The 30 GeV Dimuon Excess at ALEPH

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Abstract

A simple variation of a two-Higgs-doublet model is proposed to describe the 30 GeV dimuon excess reported by Heister in his reanalysis of $Z \to b\bar{b}$ events in ALEPH data taken in 1992-95. The heavier CP-even Higgs $H$ is the 125 GeV Higgs boson discovered at the LHC. The model admits two options for describing the dimuon excess: (1) The lighter CP-even Higgs $h$ and the CP-odd state $\eta_A$ are approximately degenerate and contribute to the 30 GeV excess. (2) Only the $h$ is at 30 GeV while the $\eta_A$ and $H$ are approximately degenerate at 125 GeV. The ALEPH data favor option 1. Testable predictions are presented for LHC as well as LEP experiments. A potential no-go theorem for models of this type is also discussed.

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1 Introduction

Figure 1: The opposite-sign (left) and same-sign (right) dimuon mass spectra in $Z \rightarrow b \bar{b} \mu^+ \mu^-$ data taken by the ALEPH Collaboration; from Ref. [1].

In a recent paper, Heister analyzed archived data of the ALEPH experiment at LEP and found apparent evidence for a narrow dimuon ($\mu^+ \mu^-$) resonance at 30 GeV [1]. The data, taken in 1992-95, involve 1.9 million hadronic decays of $Z$-bosons produced at rest in $e^+ e^-$ annihilation. This excess appears in $Z \rightarrow b \bar{b} \mu^+ \mu^-$ decays. The opposite-sign dimuon spectrum data is shown in Fig. 1a along with the expected background. The same-sign dimuon spectrum in Fig. 1b has no significant excesses. The data have the following characteristics:

1.) Two benchmark methods were used to estimate the significance of the excess. One gave a local significance of about $2.6 \sigma$, the other $5.4 \sigma$. The second method requires using the look-elsewhere effect; it reduces its significance by 1.4–1.6 $\sigma$. See Ref. [1] for details.

2.) There is an excess of $32 \pm 11$ events in the resonant peak of Fig. 2 corresponding to a mass of 30.40 GeV with a Breit-Wigner width of
Figure 2: ALEPH $Z \to \bar{b}b\mu^+\mu^-$ data with signal+background model used to extract the 30 GeV signal parameters in Ref. [1].

It should be understood that, if the dimuon excess is due to the decay of a new particle $X$, it is not known whether it is emitted from the $Z$, as in $Z \to Z^* X$ with $Z^* \to \bar{b}b$ and $X \to \mu^+\mu^-$, or from one of the $b$-quarks, as in $Z \to \bar{b}b \to \bar{b}b + X$, or from two new particles, $Z \to XY$, with $X \to \mu^+\mu^-$ and $Y \to \bar{b}b$.

3.) The decay angle ($\cos \theta^*$) distribution for muons in the dimuon rest frame, where $\theta^*$ is the angle between the dimuon boost axis and the $\mu^-$, is shown in Fig. 3a for the signal region, a mass range of $2\sigma$ around 1.78 GeV (Gaussian width of 0.74 GeV), consistent with the expected ALEPH dimuon mass reconstruction performance at 30 GeV. Using the $b$-tag and muon-ID efficiencies quoted in Ref. [1], this yields the branching ratio

$$B(Z \to \bar{b}b X(\to \mu^+\mu^-)) = (2.77 \pm 0.95) \times 10^{-4}.$$  \hspace{1cm} (1)

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Figure 3: The decay angle ($\cos \theta^*$) distribution for muons (left) in the signal region, $M_{\mu^+\mu^-} = (30.40 \pm 3.85)$ GeV and (right) in the sidebands $15 < M_{\mu^+\mu^-} < 50$ GeV, excluding the signal region; from Ref. [1].

the fitted mean mass value, $M_{\mu^+\mu^-} = (30.40 \pm 3.85)$ GeV. There is a clear preference for forward-backward production, i.e., with each muon close to a $b$-jet. Presumably, most of these events are semileptonic $b$-decays. There is also a smaller, approximately isotropic component for $|\cos \theta^*| < 0.8$. This may be indicative of a different – scalar – production mechanism in the signal region. However, Fig. 3b shows the angular distribution of events in sidebands, with $M_{\mu^+\mu^-} = 15$–50 GeV but excluding the signal-region events of Fig. 3a. It does not appear substantially different from Fig. 3a (though the ratio of events at $|\cos \theta^*| > 0.8$ to those in between is greater than it is in Fig. 3a).

4.) As noted above, there is no significant excess near $M_{\mu\mu} = 30$ GeV excess in the same-sign data, $Z \to \bar{b}b\mu^\pm\mu^\mp$. Nor is there an excess in the opposite-sign electron-muon data, $Z \to \bar{b}be^\pm\mu^\mp$.

5.) There is a small excess of $8.0 \pm 4.5$ events near $M_{e^+e^-} = 30$ GeV in the $Z \to \bar{b}be^+e^-$ data.
Figure 4: The opposite-sign dimuon mass spectrum in $Z \rightarrow \text{hadrons} + \mu^+\mu^-$ events in which the $b$-tag has been inverted, indicating no evidence for an excess near 30 GeV; from Ref. [1].

6.) There is no evidence for the 30 GeV dimuon excess in events for which the $b$-tag has been inverted; see Fig. 4 from Ref. [1]. Comparison of Fig. 4 with Fig. 1a shows that most of the events near $M_{\mu^+\mu^-} = 30$ GeV are still $\bar{b}b$, so it is not clear how dispositive this is of the excess being produced only in association with $\bar{b}b$.

7.) Ref. [1] states that, for $M_{\mu^+\mu^-}$ in the vicinity of 30 GeV, the minimum angle between one of the two muons and the leading jet was always found to be less than $15^\circ$.

