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A possible machenism for producing the events with the high mass photon pairs observed at LEP*

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Abstract

Assuming the High mass photon pairs observed at LEP arise from the decay of a massive elementary particle,we find that the observed events $e^+e^- \rightarrow l^+l^- +$ the massive particle can hardly arise from the decay of the Z boson. They are very possibly produced in the process $e^+e^- \rightarrow$ a virtual Higgs particle $\rightarrow l^+l^- +$ the massive particle. Experiment has a good way to distinquish the two cases.

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Recently the L3 and the other groups at LEP [1] observe about ten $e^+e^- \to \gamma\gamma(e^+e^-, \mu^+\mu^-,$ or two jets) events with the invariant mass $M_{\gamma\gamma}$ of the photon pairs close to 60 GeV. The probability for all these events originating from QED bremsstrahlung fluctuation is small. Therefore it is possible that these photons arise from the decay of a massive particle. In this paper we suppose the existence of such a particle as an elementary particle(not a composite one) and analyse the possible mechanism to produce the particle in the observed process $e^+e^- \to \gamma\gamma l^+l^-$. For convenience we call the massive particle as B particle. By the Yang's theorem [2] the spin of the B particle can not be one because of its decay into two photons. So we suppose it is a spin-0 particle. It is known that the B particle can not be the Higgs particle H in the minimal standard model. So we add more Higgs particles into the standard model and assume the B particle is one of them. There are three kinds of tree diagrams(Figs.1-3) which may produce the B particle in the observed processes at LEP. The A particle in the diagrams can not be the Z boson, because no events $e^+e^- \to \gamma\gamma\nu\bar{\nu}$ with $M_{\gamma\gamma} > 10\ GeV$ and $e^+e^- \to \gamma\gamma$ + hadrons with $M_{\gamma\gamma} > 40\ GeV$ has been observed by L3 [1]. Therefore the A particle has to be a spin-0 particle in Figs.1 and 3, or a photon in Fig.3. At the first glance the C particle in Figs.1 and 2 should be the Z boson. But study in detail the C particle can not be the Z boson and it should be a spin-0 particle. First we study the process in Fig.4 where a spin-0 particle ϕ and a photon are produced at an e^+e^- collider, when the mass m_ϕ of the ϕ particle is smaller than the center-of-mass energy E of the collider. If θ is the angle between the momenta e^- and γ,the total cross section measured within $\beta \leq \theta \leq \pi - \beta$ is

$$\sigma(E, m_\phi, \beta) = \alpha g_{\phi e}^2 K_1/E^2,$$

$$K_1 = \ln[(1+\cos\beta)/(1-\cos\beta)](E^4 + m_\phi^4)/[2E^2(E^2 - m_\phi^2)], \qquad (1)$$

where m_z is the mass of the Z boson and α is the electromagnetic fine structure constant. The ϕ particle couples with the electron as $g_{\phi e}\bar{\psi}\Gamma_\phi\psi$,where $g_{\phi e}$ is the coupling constant and Γ_ϕ is i or γ_5,corresponding to the scalar ϕ or the pseudoscalar ϕ. The electron mass m_e is neglected and $(1-\cos\beta) > 2m_e^2/E^2$ in Eq.(1). If ϕ is the B particle with its mass

$m_b = 60\ GeV, E = m_z = 91\ GeV$ and $\beta = 15°$,in an integrated luminosity $L \equiv 25(pb)^{-1}$,the number of the events $e^+e^- \to B\gamma \to \gamma\gamma\gamma$ is

$$N_1 = L\alpha g_{be}^2 K_1 \eta / m_z^2 = 3.66\ 10^4 g_{be}^2 \eta, \tag{2}$$

where η is the branching ratio $\Gamma(B \to \gamma\gamma)/\Gamma_b$. The three photons in the final state are energetic. One of them is monoergic with the energy $\sim$ 25.7 Gev. The other two photons have $M_{\gamma\gamma} \sim$ 60 GeV. Therefore these events if exist should be easily observed against the QED background $e^+e^- \to 3\gamma$ [3]. From the data of L3 and other groups one may suppose the A particle in Figs.1 and 3 mainly couples with the electron and the muon with equal strength. The number of the events $e^+e^- \to \gamma A \to \gamma e^+e^-$ at $E = m_z$ in the integrated luminosity L if $m_a < m_z$ is

$$N_2 \simeq L\alpha g_{ae}^2 K_1/(2m_z^2) = (1.0, 1.8, 12)\ 10^4 g_{ae}^2, \tag{3}$$

corresponding to $m_a = (32, 60, 85)\ GeV$,respectively. If m_a is not too close to m_z these events can also be easily observed with a monoergic photon and a pair of leptons which has an invariant mass of m_a. If N_1 or $N_2 \geq 5$ for example there is a good chance to find the B particle and the A particle at LEP.

