A $Z'$ Model Which May Be Relevant to the New LEP Events
(revised)

Dan-di Wu
High Energy Physics, P. O. Box 355, Prairie View A & M University
Prairie View, Texas 77446 USA

and
Superconducting Super Collider Laboratory
2550 Beckleymeade Avenue, Dallas, Texas 75237 USA

and

Chung Kao
Department of Physics, B-159, Florida State University
Tallahassee, Florida 32306 USA

Abstract

A multi-Higgs model with an extra neutral gauge boson ($Z'$) is introduced. One scalar Higgs boson ($H_2$) in this model decays dominantly into a photon pair. The $Z'$ decay to $\mu^+\mu^-$ gets a much larger branching ratio than the $Z$ decay to this channel. The $ZZ'H_2$ vertex provides a final state from $Z$ decay resembling the new $l^+l^-\gamma\gamma$ events at the LEP. Other promising phenomenology, such as $Z \rightarrow l\bar{l}Z'$ is also discussed.

PACS numbers: 12.15.Cc, 13.15.Jr.
A simple way to extend the standard model of the electroweak theory \[1\] (SM) is to add an extra \(U(1)'\) gauge boson. These so called extra \(Z\) models \[2\] may be originated from all kinds of motivations and predict different phenomenology to be tested in high energy experiments.

He-Joshi-Lew-Volkas \[3\] (HJLV) have discussed a set of three simplest \(Z'\) models. The common feature of these models is that the \(Z'\), the gauge boson of an extra \(U(1)'\) gauge symmetry, only couples to leptons and neutrinos, so the leptonic decay of \(Z'\) is greatly enhanced. This feature makes these models seem relevant to the new LEP events. Indeed, recently at the DPF92 Meeting, S. Ting \[6\] reported 4 peculiar \(l\bar{l}\gamma\gamma\) events from L3, three of them are \(\mu\bar{\mu}\gamma\gamma\) and one \(ee\gamma\gamma\). There seems to be a two photon invariant mass clustering around 59.7 GeV within two standard deviations. DELPHI \[7\] and ALEPH \[8\] also have similar events, 2 from each. In addition, there are about ten \(l\bar{l}\gamma\gamma\) events from each group that spread over a large range of \(\gamma\gamma\) invariant masses. Although it is still too early to conclude anything from these peculiar events, it is interesting to see how one of the HJLV models may be relevant to these events. We shall see that a modified HJLV model is particularly of interest in this context.

The modification of the HJLV models we shall introduce is to allow a \(Z_1 - Z_2\) mixing, where \(Z_1\) and \(Z_2\) are respectively the SM \(Z\) boson and the gauge boson of the extra \(U(1)'\) symmetry with mass eigenstates \(Z\) and \(Z'\) and we identify \(Z\) as the one actually discovered at LEP. Because of this mixing, a \(ZZ'H_2\) vertex is present in the modified models. The models then allow the following process to happen at LEP

\[
Z \rightarrow Z'\ast H_2 \rightarrow l\bar{l}H_2, \quad (1)
\]

where \(H_2\) is a scalar component of the second Higgs doublet which, we assume, does not couple to any fermions\[4, 5\] because it has a nonzero \(U(1)'\) quantum number. \(H_2\) mainly decays into two photons. Its width is about 1 keV (see later), if its mass is about 60 GeV.
and it does not significantly mix with $H_1$, the SM Higgs boson. $H_2$ therefore does not decay into fermions through tree diagrams when the small mixing is neglected. It may still decay into fermion pairs via $W^\pm$, $Z$ and charged Higgs loops. However our calculation shows that the total fermionic branching ratio of $H_2$ is small. The qualitative reason of this is that the $H_2 \rightarrow 2\gamma$ loops involve derivative couplings while $H_2 \rightarrow f \bar{f}$ loops have only direct couplings.

The first candidate which come to our consideration is model I of HJLV. In this model the $U(1)'$ quantum numbers of $e$ and $\mu$ families sum to zero. In other words, the $U(1)'$ gauge boson $Z_2$ only couples to $e$, $\mu$ and their neutrinos. Because there are only left handed neutrinos, as are in the SM, the $Z_2$ decay branching ratio satisfy $e\bar{e} : \mu\bar{\mu} : (\nu_e\bar{\nu}_e + \nu_\mu\bar{\nu}_\mu) = 1 : 1 : 1$. In any case $Z_2$ has a much larger $e, \mu$ branching ratio than $Z_1$ does. This feature allows the model to give an explanation as of why $q\bar{q}\gamma\gamma$ is not observed and, perhaps due to reasonable statistical fluctuations, $\nu\bar{\nu}\gamma\gamma$ has still been missing [6, 7, 8]. Unfortunately, this model is strongly restricted by available $\Delta R(e^+e^- \rightarrow \mu^+\mu^-)$ measurements [9, 10]. The coupling constants of $Z'$ to leptons have to be so small so that the calculated branching ratio of $Z \rightarrow Z'(\rightarrow \ell\bar{\ell})H_2$ can only reach $few \times 10^{-8}$, which is too small to account for the L3 events.

