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Excess of $\tau^+ \tau^- V$ Events in Z Decays: a Naive Look

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Abstract

The ALEPH Collaboration has analyzed the decays $Z \rightarrow \ell^+ \ell^- V$ ($V = e^+ e^-, \mu^+ \mu^-, \pi^+ \pi^-$), where ℓ is a lepton ($\ell = e, \mu, \tau$). A possible excess of events is observed when ℓ is the τ -lepton. We find that the observed kinematic distributions can be reproduced by assuming that i) a new vector boson S couples vectorially to the τ , and ii) the vector boson S decays into a V (through virtual Z -exchange) and a pair of neutral scalar particles ξ .

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1 Introduction

The ALEPH Collaboration recently reported a study [1] of Z decays with a final state consisting of two oppositely charged leptons and a charged particle-antiparticle pair originating at the interaction point:

$$Z \rightarrow \ell^+ \ell^- V. \quad (1.1)$$

In this decay, ℓ is a lepton, (i.e., e , μ , τ), and V is the charged particle-antiparticle pair, i.e., $V = e^+e^-$, $\mu^+\mu^-$, $\pi^+\pi^-$. They observed 10 e^+e^-V events, 10 $\mu^+\mu^-V$ events and 15 $\tau^+\tau^-V$ events, where, on the basis of their selection criteria, they expected 7.2, 6.6 and 3.2 events respectively. They concluded there is a possible excess in the τ -channel.

In this paper we make a first attempt to understand this ALEPH observation. For this purpose, we assume (a) that this observed effect is real, and (b) that the various observed distributions should be taken seriously in spite of the low statistics. In particular, the relevant distributions are that of the direction of the V with respect to the $\tau^+\tau^-$ directions and that of the invariant mass of the V .

From the first distribution, it seems likely that the τ emits a vector particle which leads to the V . Therefore the first question is: what can this vector particle be? The only known vector particles are the photon, the Z , and the gluon. The choice of the photon cannot explain the excess in the τ -channel as compared with the e - and the μ -channels, and that of the Z , which is heavy, is inconsistent with the angular distribution of the V with respect to $\tau^+\tau^-$. Therefore, among the known particles, the only possibility is to choose the gluon. More precisely, if the vector particle is one of the known particles, it is necessary to postulate a gluon- τ interaction, with a vertex involving the τ , the gluon, and a lepto-gluon [2]. This is a very interesting possibility that remains to be investigated.

In this paper, it is postulated that the vector particle emitted by the τ is one that is previously unknown. This new neutral vector particle is to be called S .

Attention is next turned to the second distribution mentioned above, namely that of the invariant mass of the V . In Ref. [1], it is stated that, in this mass distribution, no narrow peak is seen. If this result is accepted, then there are two possibilities: either the S has a sizable width, or the decay of this S produces one or more invisible particles in addition to the observed V . Here the latter possibility is chosen. The term “invisible” is used to describe particles which have escaped detection in the ALEPH experiment.

It is not attractive to postulate a direct interaction between the S , the invisible particle(s), and the e^+e^- , $\mu^+\mu^-$, or $\pi^+\pi^-$ pair that form the V . The alternative is to invoke an interaction between the S , the invisible particle(s), and another particle that gives the V . From this point of view, and with the desire not to introduce too many new particles, Z is the most natural choice for this particle that gives the V . Thus the vertex involves S , Z and the invisible particle(s).

Suppose for a moment that there is only one invisible particle. Then this invisible particle must be a boson. Since none of the known bosons is an attractive candidate, it is postulated that this invisible boson is again a new particle. However, to have only one invisible particle accompanying the V leads to two difficulties. First, no matter what masses are assigned to the S and this invisible boson, one generates an invariant V mass distribution which is tilted towards the higher mass values, whereas the data favor the lower values. There is also another, more theoretical difficulty. Since all the known elementary vector particles are gauge particles, it is natural to take the new vector particle S also to be a gauge particle. With the S and the Z both gauge particles, we have found no elegant way to write down a gauge coupling of S , Z and the invisible boson. In this paper, it is to be assumed that there are *two* invisible particles, which we shall call ξ and $\bar{\xi}$. (For our purposes, it is irrelevant whether or not ξ and $\bar{\xi}$ are the same.)