The obvious and simplest explanation of these features of the ALEPH data is that the 30 GeV excess is just a statistical fluctuation in semileptonic

\[1\] Ref. [1] also observed a tendency for at least one of the leading jets to be broadened when the dimuon mass is high. This may make it difficult for to define the $b$-jet axis precisely in such events.
\(Z \rightarrow \bar{b}b\) decays. On the other hand, it is possible to construct a rather minimal model that accounts for the ALEPH data and makes several testable predictions. It is a two-Higgs doublet model (2HDM) in which the heavier CP-even Higgs boson \(H\) is the 125 GeV Higgs boson discovered in 2012 at the LHC \[2, 3\]. The two other neutral Higgs bosons are a CP-even one \(h\) and a CP-odd one \(\eta_A\). The additional neutral and charged Higgs bosons couple mainly to the muon doublet and secondarily, but more weakly, to \(b\)-quarks. We shall choose parameters so that \(M_h = 30\) GeV. There are then two “natural” options for the \(\eta_A\); either (1) \(M_{\eta_A} \approx M_h = 30\) GeV or (2) \(M_{\eta_A} \approx M_H = 125\) GeV. In option 1, \(Z \rightarrow h\eta_A\) with \(h \rightarrow \mu^+\mu^-\), \(\eta_A \rightarrow \bar{b}b\) and vice-versa. There are also two “Higgsstrahlung” processes: \(Z \rightarrow Z^*h\) with \(Z^* \rightarrow \bar{b}b\) and \(h \rightarrow \mu^+\mu^-\); and \(Z \rightarrow \bar{b}b\) with \(b\) or \(\bar{b}\) radiating \(h\) or \(\eta_A\) which then decays to \(\mu^+\mu^-\). In option 2, there are only the Higgsstrahlung processes involving \(h\)-radiation. The branching ratio (1) is easily fit by the first option, but not the second. If the charged Higgs bosons in this model, \(h^\pm\), are heavier than \(M_H/2\), they may have evaded previous searches because they decay mainly to \(\mu^\pm\nu_\mu\) and rarely to \(\tau^\pm\nu_\tau, \bar{c}b, \) and \(cs\); see, e.g., Refs. \[4, 5, 6\] for \(h^\pm\) and other searches at LEP and the LHC.

The rest of this paper is organized as follows: In Sec. 2 we describe our 2HDM model: its assumptions and their rationale; its potential, extremal conditions and mass matrices; the Higgs couplings to leptons, quarks, electroweak gauge bosons and to each other. In Sec. 3 we present the two options for describing the 30 GeV dimuon excess. There we see that only option 1 can explain Eq. (1) and we present numerical values for the model’s parameters and the corresponding signal branching ratio of the \(Z\). Sec. 4 catalogs predictions of our model. Some of these may be useful for looking for the dimuon in LHC experiments. Finally, in Sec. 5, we present what appears to be a fatal flaw of the model, and a potential no-go theorem for any Higgs-based (and other scalar-based) model of the 30 GeV dimuon. However, if the excess seen in ALEPH is confirmed in other LEP and LHC experiments, it will be difficult to dismiss the dimuon as a background fluctuation and this fly in the ointment will stand as a significant challenge to model-builders.
2 The 2HDM model

The model uses the two Higgs doublets (see Ref. [7] for a review),

\[ \phi_i = \frac{1}{\sqrt{2}} \left( \frac{\sqrt{2} \phi_i^\pm}{\phi_{i0} - i \phi_{i3}} \right), \]

where \( \phi_i^\pm = 1/\sqrt{2} (\phi_{i1} \mp i \phi_{i2}) \) for \( i = 1, 2 \). Both doublets have weak hypercharge \( \frac{1}{2} \). To account for the appearance of a dimuon excess only in association with the \( \bar{b}b \) decays of \( Z \)-bosons, we assume a \( U(1)_\phi \) symmetry with \( \phi \)-hypercharge \( Y_\phi \) assignments for the Higgs doublets, left handed fermion doublets and right-handed fermion singlets as follows:

\[ Y_\phi(\phi_1) = 0, \quad Y_\phi(\phi_2) = 1; \]
\[ Y_\phi(q_{Lk}) = Y_\phi \left( \begin{array}{c} u_{Lk} \\ d_{Lk} \end{array} \right) = Y_\phi(u_{Rk}) = Y_\phi(d_{Rk}) = 0; \quad (k = 1, 2, 3) \]
\[ Y_\phi(L_{Lk}) = Y_\phi \left( \begin{array}{c} \nu_{Lk} \\ \ell_{Lk} \end{array} \right) = \frac{1}{2}; \quad Y_\phi(\ell_{Rk}) = -\frac{1}{2}; \quad (k = 1, 2) \]
\[ Y_\phi(L_{L3}) = Y_\phi(\ell_{R3}) = 0. \]

This symmetry is softly broken by the dimension-two \( \phi_1^\dagger \phi_2 \) term in the potential

\[ V(\phi_1, \phi_2) = -\mu_1^2 \phi_1^\dagger \phi_1 - \mu_2^2 \phi_2^\dagger \phi_2 - \mu_3^2 (\phi_1^\dagger \phi_2 + \phi_2^\dagger \phi_1) + \lambda_1 (\phi_1^\dagger \phi_1)^2 \]
\[ + \lambda_2 (\phi_2^\dagger \phi_2)^2 + 2\lambda_3 (\phi_1^\dagger \phi_1)(\phi_2^\dagger \phi_2) + 2\lambda_4 (\phi_1^\dagger \phi_2)(\phi_2^\dagger \phi_1). \]