We refer $\sigma_{ic}(E)(i = 1, 2)$ to the total cross sections for the processes in Figs.1 and 2 due to the exchange of the C particles. For simplicity the lepton pairs in the final state are supposed to be the muon pairs. When the C particle is the Z boson and $E = m_z$

$$\sigma_{iz}(m_z) = \sigma_{ez}\Gamma_{iz}(Z \to \gamma\gamma\mu^+\mu^-)/\Gamma_z, \tag{4}$$

where $\sigma_{ez} \sim 40\ nb$ is the cross section of $e^+e^- \to Z$ at $E = m_z$ and $\Gamma_z = 2.487\ GeV$ [4] is the width of the Z boson. When C is a spin-0 particle D,one still can write the cross section in Figs.1 and 2 as

$$\sigma_{id}(E) = g_{de}^2 K_2(E)\Gamma_{i\phi}(E)/(2E^3), \tag{5}$$

where $\Gamma_{i\phi}(E)$ is the partial width of an imaginal spin-0 particle ϕ,which has the same couplings with other particles as the D particle has. But its four-momentum $P = (E, \vec{p} = 0)$. $K_2(E)$ is the Breit-Wigner resonance factor

$$K_2(E) = 1/[(1-u^2)^2 + u^2\gamma_d^2], \tag{6}$$

where $u = m_d/E, \gamma_d = \Gamma_d/E$.

If a spin-0 particle D couples with leptons,it has to show its effects on the Z decay into the lepton pairs. One should limit the effects as small as not to contradict the data from LEP. For the process $e^+e^- \to \mu^+\mu^-$ at $E = m_z$,we demand

$$\sigma_{de\mu} \leq (y/100)\sigma_{es}\Gamma(Z \to \mu^+\mu^-)/\Gamma_z \sim 1.34\ 10^{-2} y\ nb, \tag{7}$$

where $\sigma_{de\mu}$ is the cross section of $e^+e^- \to \mu^+\mu^-$ at $E = m_z$,when only the D particle exchange exists. $\Gamma(Z \to \mu^+\mu^-)/\Gamma_z = 3.34\%$ [4].

$$\sigma_{de\mu} = g_{de}^2 g_{d\mu}^2 K_2(m_z)/(16\pi m_z^2). \tag{8}$$

The interference between the Z boson exchange and the D particle exchange,which is proportional to $m_e m_\mu$,may be neglected. From the experimental uncertainty [4] one may take $y \sim 1$. Other precise measurements may give severer limit on the effects of the D particle.

We have calculated Γ_{1z} and $\Gamma_{1\phi}$ of Fig.1 at $E = m_z$

$$\Gamma_{1z}(Z \to \gamma\gamma\mu^+\mu^-) = g_{zab}^2 g_{a\mu}^2 \eta m_z A_{1z}(m_a)/(64\pi^3), \tag{9.1}$$

$$\Gamma_{1\phi}(m_z) = g_{dab}^2 g_{a\mu}^2 \eta m_z A_{1d}(m_a)/(64\pi^3), \tag{9.2}$$

where

$$A_{1z}(m_a) = (4/3)\int_c^1 (1-x)F^{3/2}/[z^3(x^2+\gamma_a^2)]\,dx, \tag{10.1}$$

$$A_{1d}(m_a) = \int_c^1 (1-x)F^{1/2}/[z(x^2+\gamma_a^2)]\,dx, \tag{10.2}$$

where $F = (x+z^2+b^2-1)/(4z^2)-b^2, c = 1-(z-b)^2, z = m_z/m_a, b = m_b/m_a, \gamma_a = \Gamma_a/m_a$. Γ_a, m_a are the total width and mass of the A particle. In calculating Eqs.(9) and (10)

the muon mass is neglected. In the models with several Higgs doublets g_{zab},the coupling constant between the particles Z,A and B,satisfies

$$g_{zab}^2 \leq \pi\alpha/(\sin^2\theta_w \cos^2\theta_w) \sim 0.129, \tag{11}$$