In summary, the basic assumptions for this paper are the following:

1. There exists a new neutral vector boson S , which couples to the τ , but not to e nor μ ;
2. The coupling of S to τ is a purely vectorial;
3. The vector boson S decays in a V through virtual Z -exchange and in two light scalar particles, ξ and $\bar{\xi}$, i.e.,

$$S \rightarrow \xi \bar{\xi} Z \quad \hookrightarrow e^+e^-, \mu^+\mu^-, \pi^+\pi^-. \quad (1.2)$$

This paper is organized as follows. In Sect. 2, we calculate the cross section for

$$e^+e^- \rightarrow Z \rightarrow \tau^+\tau^- S, \quad (1.3)$$

assuming that the vector boson S couples to the τ through a purely vector coupling. We also present the angular distribution and the energy distribution of the vector boson S .

In Sect. 3, we calculate the decay

$$S \rightarrow \xi \bar{\xi} \mu^+ \mu^-, \quad (1.4)$$

assuming that there exists an $S_\mu Z^\mu \xi \xi^\dagger$ coupling and that the virtual Z decays in a μ -pair. We show that the invariant mass distribution of the μ -pair is in agreement with the data if $m_S - 2m_\xi \simeq 0.8 - 1.7$ GeV. Because the neutral particles ξ and $\bar{\xi}$ can be very light, they may be hard to detect. Finally, in Sect. 4, we present our conclusions.

2 S Boson Production

In this section, we study the production of the vector boson S in Z -decay. We assume that the boson S is real, i.e., that it is produced on shell. We are thus led to consider the process

$$e^+(p_+) + e^-(p_-) \rightarrow \tau^+(q_+) + \tau^-(q_-) + S(k), \quad (2.1)$$

which proceeds through virtual Z -exchange. In the process (2.1), the quantities in the parentheses denote the four-momenta of the particles. Their masses are denoted by m_τ for the τ 's, by m_S for the S -boson, by M_Z for the Z -boson, and the electrons are treated in the massless approximation.

The lowest order Feynman diagrams for this process are given in Fig. 1a, and the associated amplitudes read:

$$\begin{aligned} M_1 &= h \frac{D(s)}{2(q_- \cdot k) + m_S^2} \bar{v}(p_+) \gamma_\mu (a - b\gamma_5) u(p_-) \\ &\quad \times \bar{u}(q_-) \not{k} (\not{q}_- + \not{k} + m_\tau) \gamma^\mu (a - b\gamma_5) v(q_+), \\ M_2 &= h \frac{D(s)}{2(q_+ \cdot k) + m_S^2} \bar{v}(p_+) \gamma_\mu (a - b\gamma_5) u(p_-) \\ &\quad \times \bar{u}(q_-) \gamma^\mu (a - b\gamma_5) (-\not{q}_+ - \not{k} + m_\tau) \not{k} v(q_+). \end{aligned} \quad (2.2)$$

In Eqs. (2.2), the Z -propagator is effectively

$$D(s) = \frac{1}{s - M_Z^2 + iM_Z\Gamma_Z}. \quad (2.3)$$

Here, Γ_Z is the full width of the Z , and $s = (p_+ + p_-)^2$. We take standard couplings, a and b , of the Z to the leptons and denote by h the coupling of S to τ which is taken to be pure vector.

The cross section, averaged over the initial spins and summed over the final state degrees of freedom, then reads

$$d\sigma = \int \delta^4(p_+ + p_- - q_+ - q_- - k) \frac{\overline{|M|^2}}{512 \pi^5 s} \frac{d^3 \vec{q}_+}{q_{+0}} \frac{d^3 \vec{q}_-}{q_{-0}} \frac{d^3 \vec{k}}{k_0}, \quad (2.4)$$

with

$$\begin{aligned} \overline{|M|^2} = & \frac{2h^2}{(s - M_Z^2)^2 + M_Z^2 \Gamma_Z^2} \left[\frac{A_1}{[2(q_- \cdot k) + m_S^2]^2} + \frac{A_2}{[2(q_+ \cdot k) + m_S^2]^2} \right. \\ & \left. + \frac{2A_3}{[2(q_+ \cdot k) + m_S^2][2(q_- \cdot k) + m_S^2]} \right], \end{aligned} \quad (2.5)$$

