We have studied the $e^+e^- \to Z\phi_i \to Zb\bar{b}$ process, where ϕ_i is the Higgs and/or radion bosons. In the case where the radion is lighter than the Higgs, the enhanced coupling between the radion and two gluons due to the trace anomaly suppresses the cross section of radion production with respect to that calculated by assuming that the resonant peak indicates the SM Higgs. If the radion is highly degenerate in mass with the Higgs, the cross section can be increased more than at one sigma level. The implications of the radion effects on the preliminary ALEPH data are also discussed.

I. INTRODUCTION

The standard model (SM) has been very successful in describing the known electroweak interactions of gauge bosons and fermions. Nevertheless one of the most crucial ingredients of the SM, Higgs particles, has not been experimentally discovered yet [1]. The Higgs mechanism is responsible for the electroweak symmetry breaking in the SM, of which the effects should appear by the scale below $(8\pi\sqrt{2}/3G_F)^{1/2} \sim 1$ TeV for the preservation of unitarity in the $W_L W_L \to W_L W_L$ process [2]. Hence the primary efforts of the future collider experiments are to be directed toward the search for Higgs bosons.

The search techniques for Higgs bosons according to the Higgs mass range have been extensively studied in the literature [3]. Light Higgs bosons with mass below the Z boson mass are excluded by LEP-II experiments [4]. For *heavy* Higgs bosons ($m_h \gtrsim 2m_Z$), the experimental search is rather strait-forward by observing the Higgs decay into a Z boson pair, or by studying WW scattering at e^+e^- or hadron colliders [5]. For the *intermediate*-mass ($m_Z < m_h \lesssim 2m_Z$), one of the best reactions for their detection at e^+e^- colliders is known to be $e^+e^- \to Z^* \to Zh$ (see the corresponding Feynman diagram in Fig. 1) [6]. The Higgs boson in this mass range decays almost into $b\bar{b}$. The direct physics background from the continuum production of $e^+e^- \to Zb\bar{b}$ has been also discussed in the literature.

Theoretically, the Higgs boson holds a distinctive position in understanding the physics beyond the SM. The existence of the Higgs boson in the SM, as a fundamental scalar particle, causes the well-known gauge hierarchy problem: It is unnatural that the Higgs mass at the electroweak scale is protected from the presence of the enormous Planck scale. This gauge hierarchy problem is the main motivation for various models for new physics, such as supersymmetric models, technicolor models, and extra dimensional models. Among these, an extra-dimensional model recently proposed by Randall and Sundrum (RS) requires the existence of another scalar field, called the radion, of which the mass can be compatible with the Higgs mass [7].

In this report, we study the radion effects on the $e^+e^- \to Z\phi_i \to Zb\bar{b}$ process, where the

ϕ_i is a scalar particle. Recently, an exciting, even very preliminary, news has come from the ALEPH group [8]. From the analyses of two b-jets accompanying the gauge boson Z, the ALEPH has measured $3.8 - 3.9$ standard deviation from the SM continuum background. This result is compatible with the SM Higgs of mass around 114 GeV. Another unusual result is that the cross section with the SM Higgs is still high; the standard deviation is between 1σ to 2.5σ. If this result remains valid in the possible extension of LEP-II running, the radion, if degenerate in mass with the Higgs, can be one of the best candidates for the explanation of the excess. We caution the reader that due to the small number of events and the presence of background in the current ALEPH data, it is very impetuous to draw any physical conclusion at this moment.

In the RS model, the hierarchy problem is solved by a geometrical exponential factor, called a warp factor [7]. The spacetime has a single S^1/Z_2 orbifold extra dimension with the metric

$$ds^2 = e^{-2kr_c|\varphi|}\eta_{\mu\nu}dx^\mu dx^\nu + r_c^2 d\varphi^2, \tag{1}$$