Here, \( \mu_{1,2,3} > 0 \), all \( \lambda \)'s are real, \( \lambda_{1,2} > 0 \) for vacuum stability, and we will want to assume that \( \lambda_4 < 0 \). For a range of these parameters, then, these fields have the real vacuum expectation values (vevs)

\[ \langle \phi_i \rangle_0 = \frac{1}{\sqrt{2}} \left( \begin{array}{c} 0 \\ v_i \end{array} \right), \]
and they satisfy the extremal conditions

\[-\mu_1^2 - \mu_3^2 v_2/v_1 + \lambda_1 v_1^2 + (\lambda_3 + \lambda_4)v_2^2 = 0, \]
\[-\mu_2^2 - \mu_3^2 v_1/v_2 + \lambda_2 v_2^2 + (\lambda_3 + \lambda_4)v_1^2 = 0. \]  

The square of the electroweak vev is \( v^2 = v_1^2 + v_2^2 = (246 \text{ GeV})^2 \). The mass matrices, mass eigenstate fields and eigenvalues of the CP-even Higgs bosons are (after shifting them by their respective vevs):

\[
M^2(\phi_{10}, \phi_{20}) = \left( \begin{array}{cc}
\mu_3^2 v_2/v_1 + 2\lambda_1 v_1^2 & -\mu_3^2 + 2(\lambda_3 + \lambda_4)v_1 v_2 \\
-\mu_3^2 + 2(\lambda_3 + \lambda_4)v_1 v_2 & \mu_3^2 v_1/v_2 + 2\lambda_2 v_2^2
\end{array} \right),
\]
\[
H = \phi_{10} \cos \alpha + \phi_{20} \sin \alpha, \quad h = -\phi_{10} \sin \alpha + \phi_{20} \cos \alpha,
\]
where \( \tan 2\alpha = \frac{2\mu_3^2(v_2/v_1 - v_1/v_2) + 2(\lambda_1 v_1^2 - \lambda_2 v_2^2)}{\mu_3^2(v_2/v_1 - v_1/v_2) + 2(\lambda_1 v_1^2 - \lambda_2 v_2^2)} \).

\[
M^2(H, h) = \frac{1}{2v_1 v_2} \bigg\{ \mu_3^2 v_1^2 + 2(\lambda_1 v_1^2 + \lambda_2 v_2^2)v_1 v_2 \\
\pm \left[ [\mu_3^2 v_1^2 + 2(\lambda_1 v_1^2 + \lambda_2 v_2^2)v_1 v_2]^2 - 8[\mu_3^2(\lambda_1 v_1^4 + \lambda_2 v_2^4)v_1 v_2 \\
+ 2\lambda_1 \lambda_2 v_1^4 v_2^4 + 2\mu_3^2(\lambda_3 + \lambda_4)v_1^3 v_2^3 - 2(\lambda_3 + \lambda_4)^2 v_1^2 v_2^2] \right]^{1/2} \bigg\}.
\]

For the CP-odd Higgs bosons, they are:

\[
M^2(\phi_{13}, \phi_{23}) = \left( \begin{array}{cc}
\mu_3^2 v_2/v_1 & -\mu_3^2 \\
-\mu_3^2 & \mu_3^2 v_1/v_2
\end{array} \right),
\]
\[
\pi_A = \phi_{13} \cos \beta + \phi_{23} \sin \beta, \quad \eta_A = \phi_{13} \sin \beta - \phi_{23} \cos \beta,
\]
where \( \tan \beta = \frac{v_2}{v_1} \).

\[
M_{\pi_A}^2 = 0, \quad M_{\eta_A}^2 = \mu_3^2 \frac{v_2^2}{v_1 v_2}.
\]

The \( \eta_A \) is a pseudo-Goldstone boson of the spontaneously broken \( U(1)_\phi \) symmetry which is also softly broken by the \( \mu_3^2 \)-term in the Higgs potential. For
the charged Higgs bosons:

\[ M^2(\phi^\pm_1, \phi^\pm_2) = \begin{pmatrix} \mu_3^2 v_2/v_1 - \lambda_4 v_1^2 \\ -\mu_3^2 + \lambda_4 v_1 v_2 \end{pmatrix}; \quad (14) \]

\[ \pi^\pm = \phi^\pm_1 \cos \beta + \phi^\pm_2 \sin \beta, \quad h^\pm = \phi^\pm_1 \sin \beta - \phi^\pm_2 \cos \beta, \quad (15) \]

\[ M^2_{\pi^\pm} = 0, \quad M^2_{h^\pm} = \left( \frac{\mu_3^2}{v_1 v_2} - \lambda_4 \right) v^2. \quad (16) \]

To be consistent with the ALEPH data, we assume that the scalar doublet \( \phi_1 \) couples to all fermions except the muon and electron, while \( \phi_2 \) couples only to the \( \mu \) and \( e \) doublets.\(^4\) As noted above, this is implemented by the (softly-broken) \( U(1)_\phi \) symmetry on Higgs and fermion fields. Without loss of generality, the Yukawa terms for the leptons may then be written in terms of mass-eigenstate lepton fields as

\[ \mathcal{L}_{Y\ell} = -\sum_{\ell_k = e,\mu} \frac{m_{\ell_k}}{v \sin \beta} \bar{\ell}_k \left[ v \sin \beta + H \sin \alpha + h \cos \alpha + i \eta_A \gamma_5 \cos \beta \right] \ell_k \]
\[ - \frac{m_{\tau}}{v \cos \beta} \bar{\tau} \left[ v \cos \beta + H \cos \alpha - h \sin \alpha - i \eta_A \gamma_5 \sin \beta \right] \tau \]
\[ + h^+ \left[ \sum_{k = e, \mu} \frac{\sqrt{2} m_{\ell_k} \cot \beta}{v} \bar{\nu}_{kL} \ell_{kR} - \frac{\sqrt{2} m_{\tau} \tan \beta}{v} \bar{\nu}_{\tau L} \tau R \right] + \text{h.c.} \]