where we take $\alpha = 1/137, \sin^2\theta_w = 0.2325$ [4]. $(g_{dab}m_z)$ is the coupling constant between the particles D,A and B. In the minimal standard model the corresponding one g_{hhh} between three Higgs particles is $3m_h^2/(vm_z)$,which is 134 when $m_h = 1\ TeV, v = 246\ GeV$. Note that in Eqs.(10) $x = 1 - q^2/m_a^2$ and $q^2 = M_{\mu\mu}^2$,where $M_{\mu\mu}$ is just the invariant mass of the muon pairs. Because $M_{\mu\mu}$ has a distribution [1],$m_a > m_z - m_b$ in Eqs.(9). The numerical values of $A_{1z}(m_a)$ and $A_{1d}(m_a)$ are listed in Table 1. In calculation we neglect γ_a so that A_{1d} diverges when $m_a \to (m_z - m_b)$,while A_{1z} converges ,and $m_z = 91\ GeV, m_b = 60\ GeV$. The A_{1d} are in general one to two orders of magnitude larger than the A_{1z} because of the suppression of the factor $F^{3/2}/z^3$. Now let us have a discussion.

Case 1: the C particle is the Z boson in Fig.1. From Eqs.(4),(9.1) and (11),in the integrated luminosity L the number of $e^+e^- \to B\mu^+\mu^- \to \gamma\gamma\mu^+\mu^-$ at $E = m_z$ is

$$N \leq 2.37\ 10^3 g_{a\mu}^2 \eta A_{1z}(m_a). \tag{12}$$

The observed $N \sim 2$ is given in Ref.[1]. The A particle contributes to $\sigma_{ae\mu}$ in Eq.(8) with $g_{ae} = g_{a\mu}$. By using Eqs.(8) and (12),we obtain

$$\sigma_{ae\mu} \geq 1.66\ 10^{-4} K_2 N^2/[\eta^2 A_{1z}^2(m_a)]\ pb. \tag{13}$$

From Table 1 it is easy to see that only if $34\ GeV > m_a > 31\ GeV$, the $\sigma_{ae\mu}$ in Eq.(13) satisfies Eq.(7) with $\eta = y = 1$. On the other hand because $m_a < m_z$,by using Eqs.(12) and (3) one gets

$$N_2 \geq 1.81 N K_1/(\eta A_{1z}). \tag{14}$$

Even if $\eta = 1$ and A_{1z} takes the value at $m_a = 31.001\ GeV$, $N_2 \geq 227$. In that case

the A particle would have been already found in L3 [1]. Therefore the case 1 is excluded.

Case 2: the C particle is a spin-0 particle $\bar{D}$ in Fig.1. Because A_{1d} is much larger than A_{1s} and there is no serious limit on the value of g_{dab},one has a chance to reach the observed $N \sim 2$ [1]. Here for simplicity we only discuss the case where D and A are the same particle,in order to see the general feature. By using Eqs.(5) and (9.2),in the integrated luminosity L at $E = m_s$,

$$N = 2.96\ 10^2 \eta K_2 A_{1d} g_{de}^4 g_{ddb}^2. \tag{15}$$

By using Eqs.(7),(8),(15),and $N \sim 2$,one gets

$$g_{ddb}^2 \geq 0.472/[y\eta A_{1d}(m_s)]. \tag{16}$$

With $y = \eta = 1, g_{ddb} \geq 22, 24.7, 36.3$,corresponding to $m_d = 95, 100, 120\ GeV$,respectively. They are large,but still reasonable in comparison with the case allowed in the minimal standard model. Substituting Eq.(16) into Eq.(15),

$$g_{de}^4 \leq 1.43\ 10^{-2} y/K_2. \tag{17}$$

For example when $m_d = 95\ GeV$ with $y = 1$, $g_{de}^2 \leq 1.1\ 10^{-2}$.
When $m_d < m_s$ the coupling constants g_{ddb} and g_{de} should be further constrained by Eq.(3) with $N_2 \leq 5$:

$$g_{ddb}^2 \geq 4.97\ 10^3 K_1^2/(K_2 \eta A_{1d}), \tag{18}$$

$$g_{de}^4 \leq 1.36\ 10^{-6}/K_1^2. \tag{19}$$

For example if $\eta = 1$ and $\beta = 15°$,$g_{ddb} \geq 6.4\ 10^3, g_{de}^2 \leq 4.2\ 10^{-5}$ when $m_d = 85\ GeV$;and $g_{ddb} \geq 155, g_{de}^2 \leq 5.0\ 10^{-4}$ when $m_d = 32\ GeV$. Therefore Eqs.(18) and (19) are more stringent than Eqs.(16) and (17). So when $m_d > m_s$ Eqs.(16) and (17) are used,while $m_s - m_b < m_d < m_s$ Eqs.(18) and (19) should be considered. We will not discuss many other cases in the case 2,where some of the particles A,B and D are the same, or all of them are different. The common feature is that the coupling constant g_{dab} of three

Higgs particles is large so that the perturbation expansion may be violated.