The next candidate, which looks more promising is model III of HJLV. In this model, the $U(1)'$ quantum numbers of the $\mu$ and $\tau$ families sum to zero. A weakness of this model is that, in addition to blaming the lack of $\nu\bar{\nu}\gamma\gamma$ in the L3 experiment to statistical reasons we leave the observed $e^+e^-\gamma\gamma$ unexplained. It is worth commenting at this point that most of these 8 events (except one or two $\mu^+\mu^-\gamma\gamma$ events) are, still peculiar, but somehow one can always find a $\gamma - l$ pair whose total energy is almost the beam energy. The original version of model III is only very loosely restricted by $(g - 2)_{\mu}$ loop diagram [3]

$$m_{Z'} > 100y'g' \text{ GeV},$$

where $g'$ is the $U(1)'$ gauge coupling constant and $y'$ the $U(1)'$ quantum number of the
fermions. The modified model will be restricted by the LEP experiments. Now let us descibe this model in some detail.

The mass of $Z_2$ comes from two sources: a Higgs singlet $S$ which contributes the main part of the $Z_2$ mass and an extra Higgs doublet $\phi_2$ which contributes masses to $Z_1$, $Z_2$ and their mixing. The relevant Higgs-gauge couplings are

$$L_{HZZ} = \frac{1}{4} \frac{g_2^2}{1 - x} Z_1^2 \left( \frac{v_1 + H_1}{\sqrt{2}} \right)^2 + \frac{1}{4} \left( \frac{g_2}{\sqrt{1 - x}} Z_1 - g' Z_2 \right)^2 \left( \frac{v_2 + H_2}{\sqrt{2}} \right)^2 + g'^2 Z_2^2 \left( \frac{v_3 + H_3}{\sqrt{2}} \right)^2. \quad (2)$$

where $x = \sin^2 \theta_W$ with $\theta_W$ being the Weinberg angle [1]. $g_2$ is the $SU(2)$ gauge coupling constant, $g_2 = e/\sqrt{x}$, and $e$ is the electric charge of the proton. Here we assume that the $U(1)'$ quantum numbers for the Higgs doublets $\phi_1, \phi_2$ and the singlet $S$ are respectively 0, 1/2 and 1 and

$$< \phi_1 > = \frac{v_1}{\sqrt{2}}, \quad < \phi_2 > = \frac{v_2}{\sqrt{2}}, \quad < S > = \frac{v_3}{\sqrt{2}}. \quad (3)$$

The mass matrix in the $Z_1 - Z_2$ basis is

$$
\begin{pmatrix}
\frac{m_{Z_1}^2}{4} & -\frac{1}{4} \frac{g_2^2}{1 - x} g' v_2^2 \\
-\frac{1}{4} \frac{g_2}{\sqrt{1 - x}} g' v_2^2 & \frac{m_{Z_2}^2}{4}
\end{pmatrix}
\quad (4)
$$

with

$$m_{Z_1}^2 = \frac{1}{4} \frac{g_2^2}{1 - x} v^2, \quad m_{Z_2}^2 = g'^2 v_3^2 + \frac{1}{4} g'^2 v^2 \sin^2 \beta,$$

$$\sin \beta = \frac{v_2}{v}, \quad v^2 = v_1^2 + v_2^2. \quad (5)$$

Let $Z$ and $Z'$ be the mass eigenstates with

$$Z = Z_1 \cos \alpha_Z - Z_2 \sin \alpha_Z, \quad Z' = Z_1 \sin \alpha_Z + Z_2 \cos \alpha_Z, \quad (6)$$

after diagonalizing the mass matrix, we have, for small mixings

$$\tan \alpha_Z = \frac{g' \sqrt{1 - x}}{g_2} \left( \frac{m_{Z_2}^2}{m_{Z_1}^2} - \frac{m_{Z_2}^2}{m_{Z_1}^2} \right) \sin^2 \beta,$$

$$\frac{\Delta m_Z}{m_Z} = \frac{m_{Z} - m_{Z_1}}{m_Z} = \frac{1}{2} \left( \frac{m_{Z_2}^2 - m_{Z_1}^2}{m_{Z_1}^2} \right) \tan^2 \alpha_Z. \quad (7)$$

