

Why a Scalar Explanation of the L3 Events is Implausible *

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Abstract

We investigate the question of whether an additional light neutral scalar can explain the $l^+l^-\gamma\gamma$ events with high invariant mass photon pairs recently observed by the L3 collaboration. We parameterize the low energy effects of the unknown dynamics in terms of higher dimensional effective operators. We show that operators which allow for the scalar to be produced and decay into photon pairs will allow other observable processes that should have been seen in current experiments.

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1 Introduction

The L3 collaboration has observed recently an excess of $l^+l^-\gamma\gamma$ events with high invariant mass photon pairs, $M_{\gamma\gamma} \simeq 60$ GeV [1]. Both DELPHI and ALEPH have two similar events each, and OPAL seems to have one candidate [2]; however these experiments are not so strongly peaked. Naively, such an observation would look like evidence of the discovery of a new neutral particle. However, such an interpretation requires a detailed understanding of the standard model background. A recent calculation of the hard bremsstrahlung process $e^+e^- \rightarrow \mu^+\mu^-\gamma\gamma$ [3] yields a significantly higher cross section at the Z peak than previous theoretical predictions had indicated, pointing to the likelihood of a standard model explanation of the L3 events. In this note, we address the question of the likelihood of the discovery of a new scalar from a different vantage point; we ask whether a nonstandard model with such a scalar is consistent with other observational constraints. We systematically investigate the possible scalar couplings which could give rise to the L3 events and show they are almost all excluded.

We analyze the possibility of explaining the L3 events ¹ by assuming the existence of a light neutral scalar (ϕ) of mass $m_\phi \simeq 60$ GeV. We assume the scalar ϕ is a gauge singlet. We parameterize low energy effects of unknown dynamics at a scale M in terms of higher dimensional effective operators, constructed out of the Standard Model (SM) fields and the extra neutral scalar. These operators are suppressed by powers of M^{4-d} , where d is the dimension of the corresponding operator. We impose $SU(2)_L \times U(1)_Y$ gauge invariance, which relates the process of interest with other observable effects which in general are measurable and allows us to confirm or rule out the models. We consider the most general possible low dimension operators which can explain the observed events. Our results do not rely on assumptions

¹We will use only the L3 results (four events), but our conclusions are not essentially changed when we include the four LEP experiments.

on the expected size of the coefficients of nonrenormalizable operators. We simply analyze other experimental consequences of the operators which could produce the observed events. In almost all cases this alone is sufficient to rule out the operator.

In section 2 we briefly discuss the possibility that the new particle couples only to gauge bosons. In section 3 we assume that the scalar couples to leptons and gauge bosons through lower dimensional gauge invariant effective operators. In section 4 we analyze higher dimensional four body operators and in section 5 we summarize our conclusions.

2 Scalar Coupled to Gauge Bosons

One can consider a model in which the scalar ϕ couples to the Z boson and is produced via the reaction

$$Z \rightarrow Z^* \phi . \tag{1}$$

The case of ϕ being the lightest CP-even neutral Higgs field (h) in models with a non-minimal Higgs sector, has been analyzed in ref. [5]. To account for the fact that h decays dominantly to 2γ , one can assume that h does not couple to fermions, but has essentially SM-type couplings to the Z and W bosons. This can be achieved within the kind of models referred to as model I in the literature [4], *i.e.*, models with two Higgs doublets of which only one couples to fermions.

However, this simplest possibility encounters immediately an unavoidable problem which is independent of the particular model for the scalar ϕ . The decays of the Z boson are well known and the process (1) would yield also final states $\nu\bar{\nu}\gamma\gamma$, with a branching ratio determined by the well tested SM couplings of the Z to neutrinos. This implies that if we assume $BR(Z \rightarrow Z^* \phi \rightarrow l^+ l^- \gamma\gamma) = 4 \times 10^{-6}$ to account for the L3 events, we will immediately obtain $BR(Z \rightarrow Z^* \phi \rightarrow \nu\bar{\nu}\gamma\gamma) = 8 \times 10^{-6}$. The null results of searches for events with high

invariant mass photon pairs and missing energy [1] translate into the upper limit $BR(Z \rightarrow \nu\bar{\nu}\gamma\gamma) < 3 \times 10^{-6}$ at 95% CL, if we assume (as we have done in all our estimates) that the detection efficiency is one. Therefore we conclude that the $l^+l^-\gamma\gamma$ events can not be explained by the process (1).