with

$$\begin{aligned} A_1 = & (4m_\tau^2 + 2m_S^2) \left[(a^4 + 6a^2b^2 + b^4)(u' - m_\tau^2)(s + t - m_\tau^2) \right. \\ & \left. + (a^2 - b^2)^2(t - m_\tau^2)(s + u' - m_\tau^2) - (a^4 - b^4)2m_\tau^2 s \right], \\ A_2 = & (4m_\tau^2 + 2m_S^2) \left[(a^4 + 6a^2b^2 + b^4)(t' - m_\tau^2)(s + u - m_\tau^2) \right. \\ & \left. + (a^2 - b^2)^2(u - m_\tau^2)(s + t' - m_\tau^2) - (a^4 - b^4)2m_\tau^2 s \right], \\ A_3 = & (a^2 + b^2)^2 \left\{ 4m_\tau^2 [(t - m_\tau^2)(u' - m_\tau^2) + (t' - m_\tau^2)(u - m_\tau^2) - m_\tau^2 s] \right. \\ & \left. - 2m_S^2 [(t - m_\tau^2)(t' - m_\tau^2) + (u - m_\tau^2)(u' - m_\tau^2) - ss'] \right\} \\ & + (a^4 + 6a^2b^2 + b^4)s[u^2 + u'^2 - m_S^2(u + u')] \\ & + (a^2 - b^2)^2 s[t^2 + t'^2 - m_S^2(t + t')] \\ & + (a^4 - b^4)4m_\tau^2 [s(2s' - 2m_\tau^2 - m_S^2) - (t + u - 2m_\tau^2)(t' + u' - 2m_\tau^2)]. \end{aligned} \quad (2.6)$$

In Eqs. (2.6), we also used the notation

$$\begin{aligned} s &= 2(p_+ \cdot p_-), & t &= m_\tau^2 - 2(p_+ \cdot q_+), & u &= m_\tau^2 - 2(p_+ \cdot q_-), \\ s' &= 2m_\tau^2 + 2(q_+ \cdot q_-), & t' &= m_\tau^2 - 2(p_- \cdot q_-), & u' &= m_\tau^2 - 2(p_- \cdot q_+). \end{aligned} \quad (2.7)$$

With Eqs. (2.4)–(2.7), one can now generate the kinematic distributions one is interested in. We give two such examples. In Fig. 2a, we show the shape of the energy spectrum of the S -particle,

and, in Fig. 2b, the shape of the angular distribution of S in terms of the variable θ_S , which is defined as the angle between the S and the $\tau^+\tau^-$ rest frame. In these figures, a rather low value of the S mass has been used: $m_S = 1.7$ GeV. The absolute normalizations of these distributions are arbitrary, because the coupling constant h in Eq. (2.2) is undetermined. Note that the angular distribution is symmetric around $\cos\theta_S = 0$. If one increases m_S , the angular distribution becomes flat, in contrast to the data which show more events for $|\cos\theta_S| > 0.6$. This suggests that the S -boson should not be too heavy, $m_S < 10$ GeV, but the ALEPH data seem to indicate lower values.

3 S Boson Decay

We now consider the decay of the S boson. We assume there exists a $SZ\xi\bar{\xi}$ coupling of the form $gS^\mu Z_\mu \xi \xi^\dagger$. The decay

$$S(p) \rightarrow \mu^+(k_+) + \mu^-(k_-) + \xi(k) + \bar{\xi}(k') \quad (3.1)$$

is then given by the Feynman diagram of Fig. 1b, and the associated amplitude reads

$$M = \frac{g}{M_Z^2} \bar{u}(k_-) \not{\epsilon}(p)(a - b\gamma_5)v(k_+), \quad (3.2)$$

where we have neglected the V momentum compared to M_Z . We shall also neglect the polarization effects for the S boson. The coupling constants a and b are the standard couplings of the Z to the muons.