where the φ is confined to $0 \leq |\varphi| \leq \pi$. Two orbifold fixed points accommodate two three-branes, the hidden brane at $\varphi = 0$ and our visible brane at $|\varphi| = \pi$. The allocation of our brane at $|\varphi| = \pi$ renders a fundamental scale m_0 to appear as the four-dimensional physical mass $m = e^{-kr_c\pi}m_0$. The hierarchy problem can be answered if $kr_c \simeq 12$. In this model, very critical is the stabilization of the compactification radius r_c: Without a stabilized radius, we should impose a fine-tuning constraint between the matter densities on the two branes, which causes non-conventional cosmologies [9]. Several scenarios for the stabilization mechanism have been proposed, where the radion modulus ϕ can be significantly lighter than the geometrically suppressed Planck scale on the visible brane, $\Lambda \sim \mathcal{O}(\text{TeV})$ [10]. The phenomenology of the radion at colliders, focused on its decay modes, has been studied [11].

The interactions of the radion ϕ with the SM particles show similar behaviors to those of the Higgs boson. The interaction Lagrangian is

$$\mathcal{L} = \frac{1}{\Lambda_\phi} \, \phi \, T^\mu_\mu \, , \tag{2}$$

where the T^μ_μ is the trace of the conserved and symmetrized energy-momentum tensor of the SM fields, and the Λ_ϕ is the vacuum expectation value (VEV) of the radion. The coupling of the radion with a fermion pair, or a W, Z gauge boson pair, is the same as that of the Higgs, except for a factor of (v/Λ_ϕ). The v is the VEV of the Higgs. The massless gluons and photons also contribute to the T^μ_μ, due to the trace anomaly. It is known that the trace anomaly appears since the scale invariance of massless fields is broken by the running of gauge couplings [12]. Thus the interaction Lagrangian between two gluons and the Higgs or the radion is

$$\mathcal{L}_{h(\phi)-g-g} = \left[\left(\frac{v}{\Lambda_\phi} \right) \left\{ b_3 + I_{1/2}(z_t) \right\} \phi + I_{1/2}(z_t) h \right] \frac{\alpha_s}{8\pi v} \, \mathrm{Tr}(G^C_{\mu\nu} G^{C\mu\nu}) \, , \tag{3}$$

where $z_t = 4m_t^2/m_h^2$, and the QCD beta function coefficient is $b_3 = 11 - 2n_f/3$ with the number of dynamical quarks n_f. The loop function $I_{1/2}(z)$ is defined by

$$I_{1/2}(z) = z[1 + (1 - z) f(z)] \, , \tag{4}$$

where the $f(z)$ is

$$f(z) = \begin{cases} \arcsin^2(1/\sqrt{z}) \, , & z \geq 1 \, , \\ -\frac{1}{4} \left[\ln \left(\frac{1+\sqrt{1-z}}{1-\sqrt{1-z}} \right) - i\pi \right]^2 \, , & z \leq 1 \, . \end{cases} \tag{5}$$

It is to be noted that the phenomenology of radions can be determined by two parameters, m_ϕ and Λ_ϕ.

We consider the process $e^- e^+ \to Z\phi_i \to Zb\bar{b}$ ($\phi_{1,2} = h, \phi$). The scattering amplitudes for the process can be written as

$$\mathcal{M}(e^- e^+ \to Z\phi_i \to Zb\bar{b}) = \mathcal{M}(e^- e^+ \to Z\phi_i) \, D_i(q^2) \, \mathcal{M}(\phi_i \to b\bar{b}) \, , \tag{6}$$

where $D_i(q^2)$ is the propagation factor for the i-th scalar particle. We are interested in the circumstance where the lighter scalar is produced almost on-shell, which can be confirmed by the measurement of the invariant mass distribution of the $b\bar{b}$ jets. For much heavier radions than Higgs bosons, the ordinary analyses with the SM Higgs remain intact. In the case where the radion is lighter or almost degenerate in mass with the Higgs, however, the cross section for the process is to be modified.