3 Lowest Dimensional Operators

The next model we consider is one in which ϕ couples to leptons, and is therefore produced at LEP via

$$e^+e^- \rightarrow Z \rightarrow l^+l^-\phi. \quad (2)$$

The lowest dimensional gauge invariant operators involving the scalar and two charged leptons are of dimension d=5, namely

$$O_a = \frac{1}{M} \bar{E}_L H e_R \phi \quad (3)$$

$$O_b = \frac{1}{M} \bar{e}_R \gamma^\mu D_\mu e_R \phi, \frac{1}{M} \bar{E}_L \gamma^\mu D_\mu E_L \phi \quad (4)$$

where e_R refers to the right handed charged lepton, E_L is the $SU(2)_L$ doublet consisting of the charged left handed lepton and the neutrino and H is the standard Higgs doublet.

We first consider O_a . Notice that because ϕ is an $SU(2)_L$ singlet, it has to include the standard Higgs doublet. When the standard Higgs gets a vev, v , this operator reduces to a Yukawa coupling

$$\frac{v}{M} \bar{e} e \phi. \quad (5)$$

We present two arguments against this model. We first assume that the decay of ϕ into two photons is induced by the gauge invariant effective operator

$$O = \frac{1}{M'} \phi (a B_{\mu\nu} B^{\mu\nu} + b W_{\mu\nu}^i W^{i\mu\nu}) \quad (6)$$

where $B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$, $W_{\mu\nu}^i = \partial_\mu W_\nu^i - \partial_\nu W_\mu^i + g f^{ijk} W_\mu^j W_\nu^k$ and a, b are arbitrary coefficients. When we write this operator in terms of

the physical gauge fields, there are three pieces involving the neutral gauge bosons Z and γ :

$$O_\gamma = \frac{d}{M} \phi F_{\mu\nu} F^{\mu\nu} \quad , \quad d \equiv ac_w^2 + bs_w^2 \quad (7)$$

$$O_Z = \frac{h}{M} \phi Z_{\mu\nu} Z^{\mu\nu} \quad , \quad h \equiv as_w^2 + bc_w^2 \quad (8)$$

$$O_{\gamma Z} = \frac{2k}{M} \phi F_{\mu\nu} Z^{\mu\nu} \quad , \quad k \equiv (b-a)c_ws_w \quad (9)$$

where s_w (c_w) denotes the sine (cosine) of the electroweak mixing angle.

The two Feynman diagrams that contribute to the process $Z \rightarrow l^+l^-\phi$ are depicted in Fig. 1. A tedious but straightforward calculation leads to the following result for the partial decay width:

$$\Gamma(Z \rightarrow l^+l^-\phi) = \frac{\alpha}{s_w^2 c_w^2} \frac{1}{192\pi^2} \left(\frac{v}{M}\right)^2 M_Z [v^2 C_V(r) + a^2 C_A(r)] \quad (10)$$

where v (a) is the vector (axial) coupling of the lepton to the Z , given by

$$v = -\frac{1}{2} + 2s_w^2 \quad a = -\frac{1}{2} \quad (11)$$

and $r \equiv (\frac{m_\phi}{M_Z})^2$. The functions $C_V(r)$ and $C_A(r)$ take the form

$$C_V(r) = 2r^2 F(r) - (1 - 2r - 3r^2) \log r - 2 + 8r - 6r^2 \quad (12)$$

$$C_A(r) = -2r^2 F(r) - (1 + 8r + 3r^2) \log r \quad (13)$$

$$- \frac{11}{3} - 5r + 9r^2 - \frac{r^3}{3} \quad (14)$$

with

$$F(r) = 2L_2\left(\frac{r}{1+r}\right) + \log^2\left(\frac{r}{1+r}\right) - \frac{1}{2} \log^2 r - \frac{\pi^2}{6} \quad , \quad (15)$$

and L_2 is the dilogarithm or Spence function.