These interactions induce no detectable charged-lepton flavor violation.\(^5\) The Yukawa interactions of the quarks are

\[ \mathcal{L}_{Yq} = -\sum_{d_k = d, s, b} \frac{m_{d_k}}{v \cos \beta} \bar{d}_k \left( v \cos \beta + H \cos \alpha - h \sin \alpha - i \eta_A \gamma_5 \sin \beta \right) d_k \]
\[ - \sum_{u_k = u, c, t} \frac{m_{u_k}}{v \cos \beta} \bar{u}_k \left( v \cos \beta + H \cos \alpha - h \sin \alpha + i \eta_A \gamma_5 \sin \beta \right) u_k \]
\[ - \frac{\sqrt{2} \tan \beta}{v} \sum_{k, l = 1}^3 \left[ \bar{u}_{kL}(V \mathcal{M}_d)_{kl} h^+ d_{lR} - \bar{d}_{kL}(V^\dagger \mathcal{M}_u)_{kl} h^- u_{lR} \right] + \text{h.c.} \]

Here, \( \mathcal{M}_{u,d} \) are the diagonal up and down-quark matrices and \( V \) is the Cabibbo-Kobayashi-Maskawa (CKM) matrix. For small \( \alpha \) and \( \beta \), \( h \) and

\(^4\)Alternatively, we could just as well couple the electron to \( \phi_1 \).

\(^5\)The \( h^\pm \)-contribution to the rate for \( b \to s\gamma \) is suppressed by \( \tan^4 \beta \).
\( \eta_A \) decay mainly to \( \mu^+\mu^- \) and, at most at the percent level, to \( \bar{b}b \). The \( h^\pm \) decay almost entirely to \( \mu^\pm\nu_\mu \). Because of this, the limits on charged Higgses from \( Z \) and \( t \)-decay appear to be inapplicable because they assume \( h^\pm \to \tau^\pm\nu_\tau, \ c\bar{b}, \ c\bar{s} \) \cite{4}, modes with very small branching ratios in our model. In Sec. 3, we shall find it prudent to assume \( M_{h^\pm} > M_H/2 \), hence \( \lambda_4 < 0 \).

The most important couplings of the Higgses to electroweak bosons are (in unitary gauge):

\[
\mathcal{L}_{EW} = \frac{e}{\sin 2\theta_W} \left[ (h \cos(\beta - \alpha) - H \sin(\beta - \alpha)) \overleftrightarrow{\partial_\mu} \eta_A \right] Z^\mu
\]
\[
+ \frac{e}{2\sin \theta_W} \left[ (\eta_A \pm ih \cos(\beta - \alpha) \mp iH \sin(\beta - \alpha)) \overleftrightarrow{\partial_\mu} h^\pm \right] W^{\mp\mu} \tag{19}
\]
\[
+ \left[ \frac{2e^2}{\sin^2 2\theta_W} Z^\mu Z_\mu + \frac{e^2}{\sin^2 \theta_W} W^{+\mu}W^-_\mu \right] [H \cos(\beta - \alpha) + h \sin(\beta - \alpha)] .
\]

For small \( \alpha \) and \( \beta \), the couplings of \( H \) are close to the Standard Model (SM) in all cases. Note the strong \( Z \to h\eta_A \) coupling.

Finally, for light \( h, \eta_A \) and \( h^\pm \), there is the possibility of \( H \)-decay to pairs of them. The relevant Lagrangian for this is:

\[
\mathcal{L}_{H\phi} = vHh^2 [3(\lambda_1 c_\beta c_\alpha s_\alpha^2 + \lambda_2 s_\beta s_\alpha c_\alpha^2) + (\lambda_3 + \lambda_4)(c_\beta c_\alpha (1 - 3s_\alpha^2) + s_\beta s_\alpha (1 - 3c_\alpha^2))] + vH\eta_A^2 [\lambda_1 c_\beta c_\alpha s_\beta^2 + \lambda_2 s_\beta s_\alpha c_\beta^2 + (\lambda_3 + \lambda_4)(c_\beta^3 c_\alpha + s_\beta^3 s_\alpha)]
\]  
\[
+ 2vHH^+h^- [\lambda_1 c_\beta c_\alpha s_\beta^2 + \lambda_2 s_\beta s_\alpha c_\beta^2 + \lambda_3 (c_\beta^3 c_\alpha + s_\beta^3 s_\alpha) - \lambda_4 c_\beta s_\beta \sin(\beta + \alpha)] . \tag{20}
\]

where \( c_\beta = \cos \beta \), etc.

### 3 Options for the 30 GeV Dimuon Excess

We identify \( H \) as the 125 GeV Higgs boson and \( h \) and possibly \( \eta_A \) as the 30 GeV excess in Ref. \cite{1}. In order that this be consistent with LHC data on \( H \), particularly the Higgs signal strengths \cite{4}, we require rather weak coupling between \( \phi_1 \) and \( \phi_2 \). This means small \( \alpha \) for \( \phi_{10} - \phi_{20} \) mixing and small \( \beta \) for mixing of the CP-odd scalars and of the charged scalars, i.e.,

\[
v^2 \cong v_1^2 \gg v_2^2 . \tag{21}
\]
Then we can make the further reasonable assumption that \((\mu_3^2 - 2\lambda_1 v_1 v_2)^2 \gg 8(\lambda_1 \lambda_2 - (\lambda_3 + \lambda_4)^2)v_2^4\), and we obtain
\[
M^2(H, h) \simeq \begin{cases} 
\max(2\lambda_1 v_1^2, \mu_3^2 v^2/v_1 v_2) \\
\min(2\lambda_1 v_1^2, \mu_3^2 v^2/v_1 v_2)
\end{cases}.
\tag{22}
\]

Thus, there are two options for the extra Higgs bosons’ masses:

\(1\) \(M_H^2 \simeq 2\lambda_1 v^2\) and \(M_h^2 \simeq M_{\eta_A}^2 \simeq \mu_3^2 v^2/v_1 v_2\); \(23\)

\(2\) \(M_H^2 \simeq M_{\eta_A}^2 \simeq \mu_3^2 v^2/v_1 v_2\) and \(M_h^2 \simeq 2\lambda_1 v^2\). \(24\)

The solution \(M_H^2 = 2\lambda_1 v_1^2\) is the SM formula for the Higgs boson’s mass. If this option is preferred by the ALEPH data, then \(h\) and \(\eta_A\) are nearly degenerate. In either case, the charged Higgs boson mass, \(M_{h^\pm}^2 = \mu_3^2 v^2/v_1 v_2 - \lambda_4 v^2 = M_{\eta_A}^2 - \lambda_4 v^2\), depends on the sign and magnitude of \(\lambda_4\).

For small \(\beta\) there is not much leeway in the masses of these two options. In option 1, making \(M_{\eta_A} < M_h\) quickly leads to \(\lambda_3\) an order of magnitude larger than \(\lambda_1\) and potentially to trouble with \(H\) decays to the light scalars (see below). Anyway, there is little motivation for \(M_{\eta_A} < M_h\). Making \(M_{\eta_A} > M_h\) even more quickly leads to \(\lambda_2 < 0\) and an unstable Higgs potential.

Another feature of option 1 is that \(H\) can decay to \(hh\), \(\eta_A\eta_A\) and \(h^+h^-\). A glance at Eq. (20) shows that these decays are strongly dominated by the \(O(\cos \beta \cos \alpha)\) terms in the \(\lambda_3\) and \(\lambda_4\) interactions; for moderate values of \(\lambda_1\) and \(\lambda_2\), their interactions contribute negligibly to the Higgs width. For \(|\lambda_3|, |\lambda_4| = \text{few} \times 10^{-2}\), these processes contribute several 10’s of MeV to the Higgs width, an order of magnitude more than its SM width of 4.07 MeV.

We choose \(\lambda_3 + \lambda_4\) so that the \(hh\) and \(\eta_A\eta_A\) contributions to the Higgs width are each \(\lesssim \frac{1}{2}\) MeV. This implies \(|\lambda_3 + \lambda_4| \lesssim 5.44 \times 10^{-3}\) and, in turn, small values and range for \(\alpha\). \(7\)

\[
-4.30 \times 10^{-3} \lesssim \alpha \lesssim -0.671 \times 10^{-3} \quad \text{for } v_2 = 10\text{ GeV}.
\tag{25}
\]

\(6\) Option 1 is the same as considered in Ref. \[11\], except that we forbid the \(\lambda_{5,6}\) quartic couplings of the 2HDM.

\(7\) This and other such constraints on 2HDM quartic couplings were discussed in Ref. \[12\].

\(8\) This constraint is consistent with limits on \(H\)-decays to light bosons in Ref. \[13\].
In addition, we shall take $\lambda_4 < 0$ so that $M_{h^\pm} = 65 \text{ GeV} > M_H/2$.

The range of $\alpha$ in Eq. (25) may seem unnaturally small. But it is not our model’s purpose to be devoid of all fine-tuning. Certainly not with the enormous renormalizations of the Higgs boson masses in this or any such model. The point here is that we can choose the model’s parameters to be consistent with ALEPH’s $Z \rightarrow \bar{b}b \mu^+ \mu^-$ and Higgs-decay data, and so we will.

In option 2, we will see that it would be desirable to have $M_{\eta_A} < M_Z - M_h$ there. But this is also excluded by the simultaneous requirements of a stable Higgs potential, perturbative $|\lambda_i| < 4\pi$, $0 < \cos(\beta - \alpha) - \text{a generous lower bound given the Higgsstrahlung processes (1) } Z \rightarrow Z^* + h \text{ with } Z^* \rightarrow \bar{b}b \text{ and } h \rightarrow \mu^+ \mu^- \text{ and (2) } Z \rightarrow \bar{b}b \text{ with } b(\bar{b}) \rightarrow b(\bar{b}) + h \text{ or } \eta_A \text{ and } h/\eta_A \rightarrow \mu^+ \mu^-.

In option 1, with $M_{\eta_A} \cong M_h \cong 30 \text{ GeV}$, the plausible origins of the dimuon signal at ALEPH are $Z \rightarrow h\eta_A$ with $h \rightarrow \mu^+ \mu^-$ and $\eta_A \rightarrow \bar{b}b$, and vice-versa. There are also the “Higgsstrahlung” processes (1) $Z \rightarrow Z^* + h$ with $Z^* \rightarrow \bar{b}b$ and $h \rightarrow \mu^+ \mu^-$ and (2) $Z \rightarrow \bar{b}b$ with $b(\bar{b}) \rightarrow b(\bar{b}) + h$ or $\eta_A$ and $h/\eta_A \rightarrow \mu^+ \mu^-.

In option 2, with $\eta_A$ and $H$ nearly degenerate at 125 GeV, the only kinematically plausible candidates for ALEPH are the Higgsstrahlung processes with $h$-radiation. Their contribution to the $Z \rightarrow \bar{b}b \mu^+ \mu^-$ branching ratio is tiny, $\lesssim 5 \times 10^{-10}$ for any $v_2 < 35 \text{ GeV}$, mainly because of suppression by the off-shell $Z$-propagator, the smallness of $\sin(\beta - \alpha)$, and the weak coupling of $h$ to $\bar{b}b$. So, option 2 cannot explain the 30 GeV dimuon excess.