First, when the radion is lighter, the cross section of the radion production is different from the cross section calculated by assuming that the on-shell scalar particle is the SM Higgs:

$$\sigma(e^-e^+ \to Z\phi \to Zb\bar{b}) = \left(\frac{v^2}{\Lambda_\phi^2}\frac{\Gamma_h(m_h = M_{bb}^{(\mathrm{res})})}{\Gamma_\phi(m_\phi = M_{bb}^{(\mathrm{res})})}\right)^2 \sigma(e^-e^+ \to Zh \to Zb\bar{b})_{m_h = M_{bb}^{(\mathrm{res})}}\,, \qquad (7)$$

where the $M_{bb}^{(\mathrm{res})}$ is the invariant mass of the $b\bar{b}$ jets at its peak, and the Γ_{h} and Γ_ϕ are the total decay rates for the Higgs and radion, respectively. Note that we have used the resonant invariant mass of two b-jets, $M_{bb}^{(\mathrm{res})}$, for the Higgs and radion masses, since the mass of the on-shell scalar would be deduced from the $M_{bb}^{(\mathrm{res})}$. In order to explain the hierarchy problem, the Λ_ϕ should be at the electroweak scale ($\Lambda_\phi > 500$) GeV, implying the ratio (v/Λ_ϕ) is small. On the other hand, the decay-rate ratio Γ_h/Γ_ϕ is inversely proportional to $(v/\Lambda_\phi)^2$, resulting in substantial cross section for the radion production compared to the SM Higgs production. For the intermediate-mass scalar particle, the main decay modes are into $b\bar{b}$, $\tau^+\tau^-$, and gg. Then, Eq. (7) reduces to

$$\frac{\sigma(\phi)_{m_\phi = M_{bb}}}{\sigma(h)_{m_h = M_{bb}}} = \frac{1 + C_{\tau b} + C_{\mathrm{QCD}}(M_{bb})|I_{1/2}(z_t)|^2}{1 + C_{\tau b} + C_{\mathrm{QCD}}(M_{bb})|b_3 + I_{1/2}(z_t)|^2}\,, \qquad (8)$$

where $z_x = 4m_x^2/M_{bb}^2$, and the $C_{\tau b}(M_{bb})$ and $C_{\mathrm{QCD}}(M_{bb})$ are,

$$\begin{aligned} C_{\tau b} &= \frac{1}{3}\left(\frac{m_\tau}{m_b}\right)^2 \left(\frac{1 - z_\tau}{1 - z_b}\right)^{3/2}\,, \\ C_{\mathrm{QCD}}(M_{bb}) &= \frac{\alpha_s^2}{12\pi^2}\left(\frac{M_{bb}}{m_b}\right)^2\,. \end{aligned} \qquad (9)$$

Since the QCD beta function coefficient b_3 is 7 for $n_f = 6$, the cross section for the lighter radion production is less than the calculated one with the SM Higgs assumption. In Fig. 2, we plot the ratio in Eq. (8) as a function of the b-jet invariant mass; the ratio is from ten to twenty percent, decreasing with increasing M_{bb}. This ratio would be one if the b_3 were to be zero; the QCD trace anomaly effects suppress the production of the lighter radion with intermediate mass through the process $e^+e^- \to Z\phi \to Zb\bar{b}$, compared to that of the SM Higgs.

Second, the radion, if almost degenerate in mass with the Higgs, will also modify the cross section. The effects can be casted into the ratio between the total cross sections with and without the radion effects, called $\mathcal{R}_{\rm deg}$. Since the Higgs production is dominant over the radion production as discussed before, we assume that the $b\bar{b}$ invariant mass distribution peaks at the mass of the Higgs. The $\mathcal{R}_{\rm deg}$ is

$$\begin{aligned}
\mathcal{R}_{\rm deg} &\equiv \frac{\sigma_{\rm Higgs+\phi}}{\sigma_{\rm Higgs}} \qquad (10) \\
&= \left| 1 + \left(\frac{v}{\Lambda_\phi}\right)^2 \frac{D_1(q^2 = m_h^2)}{D_2(q^2 = m_h^2)} \right|^2 \\
&= \left| 1 + \left(\frac{v}{\Lambda_\phi}\right)^2 \frac{i\Gamma_{\rm h} m_{\rm h}}{m_h^2 - m_\phi^2 + i\Gamma_\phi m_\phi} \right|^2 \qquad (11)
\end{aligned}$$

where $m_\phi \equiv m_h + \Delta m$. The difference in mass between the Higgs and radion, Δm, is assumed to be below the mass resolution at e^+e^- colliders. Note that whether the radion is slightly lighter or heavier does not affect the results because the $\mathcal{R}_{\rm deg}$ depends on the $(\Delta m)^2$. In general the $\mathcal{R}_{\rm deg}$ is larger than one, implying that the presence of degenerate radions with Higgs bosons increases the cross section.