L3 has a total of $\sim 10^6 Z$ events and 4 $l^+l^-\gamma\gamma$ events have been observed, therefore we assume

$$BR(Z \rightarrow l^+l^-\phi) \times BR(\phi \rightarrow \gamma\gamma) \sim 4 \times 10^{-6} \quad , \quad (16)$$

which yields a lower bound on v/M . We obtain $v/M \geq 3.3$, and therefore $M \sim 75$ GeV for $v = 250$ GeV. This scale is so low that the validity of treating this as an effective operator might be questioned. This would be true particularly if one were to assume the operator arose from a loop diagram in a more fundamental theory. Furthermore, this particle would have quite a large width, on the order of its mass. Presumably we should not consider this operator further. We nevertheless show that such an operator is decisively ruled out in any case by current experimental data.

The experimental results on four fermion events at LEP constrain the partial decay width of ϕ into two photons to be at least of the same order of magnitude as the corresponding decay width into leptons². In our model, these partial widths are, respectively:

$$\Gamma(\phi \rightarrow \gamma\gamma) = \left(\frac{d}{M'}\right)^2 \frac{m_\phi^3}{2\pi} \quad (17)$$

$$\Gamma(\phi \rightarrow l^+l^-) = 3 \left(\frac{v}{M}\right)^2 \frac{m_\phi}{8\pi} \quad (18)$$

where we have incorporated three lepton flavors. We then impose $BR(\phi \rightarrow \gamma\gamma) \geq 0.5$. This experimental constraint can be satisfied only if $d^2 \sim 13$ when $M' = M$. Notice that taking $M' > M$ makes d even larger, well beyond the realm of perturbation theory. We therefore take $M' = M$ below.

Let us analyze now the remaining terms in eq. (9). The operator $O_{\gamma Z}$ leads to the process $Z \rightarrow \phi\gamma$ and the width is easily found to be

$$\Gamma(Z \rightarrow \phi\gamma) = \frac{s_w^2 c_w^2 (b-a)^2}{6\pi M^2} \left(\frac{M_Z^2 - m_\phi^2}{M_Z}\right)^3 \quad (19)$$

Since M can be no larger than determined by eq. (16), the difference $|b-a|$ must be less than $5 \cdot 10^{-2}$. This is determined since $BR(Z \rightarrow 3\gamma) = BR(Z \rightarrow \phi\gamma) \times BR(\phi \rightarrow \gamma\gamma)$, and $BR(\phi \rightarrow \gamma\gamma) \geq 0.5$, so we obtain $BR(Z \rightarrow 3\gamma) \geq 5 \times 10^{-2} (b-a)^2$. The experimental upper limit

²We thank B. Wyslouch for private communication.

for this process, at 95% confidence level, is $BR(Z \rightarrow 3\gamma) < 1.4 \times 10^{-4}$ [6] and thus we conclude that $|b - a| < 5 \times 10^{-2}$. This means that in order to be consistent with the experimental data we have to assume $b \sim a$ and therefore $d \sim h$ in eq. (9).

Finally, the last piece in eq. (9), O_Z , contributes to the process $Z \rightarrow Z^* \phi$, which produces final states of two fermions and the scalar when the Z^* decays. The expression for the branching ratio of the process $Z \rightarrow \bar{f} f \phi$, after the phase space integration, is rather cumbersome, so we only give here the numerical result for the neutrino decay channel:

$$BR(Z \rightarrow Z^* \phi \rightarrow \bar{\nu} \nu \phi) = \left(\frac{h}{M} \right)^2 \cdot 3.5 \cdot 10^{-2} \text{GeV}^2 \quad (20)$$

Since $h \sim d$, this branching ratio is entirely determined. Together with the constraint $BR(\phi \rightarrow \gamma\gamma) \geq 0.5$ it implies that $BR(Z \rightarrow \bar{\nu} \nu \gamma\gamma) \sim 4 \times 10^{-5}$, which is excluded by LEP data [1].