The only source of the excess in option 1 is $Z \rightarrow h\eta_A$ because the Higgsstrahlung processes are still negligible. In the narrow-width approximation, the decay rate is

$$\Gamma(Z \rightarrow h\eta_A \rightarrow \bar{b}b \mu^+ \mu^-) = \Gamma(Z \rightarrow h\eta_A) [B(h \rightarrow \bar{b}b)B(\eta_A \rightarrow \mu^+ \mu^-) + (h \leftrightarrow \eta_A)],$$

where

$$\Gamma(Z \rightarrow h\eta_A) = \frac{2\alpha_{EM} p^3}{3M_Z^2 \sin^2 2\theta_W} \cos^2 (\beta - \alpha),$$

(26)

with $p$ the momentum of $h$ in the $Z$ rest frame. For $M_h = M_{\eta_A} = 30 \text{ GeV},$ [9]

It is possible that the main decay mode, $h^\pm \rightarrow \mu^\pm \nu_\mu$, has evaded searches for lighter charged Higgses; see Ref. [1] [3] [6]. It is also possible that limits on supersymmetric scalar muons decaying as $\tilde{\mu} \rightarrow \mu + E_T$ require $M_{h^\pm} > 95 \text{ GeV}$ [3]. A mass this large does not affect our results in Tables 1 and 2.
Table 1: The parameters in option 1 of the two-Higgs doublet model vs. the vev $v_2 = \sqrt{2}\langle \phi_2 \rangle_0$. The other input parameters are $M_h = M_{\eta_A} = 30$ GeV, $M_H = 125$ GeV, $M_{h^\pm} = 65$ GeV. The quartic coupling combination $\lambda_3 + \lambda_4$ is held fixed at $-3.00 \times 10^{-3}$ and $\lambda_4$ is chosen so that $M_{h^\pm} = 65$ GeV. The results are insensitive to $|\lambda_3 + \lambda_4| \lesssim 5 \times 10^{-3}$.

| $v_2$ (GeV) | $\beta$ | $\alpha$ | $\mu_3^2$ (GeV$^2$) | $\lambda_1$ | $\lambda_2$ |
|-------------|---------|---------|----------------|--------|--------|
| 10          | 0.04066 | -0.348 $\times 10^{-2}$ | 36.6 | 0.1293 | 0.833 $\times 10^{-2}$ |
| 12.5        | 0.05084 | -0.435 $\times 10^{-2}$ | 45.7 | 0.1294 | 0.833 $\times 10^{-2}$ |
| 15          | 0.06101 | -0.522 $\times 10^{-2}$ | 54.8 | 0.1295 | 0.833 $\times 10^{-2}$ |
| 20          | 0.08139 | -0.695 $\times 10^{-2}$ | 72.9 | 0.1299 | 0.832 $\times 10^{-2}$ |

Tables 1 and 2 list quantities of interest for a range of $v_2$ and other inputs, including the choice $M_{h^\pm} = 65$ GeV. There is no difficulty choosing parameters that produce a branching ratio in the neighborhood of the value $B(Z \to b\bar{b} \mu^+ \mu^-) = 2.77 \times 10^{-4}$ deduced from the ALEPH data [1]. Note that, because of the relative smallness of $\sin \alpha$, most of the dimuon signal comes from $h \to \mu^+ \mu^-$.

| $v_2$ (GeV) | $B(h \to \mu^+ \mu^-)$ | $B(h \to bb)$ | $B(\eta_A \to \mu^+ \mu^-)$ | $B(\eta_A \to bb)$ | $B(Z \to b\bar{b} \mu^+ \mu^-)$ |
|-------------|-------------------------|----------------|-----------------------------|-----------------|-------------------------------|
| 10          | 0.9999                   | 0.444 $\times 10^{-4}$ | 0.9923                      | 0.667 $\times 10^{-2}$ | 0.950 $\times 10^{-4}$ |
| 12.5        | 0.9998                   | 1.085 $\times 10^{-4}$ | 0.9814                      | 1.613 $\times 10^{-2}$ | 2.297 $\times 10^{-4}$ |
| 15          | 0.9997                   | 2.249 $\times 10^{-4}$ | 0.9622                      | 3.286 $\times 10^{-2}$ | 4.673 $\times 10^{-4}$ |
| 20          | 0.9991                   | 7.105 $\times 10^{-4}$ | 0.8889                      | 0.09652         | 1.367 $\times 10^{-3}$ |

Table 2: The principal branching ratios of $h$, $\eta_A$ and of $Z \to b\bar{b} \mu^+ \mu^-$ vs. the vev $v_2 = \sqrt{2}\langle \phi_2 \rangle_0$ in option 1 of the two-Higgs doublet model. The other input parameters are $M_h = M_{\eta_A} = 30$ GeV, $M_H = 125$ GeV, $M_{h^\pm} = 65$ GeV. The results are insensitive to $|\lambda_3 + \lambda_4| \lesssim 5 \times 10^{-3}$.

\[\text{\footnote{The question of what to do about an additional } \sim 1.4\% \text{ in the } Z \text{ width is discussed briefly in Sec. 5.}}\]

\[\text{\footnote{We used } m_s = 0.057 \text{ GeV, } m_c = 0.71 \text{ GeV and } m_b = 2.96 \text{ GeV at } M_h = 30 \text{ GeV.}}\]
4 Predictions

This model makes a number of predictions, some obvious, some not so, that we enumerate here.

1.) The dimuon signal in ALEPH and in other detectors, at LEP or at the LHC, will be observed only in $Z$-decay and almost exclusively in association with $\bar{b}b$.

2.) Dimuons from the signal will have a common production vertex. Those outside the signal region are due to semileptonic $b$-decays and will not.