Case 3: the C particle in Fig.2 is the Z boson or the spin-0 particle D. One still has

$$\Gamma_{2z}(Z \to \gamma\gamma l^+ l^-) = g_{zl}^2 g_{bl}^2 m_z A_{2z}\eta/(64\pi^3), \tag{20.1}$$

$$\Gamma_{2\phi}(m_z) = g_{dl}^2 g_{bl}^2 m_z A_{2d}\eta/(64\pi^3), \tag{20.2}$$

where $g_{zl}^2 = e^2(v_l^2 + a_l^2)$ and v_l, a_l are the neutral current coupling constants of the Z boson. Here the lepton pairs l^+l^- appear in the final state. By using Eqs.(20),(17) and (2) in the integrated luminosity L one gets

$$N = 1.62\ 10^{-2} N_1 A_{2z}, \tag{21.1}$$

$$N = 1.16\ 10^{-2} N_1 y A_{2d}, \tag{21.2}$$

corresponding to Eq.(20.1) and Eq.(20.2),respectively. The branching ratio BR($Z \to \gamma\gamma\gamma$) $\leq$ 3.3 10^{-5} is given in Ref.[3],which means $N_1 < 33$. A_{2z} and A_{2d} have been calculated with $m_z = 91\ GeV$ and $m_b = 60\ GeV$: $A_{2z} = 5.47\ 10^{-4}$ and $A_{2d} = (0.14, 5.86)\ 10^{-3}$, where the two numbers of A_{2d} correspond to the particles D and B having the same parity and the opposite parity,respectively. The $N's$ in Eqs.(21) are too small to be the observed $N \sim 2$. Therefore the case 3 is excluded.

Case 4: the particle in Fig.3 is a photon or a spin-0 particle D. One may write the corresponding cross sections as

$$\sigma_{3\gamma}(m_z) = e^4 g_{be}^2 \eta A_{3\gamma}/(128\pi^3 m_z^2), \tag{22.1}$$

$$\sigma_{3d}(m_z) = g_{de}^2 g_{d\mu}^2 g_{be}^2 \eta A_{3d}(m_d)/(128\pi^3 m_z^2). \tag{22.2}$$

For comparison we also write the corresponding one in Fig.1 with C being the D particle:

$$\sigma_{1d}(m_z) = g_{de}^2 g_{dab}^2 g_{a\mu}^2 K_2 \eta A_{1d}(m_a)/(128\pi^3 m_z^2). \tag{22.3}$$

By using Eqs.(2) and (17),we get

$$N \leq 2.25\ 10^{-3} A_{3\gamma}, \tag{23.1}$$

$$N \leq 3.82\ 10^{-3} y A_{3d}/K_2, \tag{23.2}$$

corresponding to Eq.(22.1) and Eq.(22.2),respectively. We have not calculated $A_{3\gamma}$ and A_{3d} yet. From the above experience the coefficients A's are usually much less than one,unless the propagator becomes large(near a pole),such as $m_a \rightarrow m_s - m_b$. In the later case the invariant mass of the lepton pairs should concentrate in a narrow range,which seems not the case observed by L3 [1]. Therefore if in general $A_{3\gamma}, A_{3d} < 1$,the numbers N in Eqs.(23) are too small to be the observed $N \sim 2$.

In the discussions we often set $\eta = 1$,which is the branching ratio of BR(B$\rightarrow \gamma\gamma$). If $\eta << 1$ the criteria will besome more stringent in genaral. Experiments may soon give an answer to $\eta \sim 1$ or $\eta << 1$.

From the above discussions one is forced to accept the case 2 as a possible explanation for producing those events observed by L3 and other groups at LEP. The essential idea of the case 2 is that the observed events do not come from the decay of the Z boson. They come from the exchange of a spin-0 particle. So experiment has a good way to check the idea. If the mass of the spin-0 particle does not fall into the peak of the Z boson,one can repeat the experiment at an energy E just above or bellow the Z peak. If the observed events come from the Z decay,their number will certainly drop down. But if they come from the exchange of a new particle the number will not change too much in general and even increase if the energy E is close to the mass of the particle. But if the mass of the particle occasionally falls into the Z peak one has to carefully scan the Z peak to see if there is a narrow peak in it. If experiments give a favor to the case 2,one should pay more attention to it. The detail analyses of the case 2 conbined with model constuction is just under investigation.