One can also rule out this model by considering the rate for the scalar to be produced at TRISTAN. The interaction (5) would also yield the direct production $e^+ e^- \rightarrow \phi$. The cross section for the process $e^+ e^- \rightarrow \phi \rightarrow \gamma\gamma$ is easily found to be

$$\sigma(s) = \frac{1}{4\pi} \left(\frac{dv}{M^2} \right)^2 \frac{s^2}{|s - m_\phi^2 + im_\phi \Gamma_\phi|^2} \quad (21)$$

where Γ_ϕ is the total width of the scalar and \sqrt{s} is the center of mass energy.

Using that $BR(\phi \rightarrow \gamma\gamma) \sim 0.5$ we obtain $\sigma = 120$ nb, which is inconsistent with current experimental data ($\sigma \sim 50$ nb for $\sqrt{s} = 60$ GeV) [7]. This number was obtained within the framework of this model, in which the scalar is very broad. The width determined at LEP would make the situation even worse.

We now consider the possibility that the Z decays into ϕ and two leptons directly through the contact term O_b in eq. (4). Since the second of these operators would yield $Z \rightarrow \nu \bar{\nu} \phi$ with a branching ratio of the same order of magnitude as $Z \rightarrow l^+ l^- \phi$, it is excluded. We

therefore assume this operator is suppressed and restrict our attention to the first one.

In terms of the physical gauge fields, O_b is written as

$$O_b = \frac{1}{M} \phi \bar{e}_R \gamma^\mu (\partial_\mu + ieA_\mu - ie \frac{s_w}{c_w} Z_\mu) e_R, \quad (22)$$

The last term yields the following partial decay width for the process $Z \rightarrow l^+ l^- \phi$:

$$\Gamma(Z \rightarrow l^+ l^- \phi) = \frac{\alpha}{24\pi^2} \frac{s_w^2}{c_w^2} \frac{M_Z^3}{M^2} H(r) \quad (23)$$

where

$$H(r) = \left(\frac{3r^2}{16} + \frac{r}{4} \right) \log r + \frac{1}{8} \left(\frac{3}{8} + \frac{8r}{3} - 3r^2 - \frac{r^4}{24} \right) \quad (24)$$

and $r = (m_\phi/M_Z)^2$.

Using again equation (16) derived from the L3 events, we obtain

$$\frac{1}{M^2} \sim 2. \times 10^{-3}. \quad (25)$$

Although this result implies a very light mass scale ($M \sim 22$ GeV), it depends also on the assumptions about unknown coefficient in front of O_b . So we choose to study the further consequences of the operator and we will show that it can be excluded solely on an experimental basis.

The first term in O_b yields also a derivative coupling ϕll . It is straightforward to compute the width for the decay $\phi \rightarrow l^+ l^-$ induced by this coupling,

$$\Gamma(\phi \rightarrow l^+ l^-) = \frac{m_\phi}{16\pi} \left(\frac{m_l}{M} \right)^2 \quad (26)$$

It is suppressed by the mass of the corresponding lepton, m_l , and with the mass scale given by (25) it turns out to be 5.9×10^{-10} GeV, 2.6×10^{-5} GeV and 7.5×10^{-3} GeV for e , μ and τ respectively.

The analysis done for the previous operators would not apply here because of the helicity suppression in the operator O_b . In this case,

the dominant ϕ decay model is naturally to photons. Furthermore, the production cross section at TRISTAN would be quite small. It is therefore best to rule out the operator directly, by calculating the production cross section for three photons with the mass scale M we have already determined.