From Eq. (3.2), we obtain the squared matrix element, summed over the final state spins and averaged over the S -polarizations, which reads

$$\begin{aligned} \overline{|M|^2} &= \frac{4g^2}{3M_Z^4 m_S^2} \left\{ (a^2 + b^2) [2(p \cdot k_+)(p \cdot k_-) + m_S^2(k_+ \cdot k_-)] \right. \\ &\quad \left. + (a^2 - b^2) 3m^2 m_S^2 \right\}, \end{aligned} \quad (3.3)$$

where m is the muon mass.

The squared matrix element (3.3) depends only on the sum $K = k + k'$, but not on k and k' separately. This implies that the four-body phase space is effectively a three-body phase space. The invariant mass distribution of the muons is then given by

$$\begin{aligned} \frac{d\Gamma}{dm_{12}} &= \frac{g^2(a^2 + b^2)}{3072 \pi^5 M_Z^4 m_S^5} \int_{4m_\xi^2}^{(m_S - m_{12})^2} dK^2 \left[\frac{K^2 - 4m_\xi^2}{K^2} \right]^{\frac{1}{2}} \sqrt{\Delta} \\ &\quad \times \left[\frac{1}{4}(m_S^2 - m_{12}^2 + K^2 + 2m^2)^2 - \frac{\Delta}{12m_{12}^2} \right. \\ &\quad \left. + (m_S^2 + m^2)(m_{12}^2 - K^2 - m^2) + m_S^2(m_{12}^2 - \beta m^2) \right], \end{aligned} \quad (3.4)$$

with

$$\begin{aligned} m_{12}^2 &= (k_+ + k_-)^2, \\ K^2 &= (p - k_+ - k_-)^2, \end{aligned}$$

$$\Delta = (m_{12}^2 - 4m^2)(m_S^4 + K^4 + m_{12}^4 - 2K^2m_S^2 - 2m_S^2m_{12}^2 - 2K^2m_{12}^2), \quad (3.5)$$

and

$$\beta = 2 - 6 \frac{a^2 - b^2}{a^2 + b^2}. \quad (3.6)$$

The integral over K^2 in Eq. (3.4) can be expressed in terms of complete and incomplete elliptic integrals of the first and second kind, but, for numerical purposes, the expression (3.4) is quite adequate.

The shape of the invariant mass spectrum of the V is largely independent of m_S and m_ξ , and consistent with the observed distribution. Except for one data point at 1.8 GeV, the data extend up to $m_{12} \simeq 1.3$ GeV. This suggests $m_S - 2m_\xi \simeq 1.3$ GeV. However, it may be that up to 5 of the events originate from processes which respect lepton universality. On this basis, one can exclude $m_S - 2m_\xi < 0.8$ GeV. In Fig. 2c, we exhibit the invariant mass distribution for $m_S = 1.7$ GeV and $m_\xi = 0.1$ GeV. Again, the normalization is arbitrary because the coupling constant g in Eq. (3.2) is undetermined. We verified that the case of final state electrons instead of muons does not alter this distribution in any significant way.

4 Conclusions

The ALEPH Collaboration has observed a possible excess in the $\tau^+\tau^-V$ channel in Z decay. From our analysis, it is seen that the observed events can be interpreted as the production of a new vector particle S in the τ -channel followed by its decay into a pair of light scalars, ξ and $\bar{\xi}$, and a pair of e^+e^- , $\mu^+\mu^-$ or $\pi^+\pi^-$ through virtual Z -exchange. We find that the observed kinematic distributions are reproduced if we assume that the S boson couples purely vectorially to the τ -leptons, and if m_S lies in the range 1 to 10 GeV (with a marked preference for the lower values), and $m_S - 2m_\xi \simeq 0.8 - 1.7$ GeV.

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Figure 1: a) Feynman diagrams for $e^+e^- \rightarrow \tau^+\tau^- S$.

Figure 1: b) Feynman diagram for $S \rightarrow \mu^+ \mu^- \xi \bar{\xi}$.

Figure 2: a) Energy distribution of S .

Figure 2: b) Angular distribution of S .

Figure 2: c) Invariant mass distribution of V .

Figure Captions

Fig. 1: a) Feynman diagrams for $e^+e^- \rightarrow \tau^+\tau^-S$.
b) Feynman diagram for $S \rightarrow \mu^+\mu^-\xi\bar{\xi}$.

Fig. 2: a) Energy distribution of S .
b) Angular distribution of S .
c) Invariant mass distribution of V .