Now we discuss the implications of the radion effects for the preliminary ALEPH results. As discussed in the lighter radion case, the intermediate-mass scalar produced at LEP II of the cross section compatible with the SM Higgs prediction cannot be the radion, of which the physical origin is the QCD trace anomaly. In the degenerate case, it is possible to explain one of the preliminary ALEPH results; the cross section is measured still higher than that with the SM Higgs. Figures 3 and 4 present, in two parameter $(\Delta m, \Lambda_\phi)$ space, contours which explain the 1σ and 2σ excesses in the cross section at $\sqrt{s} = 207$ GeV. The Higgs mass m_h is set to be 114 GeV, used as the QCD scale in α_s. In Fig. 3 the integrated luminosity is 170 pb^{-1} as considering the current LEP II status. Figure 4 is obtained with luminosity 700 pb^{-1}. It is concluded that highly degenerate radions with the SM Higgs can be a good explanation for the excess of the scalar production accompanying Z at e^+e^- colliders.

In summary, we studied the $e^+e^- \to Z\phi_i \to Zb\bar{b}$ process, where ϕ_i is the Higgs and/or radion particles. In the case of the lighter radion than the Higgs, the QCD trace anomaly suppressed the cross section with respect to that calculated by assuming that the resonant peak is the SM Higgs. If the radion is highly degenerate in mass with the Higgs, the cross section can be increased more than at one sigma level. This can be one of the most natural explanation for the preliminary ALEPH results of the excess in the cross section with the SM Higgs. Increasing luminosity at LEP II could provide interesting implication on the radion phenomenology, as well as the historic discovery of the Higgs.

ACKNOWLEDGMENTS

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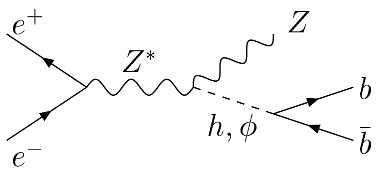

FIG. 1. The Feynman diagram of the $e^+e^- \to Z\phi_i \to Zb\bar{b}$ process with the Higgs and radion.

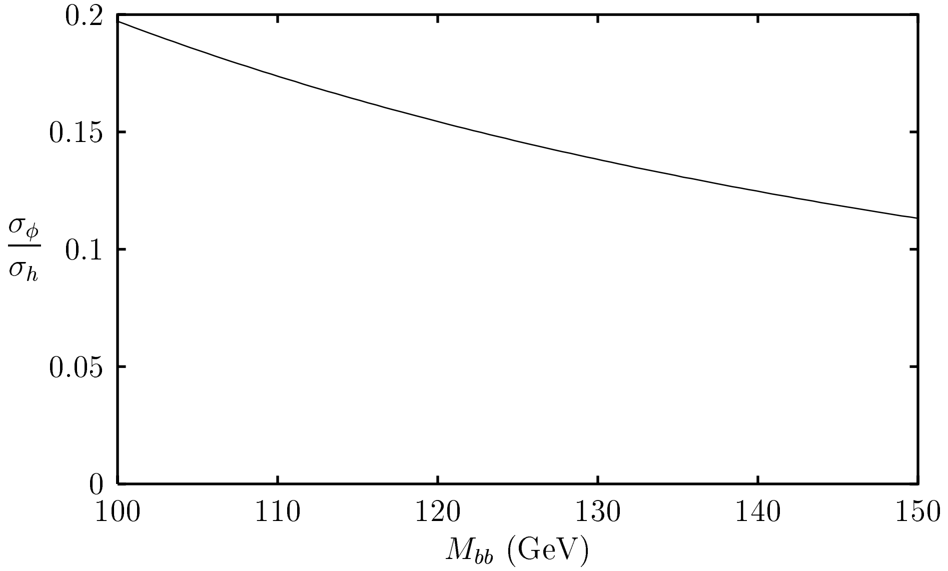

FIG. 2. The ratio of the cross section for the lighter radion production to that calculated by assuming that the resonant peak is the SM Higgs.