3.) Signal dimuons have an isotropic $\cos \theta^*$ distribution. Its flat shape is modified to a hump when there is a cut of $p_T > 5$–10 GeV on both muons. In that case, all of the signal lies in $\theta^*_T < \theta^* < \pi - \theta^*_T$, where $\theta^*_T$ is an increasing function of the $p_T$ cut. The effect is illustrated in Fig. 5 for LEP, where the $Z$ is produced at rest, and for the LHC, where the $Z$ tends to be produced with low $p_T$ and a large boost. Note that the histograms are normalized to unit area so that, for a large $p_T$ cut, little signal data remains.

4.) In our model, signal dimuons will not have a strong tendency to be close to the $b$-jets in the $Z$-boson’s rest frame. We have checked that this obvious kinematical fact is true in any model in which $Z \rightarrow XY$ with $X \rightarrow \mu^+\mu^-$ and $Y \rightarrow \bar{b}b$, for $X,Y$ with spin-zero or one. This is in contradiction with the ALEPH data for which, when $M_{\mu^+\mu^-} \sim 30$ GeV, the minimum angle between a muon and a leading jet is always less than 15° degrees [1]. We have no explanation for this difference. On the other hand, at the LHC, the rather large $Z$-boost makes the signal as well as semileptonic background muons less isolated. This tendency is stronger at 13 TeV than at 8 TeV. If muon isolation is an important signal criterion at 13 TeV, it may be possible to enhance it by selecting $Z$ + jet production. According to Ref. [14], approximately 15% of $Z$-production at 13 TeV is accompanied by one jet with $p_T > 30$ GeV.

5.) In the dimuon signal region, the $\bar{b}b$ invariant mass should have a significant excess near $M_{\eta_A}$, nominally 30 GeV in our model.
Figure 5: The $\cos\theta^*$ distribution of the $\mu^-$ in $h, \eta_A \rightarrow \mu^+ \mu^-$ as a function of the $p_T$ cut on each muon for LEP (left), where the $Z$ is produced at rest, and the LHC for collisions at 8 TeV (right), assuming negligible $p_T(Z)$. From A. Heister, private communication.

6.) Charged Higgses, $h^\pm$, decay mainly to $\mu^\pm \nu_\mu$. Light charged Higgses may not have been excluded in this mode by previous searches [4, 5, 6]. If they were, they need to be heavier than $M_{H}/2 = 62.5$ GeV. If they are excluded by LEP searches for supersymmetric scalar muons, they must be heavier than 95 GeV [4]. They are most readily sought in $\gamma^* \rightarrow h^+ h^- \rightarrow \mu^+ \mu^- + \not{E_T}$ in LEP-2 data and at the LHC and in $W^* \rightarrow h/\eta_A + h^\pm \rightarrow \mu^+ \mu^- + \not{E_T}$ at the LHC.

7.) If $\alpha \ll \beta$, as in Table 1, $H(125)$ couples only weakly to $\mu^+ \mu^-$, so this decay mode may be unobservably small.

8.) There will be no observable 30 GeV excess in $M_{e^+ e^-}$ in $Z \rightarrow \bar{b}b e^+ e^-$ events.

An interesting question is how to tell $h$ from $\eta_A$. The answer is not obvious if they are nearly degenerate at 30 GeV. Another question for which we have no ready answer is how to determine the mixing angles $\alpha$ and $\beta$
other than by naive fitting.

5 A No-Go Theorem?

To account for the apparently exclusive appearance of the 30 GeV dimuon excess in association with $Z \to \bar{b}b$, we used a 2HDM in which the Yukawa couplings of the second Higgs doublet $\phi_2$ involve only the muon and electron doublets. The Yukawa couplings of the $\tau$ and quark doublets are to $\phi_1$.

Only option 1 with $Z \to h\eta_A \to \bar{b}b\mu^+\mu^-$ can explain the rate of the ALEPH dimuon. In our model, for parameters that give $B(Z \to h\eta_A \to 4\mu) \simeq 0.014$, 3300 times larger than its measured value of $4.2 \times 10^{-6}$.

We have considered several modifications of our model that decrease the branching ratios of $h$ and $\eta_A$ to $\mu^+\mu^-$ while increasing the $\bar{b}b$ yield. We already mentioned that, for small $\beta$ and $\alpha$, $M_{\eta_A}$ cannot be much different from $M_h$. In our model, $B(h \to \mu^+\mu^-)B(\eta_A \to \bar{b}b) \propto \cos^2 \alpha/\cos^2 \beta$ and $B(h \to \bar{b}b)B(\eta_A \to \mu^+\mu^-) \propto \sin^2 \alpha/\sin^2 \beta$, with $\sin \alpha/\sin \beta \sim 0.1$. So, the next simplest thing we considered was to decrease $\cos \beta$. But since several production $\times$ decay-rate signal strengths of the Higgs boson $H$ are also proportional to $\cos^2 \alpha/\cos^2 \beta$, their measured values would no longer agree with the SM expectation of unity. If we counter this by increasing $\alpha$, with $\beta - \alpha$ still small and $B(Z \to h\eta_A \to \bar{b}b\mu^+\mu^-)$ still in the $10^{-4}$ range, we find again that the decay rates for $H \to hh, \eta_A\eta_A$ are many $10$'s of MeV. Further, when increasing $\beta$, other conflicts may arise, e.g., with $b \to s\gamma$ mediated by $h^\pm$-exchange.

In the context of a 2HDM, we also tried to ameliorate the 4-muon problem with the Branco-Grimus-Lavoura (BGL) mechanism [8, 9, 10] to dilute $B(h, \eta_A \rightarrow \mu^+\mu^-)$. The BGL scheme admits Higgs-induced flavor-changing neutral current interactions (FCNC) through a softly-broken $U(1)_\phi$ symmetry that allows a set of quarks with the same electric charge and color to couple to and get mass from both Higgs doublets [15]. The resulting FCNC

\footnote{We remind the reader that this setup induces no observable charged-lepton flavor violation.}
involve only the quark masses and elements of the CKM matrix $V$. If the third generation is treated differently than the first two, the FCNC are suppressed by factors of $V_{3i}^2$ or $V_{i3}^2$ and they can be sufficiently small even for Higgs masses much less than the 100-1000 TeV scale ordinarily required by $|\Delta S| = 2$ and $|\Delta B| = 2$ constraints.