We look now at the piece of O_b involving the photon field in eq. (22). This term of O_b yields $e^+e^- \rightarrow \phi\gamma \rightarrow 3\gamma$, which can also be measured at LEP. We obtain

$$\sigma(e^+e^- \rightarrow \phi\gamma) = \frac{\alpha}{8M^2} \left(\frac{s - m_\phi^2}{s} \right) \quad (27)$$

As the branching ratio of $\phi \rightarrow 2\gamma$ is one in very good approximation, we just have to plug in eq.(27) the value of M determined by the L3 experiments to find $\sigma(e^+e^- \rightarrow 3\gamma) \sim 0.4$ nb. On the Z pole, the peak cross-section for Z production is roughly 55 nb. Combined with the experimental upper limit on the branching ratio for $Z \rightarrow 3\gamma$ [6], we get $\sigma(e^+e^- \rightarrow 3\gamma) < 8 \times 10^{-3}$ nb and thus we conclude that the L3 events can not be due to O_b .

4 Higher Dimension Four Body Operators

If the neutral scalar is a singlet, the available higher dimensional gauge invariant operators have dimension $d=7$ and there are three kinds of which we present three representatives

$$O_2 = \frac{1}{M^3} \bar{E}_L (D_\mu H) e_R D^\mu \phi \quad (28)$$

$$O_3 = \frac{1}{M^3} \bar{E}_L H (D_\mu e_R) D^\mu \phi \quad (29)$$

$$O_4 = \frac{1}{M^3} B_{\mu\nu} \bar{e}_R \gamma^\mu e_R \partial^\nu \phi \quad (30)$$

It is worth pointing out that these higher dimensional operators do not contain any vertex involving only two fermions and the scalar. Thus,

in all these models ϕ decays dominantly into two photons, through the effective operator O introduced in section 3 (eq. (6)). Furthermore, unlike the lower dimensional operators considered in section 3, they can not be probed by direct production of the scalar at TRISTAN.

Recall that in principle there are also operators analogous to O_4 but involving the left handed $SU(2)_L$ doublets; however those would once again yield the unobserved $\nu\bar{\nu}\gamma\gamma$ events at LEP.

Notice that there can not be dimension 6 operators involving the Higgs field because, as it is an $SU(2)_L$ doublet, both E_L and e_R are necessary to make an $SU(2)_L \times U(1)_Y$ invariant and by Lorentz invariance this implies that two covariant derivatives are needed and therefore the lowest dimensional operator has dimension $d=7$.

There are many other operators involving two covariant derivatives as they can act on any couple of the four fields involved, as well as both on the same field. However, there is an essential difference between O_2 -type operators, in which one of the covariant derivatives acts on the Higgs doublet, and operators of type O_3 , in which no covariant derivative acts on the Higgs. The reason is that O_2 -type operators only contain Z and W gauge bosons and we will show that this fact prevents us from ruling them out with current experimental data. Operators of the O_3 kind involve also the photon and thus they yield to 3γ events at LEP with a cross section directly dictated by the related $Z \rightarrow l^+l^-\gamma\gamma$ branching ratio, as we have shown for the lower dimensional operator O_b in section 3. The same applies to O_4 .

In particular, the operator O_4 defined in eq. (30) has qualitatively the same consequences as the operator O_b . In terms of the physical fields we have

$$O_4 = \frac{1}{M^3} \bar{e}_R \gamma^\mu e_R \partial^\nu \phi (c_w F_{\mu\nu} - s_w Z_{\mu\nu}) \quad (31)$$

The second piece leads to the process $Z \rightarrow l^+l^-\phi$ with a branching ratio which agrees with the L3 results (eq. (16)) for $M \sim 74$ GeV. Then, we compute the cross section for the process $e^+e^- \rightarrow \phi\gamma \rightarrow 3\gamma$, induced by the first term in eq. (31), using the same mass scale. We

obtain $\sigma(e^+e^- \rightarrow 3\gamma) \sim 8 \cdot 10^{-2}\text{nb}$, which is excluded by LEP data [6].

Similar conclusions will hold for other operators of this sort. Of course there is a possibility of a fine tuned cancellation among the many operators but this is even sillier than the model already is.