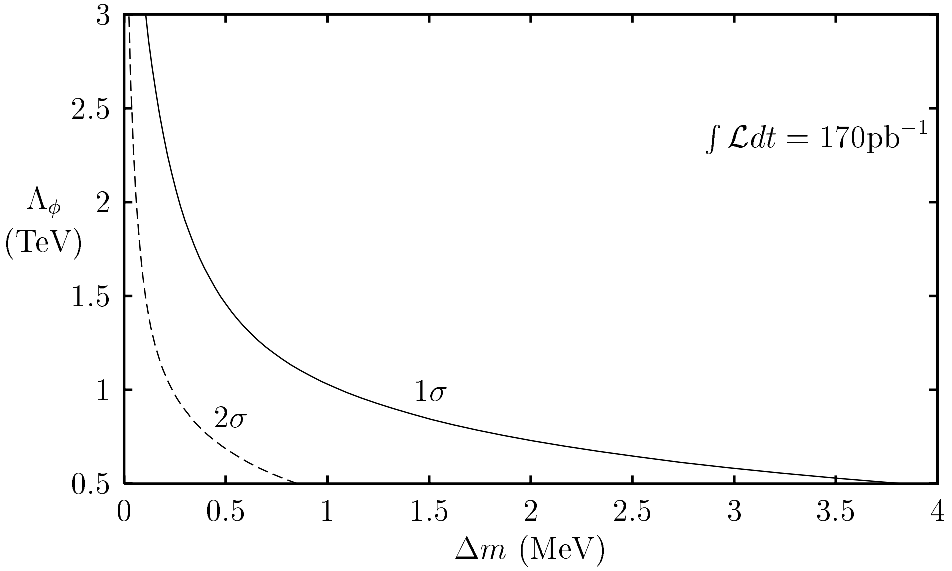

FIG. 3. The contours of 1σ and 2σ cross section excess in the parmeter space $(\Delta m, \Lambda_\phi)$. The integrated luminosity is 170 pb^{-1}, and $\sqrt{s} = 207$ GeV.

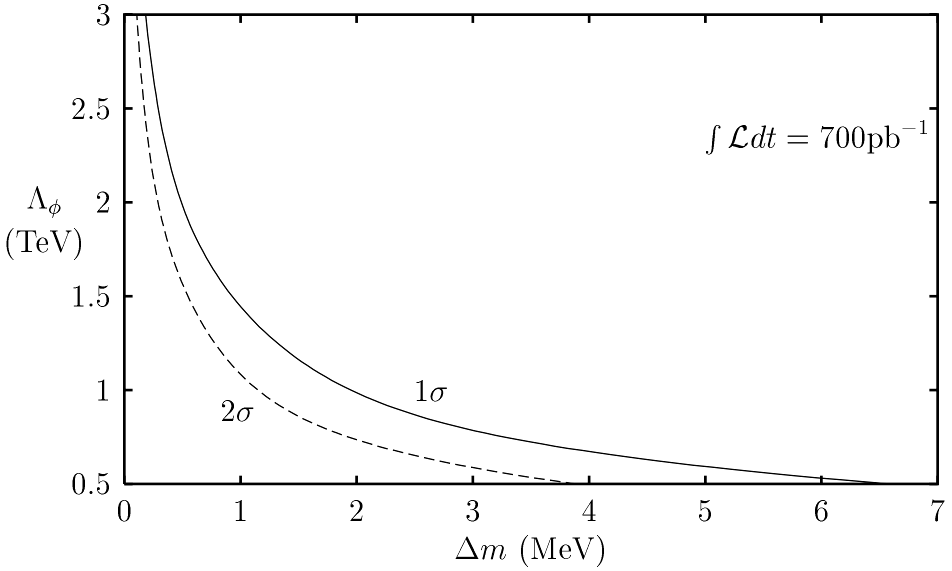

FIG. 4. The same plot with Fig. 3 except for the integrated luminosity 700 pb^{-1}.