We considered plausible alternatives in which the Yukawa couplings to $\phi_1$ and $\phi_2$ of one type of quark, up or down, have the form (here $\times$ denotes a nonzero entry):

$$\Gamma_1 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \times & \times & \times \end{pmatrix}, \quad \Gamma_2 = \begin{pmatrix} \times & \times & \times \\ 0 & 0 & 0 \end{pmatrix}, \quad \text{or vice-versa,} \quad (27)$$

while those of the other type are

$$\Gamma_1 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \times \end{pmatrix}, \quad \Gamma_2 = \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & 0 \end{pmatrix}, \quad \text{or vice-versa.} \quad (28)$$

The Yukawa textures of the leptons are the same as those displayed in Eq. (28). The “vice-versa” textures in these two equations are excluded for the $u$ and the $d$-sectors. If used for the $u$-sector, they imply $tt$ couplings to $h, \eta_A$ of $O((m_t/v)\cot\beta)$ and to $H$ of $O((m_t/v)\tan\beta)$. This ruins the agreement of the $H$-signal strengths with the SM and implies that by far the dominant decay modes of $h, \eta_A$ are to two gluons! Using them for the $d$-sector implies, among other things, that $B(h, \eta_A \to \bar{b}b)/B(h, \eta_A \to \mu^+\mu^-) = (3m_b/m_d)^2$, so that it is impossible to have $B(Z \to h\eta_A \to \bar{b}b\mu^+\mu^-) \sim 10^{-4}$.

For the displayed textures, the $|\Delta \text{Flavor}| = 2$ interactions induced by light $h$ and $\eta_A$ exchange are all very small because of a near cancellation between the two terms as well as the suppression by $V_{3i}$ or $V_{i3}$.\footnote{This cancellation $h-\eta_A$ was noted in Ref [9] but there was no reason for $M_h = M_{\eta_A}$ in that paper.} However, the textures in Eq. (27) for the $d$-sector give $B(B_{d,s} \to \mu^+\mu^-)$ which are $10^7$ times larger than their experimental upper limits. Furthermore, for $\Gamma_1^d$ and $\Gamma_2^d$ as displayed in either of these two sets of textures, $B(h, \eta_A \to \bar{s}s)$ is
almost as large as for $\mu^+\mu^-$. Such a large rate would have been captured in
the ALEPH data for which the $b$-tag was inverted (see Fig. 4).

For $u$-sector FCNC with Eq. (27),

$$B_{\text{BGL}}(D^0 \to \mu^+\mu^-) = \left[ \frac{f_D M^2_{D^0} m_u V_{ub} V^*_{cb}}{v^2 M_h^2 \sin^2 \beta} \right]^2 \frac{M_{D^0}}{16\pi \Gamma_{D^0}} = 1.65 \times 10^{-10},$$

for $\sin \beta = 0.05$ and $f_D = 212$ MeV. This is to be compared to the limit
$B(D^0 \to \mu^+\mu^-) < 6.2 \times 10^{-9}$ [4]. However, $B(h, \eta_A \to c\bar{c}) = 0.993,$
$B(h, \eta_A \to \mu^+\mu^-) = 0.733 \times 10^{-2}$ and $B(h, \eta_A \to b\bar{b}) = 1.08 \times 10^{-4},$ and
that kills off this BGL version of our model. To sum up, then, none of the
BGL models alleviates the $Z \to 4\mu$ problem without introducing others that
are just as bad and, generally, even give up on explaining the $Z \to b\bar{b} + 30-
GeV$ dimuon rate in ALEPH.

Another way to look at the $Z \to 4\mu$ problem is that the ALEPH signal
accounts for only about 2% of the $Z \to h\eta_A$ decay rate predicted by the
model for the nominal case $M_h \simeq M_{\eta_A} \simeq 30$ GeV. Where is the other
98% going if not into four muons? Can it be into quarks? Our foray into
BGL models suggests not but, at bottom, this is an experimental question
of determining individual $Z$-decay branching ratios. Can it be going into
something invisible? How can we account for $B(Z \to h\eta_A) \simeq 1.4\%$ when
the $Z$ width is measured to 0.1% and the $Z \to$ invisibles width implies the
number of neutrinos is $2.92 \pm 0.05$ [4]?

These sorts of problems would seem to infect any scalar-based model
of the ALEPH dimuon excess, especially because a novel scalar coupling
to leptons and quarks must involve Higgs multiplets beyond the Standard
Model. We have not considered vector-based models in much depth. Our
prejudice is that all vector bosons are gauge bosons. One example would
be to set $\mu_3^2 = 0$, gauge $U(1)_\phi$, and absorb $\eta_A$ in the corresponding gauge
boson. However, assuming no other fermions than those in the SM, it is
straightforward to see that canceling all gauge anomalies is possible only
if the $U(1)_\phi$ hypercharge of each fermion is proportional to its weak-$U(1)$
hypercharge. So, a more complicated setup is needed. What guidance does
the data give us that might evade the $4\mu$ problem?

Are we faced with a no-go theorem for explaining the ALEPH dimuon
excess? It has been said that there are no no-go theorems. Evading one is “simply” a matter of changing the assumptions of the theorem. But what assumptions should we change? If the narrow 30 GeV ALEPH dimuon, its apparent $Z$-boson source, and its association with $\bar{b}b$ production are confirmed in data from other LEP or LHC experiments, the challenge will be to theorists to account for it within the constraints of the PDG book.

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