Finally, we consider the operators of type O_2 . Since the results for all the operators of this kind are similar, we present here only the detailed calculation for the operator in eq. (29). When the Higgs field acquires a vacuum expectation value, O_2 contains the piece

$$O_2^{nc} = \frac{v}{M^3} \frac{ie}{2c_w s_w} Z_\mu \bar{e}_L e_R \partial^\mu \phi, \quad (32)$$

which leads to the following partial decay width for the process $Z \rightarrow l^+ l^- \phi$:

$$\Gamma = \frac{1}{(4\pi)^3} \left(\frac{e}{2c_w s_w} \right)^2 \left(\frac{v}{M^3} \right)^2 M_Z^5 G(r) \quad (33)$$

where

$$G(r) = -\frac{4}{15} \left(\frac{1-r}{2} \right)^5 + \frac{1+r}{6} \left[\frac{(1-r)^3(1+r)}{16} - \frac{3r(1-r^2)}{8} - \frac{3r^2}{4} \log r \right] \quad (34)$$

and $r \equiv \frac{m_\phi^2}{M_Z^2}$. As in the previous models considered, the branching ratio inferred from the L3 events (eq. (16)) provides an upper limit for the coupling,

$$\frac{e}{2c_w s_w} \frac{v}{M^3} \sim 5.2 \cdot 10^{-4}, \quad (35)$$

which implies $M \sim 56$ GeV.

The operator O_2 also induces $e^+e^- \rightarrow \phi Z^*$, which would produce photons and missing energy. However, the rate is too small to be observable. The operator also contains a charged current piece

$$O_2^{cc} = -\frac{v}{M^3} \frac{ie}{\sqrt{2}s_w} W_\mu \bar{\nu}_L e_R \partial^\mu \phi \quad (36)$$

which induces the W decay $W^+ \rightarrow l^+ \nu_l \phi$. It is straightforward to obtain that the width for this decay channel is given by

$$\Gamma(W^+ \rightarrow l^+ \nu_l \phi) = \frac{1}{(4\pi)^3} \left(\frac{e}{2s_w} \right)^2 \left(\frac{v}{M^3} \right)^2 M_W^5 G(r') \quad (37)$$

where $r' \equiv \frac{m_\phi^2}{M_W^2}$ and the function G was defined in eq. (35). When we incorporate in this expression the result (35) we get $\Gamma(W^+ \rightarrow l^+ \nu_l \phi) \sim 2 \cdot 10^{-3}$ MeV, which is not measurable in current and projected experiments (it is expected that the total width of the W boson will be measured with a precision of 200 MeV at LEP II [8].).

We conclude that an operator of O_2 type cannot be ruled out as decisively as the others we have considered. It is however extremely unlikely that it is responsible for the observed events. First of all, the scale of mass suppression is once again too low to be really believable. Furthermore, the operator, if it existed, would most likely be chirally suppressed. And finally, it would be hard to understand why this operator should be induced and not the others which we have successfully excluded. We conclude that it is possible that a scalar could be produced through this direct contact term at the rate required, but it is extremely unlikely.

5 Conclusions

In this paper, we have considered the possibility that there is a singlet scalar responsible for the observed two photon invariant mass peak observed at LEP. Of course, there are more general possibilities one can consider. For example, ϕ might have been part of an SU(2) gauge multiplet. Presumably since the scale of the operators is always very low, this will not matter since one can insert the Higgs field (VEV) to make gauge invariant operators and pursue an analysis identical to this one. We suspect methods similar to these will rule out most particle models.

It might be objected that the scale of the operators is always so low that we were not justified in only considering the lowest dimension operators. Again, with a more complete model of what induced these operators one can mimic our analysis. Given the full operator contributing to ϕ production and decay, gauge invariance will ensure that there are related operators which lead to three photon production at LEP or excess two photon production at TRISTAN. Therefore, despite the limitations of this approach, we anticipate that the conclusion will be quite robust.

We conclude that it is very unlikely that the L3 events represent the discovery of a new particle. Even without information on the angular distribution or the standard model background, we see that the events are not easily explained in a particle physics model.

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