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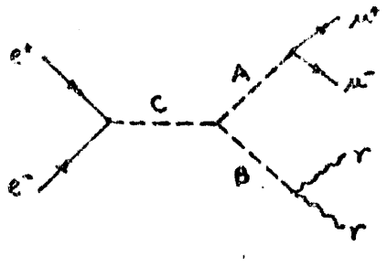

Fig.1.

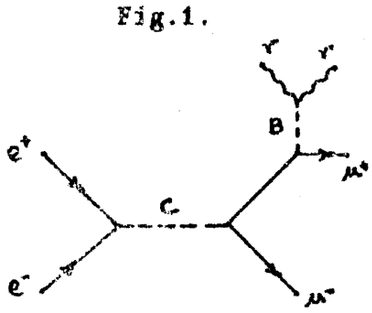

Fig.2.

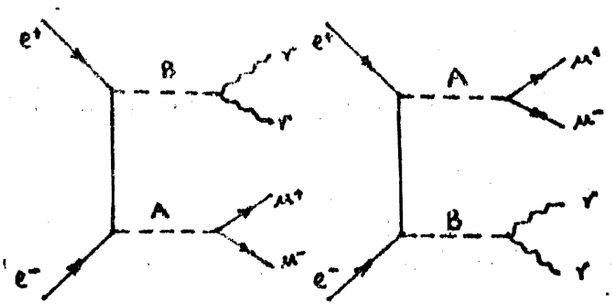

Fig.3.

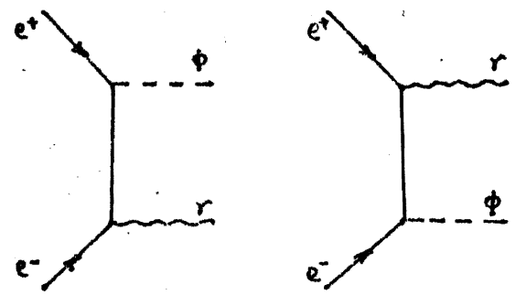

Fig.4.

$m_a(GeV)$	31.001	31.5	32	34	36	38	40
$A_{1s}(m_a)$	$3.707\cdot10^{-2}$	$2.021\cdot10^{-2}$	$1.548\cdot10^{-2}$	$7.902\cdot10^{-3}$	$4.969\cdot10^{-3}$	$3.413\cdot10^{-3}$	$2.471\cdot10^{-3}$
$A_{1d}(m_a)$	53.01	1.519	$8.801\cdot10^{-1}$	$3.055\cdot10^{-1}$	$1.655\cdot10^{-1}$	$1.044\cdot10^{-1}$	$7.149\cdot10^{-2}$

$m_a(GeV)$	50	60	70	80	85	90	92
$A_{1s}(m_a)$	$7.388\cdot10^{-4}$	$3.101\cdot10^{-4}$	$1.552\cdot10^{-4}$	$8.680\cdot10^{-5}$	$6.696\cdot10^{-5}$	$5.253\cdot10^{-5}$	$4.788\cdot10^{-5}$
$A_{1d}(m_a)$	$1.877\cdot10^{-2}$	$7.501\cdot10^{-3}$	$3.659\cdot10^{-3}$	$2.017\cdot10^{-3}$	$1.548\cdot10^{-3}$	$1.209\cdot10^{-3}$	$1.110\cdot10^{-3}$

$m_a(GeV)$	95	100	120	140	160	180	200
$A_{1s}(m_a)$	$4.182\cdot10^{-5}$	$3.373\cdot10^{-5}$	$1.582\cdot10^{-5}$	$8.402\cdot10^{-6}$	$4.874\cdot10^{-6}$	$3.021\cdot10^{-6}$	$1.972\cdot10^{-6}$
$A_{1d}(m_a)$	$9.591\cdot10^{-4}$	$7.711\cdot10^{-4}$	$3.587\cdot10^{-4}$	$1.836\cdot10^{-4}$	$1.096\cdot10^{-4}$	$6.780\cdot10^{-5}$	$4.419\cdot10^{-5}$

Table 1. The values of $A_{1s}(m_a)$ and $A_{1d}(m_a)$ in Eq.(10) where γ_a is neglected and $m_s = 91GeV$, $m_b = 60GeV$