3
The relevant fermion-gauge sector is, assuming the $U(1)'$ quantum numbers for the $\mu$'s and $\tau$'s are respectively $-y'$ and $y'$ with $y' > 0$,

$$
\mathcal{L}_{Zff} = Z^\mu[(e_a L \cos \alpha_Z + g' y' \sin \alpha_Z)\bar{\mu}_L \gamma_\mu \mu_L + (ea_R \cos \alpha_Z - g'y' \sin \alpha_Z)\bar{\tau}_R \gamma_\mu \mu_R \\
+ (ea_L \cos \alpha_Z - g'y' \sin \alpha_Z)\bar{\tau}_L \gamma_\mu \mu_L + (ea_R \cos \alpha_Z + g'y' \sin \alpha_Z)\bar{\tau}_R \gamma_\mu \mu_R]
$$

and

$$
\mathcal{L}_{Z'ff} = Z'^\mu[(-g'y' \cos \alpha_Z + ea_L \sin \alpha_Z)\bar{\mu}_L \gamma_\mu \mu_L + (g'y' \cos \alpha_Z + ea_R \sin \alpha_Z)\bar{\tau}_R \gamma_\mu \mu_R \\
+ (g'y' \cos \alpha_Z + ea_L \sin \alpha_Z)\bar{\tau}_L \gamma_\mu \mu_L + (-g'y' \cos \alpha_Z + ea_R \sin \alpha_Z)\bar{\tau}_R \gamma_\mu \mu_R]
$$

with

$$a_L = (x - \frac{1}{2})/\sqrt{x(1-x)}, \ a_R = \sqrt{x/(1-x)}, \ a_\nu = 1/2\sqrt{x(1-x)}.$$

Note that the charged lepton-$Z_2$ coupling here is axial-vector like.

The branching ratio of process (2) is

$$B_{new} = \frac{1}{288\pi} \frac{\alpha^2}{\sqrt{x(1-x)}} \tan \alpha_Z(\frac{g'}{e})[0.711 \frac{\Gamma_{Z'}(m_Z^2 - m_{Z'}^2)}{\Gamma_{\mu\mu} \Gamma_{ZZ'}}] \mathcal{I}
$$

where $\Gamma_{Z'}$ and $\Gamma_{\mu\mu}$ are respectively the total width of the $Z'$ and the leptonic width of the $Z$. $\mathcal{I}$ is proportional to the integral of the matrix element in the phase space and $\alpha = e^2/4\pi$.

$$\mathcal{I} = \frac{1}{2}(47 - y^2 - 8\delta - \frac{8(y^2 - \delta^2)}{z^2})(1 - y^2) + 3(4 + 2y^2 - 16\delta + 4\delta^2)ln(1/y)

+ \frac{3(8y^2 + 4\delta - 16\delta^2 + 4\delta^3)}{\sqrt{y^2 - \delta^2}} \cos^{-1}\left[\frac{2y^2 - \delta(1 + y^2)}{z^2y}\right]
$$

with

$$y = \frac{m_{H_2}}{m_Z}, \ z = \frac{m_{Z'}}{m_Z}, \ \delta = \frac{1}{2}(1 + y^2 - z^2).$$
When \( z = 1 \), this integral becomes the Bj-function \[11, 12\]. \( I \) in Eq. (11) is only valid for
\[
1 - y < z < 1 + y, \quad \Gamma_{Z^{'}}/m_Z << z - (1 - y),
\]
and it is enhanced quickly when \( z \) approaches \( 1 - y \), i.e., \( m_{Z^{'}} \) approaches \( m_Z - m_{H^2} \). Although the parameters in the original model III are quite arbitrary, the modified model is strongly restricted by the available LEP data. The small inaccuracy in the leptonic width of the \( Z \) and the forward-backward asymmetry of the muon and the tau \[9\] require \( g'y' \sin \alpha_Z / e \) to be less than about 0.01. The small deviation between estimated and measured \( Z \) mass puts a constraint on \( (m_Z^2 - m_{Z^{'}}^2) \tan^2 \alpha_Z / m_Z^2 \) which must be less than about 0.01. In order that \( B_{\text{new}} \) has a reasonable value to be relevant to the L3 events, all parameters, \( \sin \alpha_Z, g'y' \) and \( m_{Z^{'}} \) have to take the most optional values. \( B_{\text{new}} \) will be too small if \( m_{Z^{'}} \) value is larger than 40 GeV because \( B_{\text{new}} \) is very sensitive to \( m_{Z^{'}} \), see Figure.1. As an example, setting \( (g'y')^2 / e^2 = 0.01, \sin \alpha_Z = 0.1 \) and \( x = 0.23 \) we find
\[
B_{\text{new}} \sim 0.60 \times 10^{-7} |1 - z^2| I,
\]
\[
B_{\mu} : B_{\tau} : B_{\nu} = 50 : 3 : 47.
\]
Setting further \( g' = e \), \( m_{H^2} = 59.7 \) GeV and \( B_{\text{new}} = (0.5 - 1.2) \times 10^{-6} \) we obtain
\[
32.5 < m_{Z^{'}} < 34.0 \text{ GeV}, \quad \Gamma_{Z^{'}} = 4.2 - 4.4 \text{ MeV}.
\]
A lighter \( Z^{' \prime} \) than those in this region can provide a larger branching ratio of process (2), however, it will require \( Z^{' \prime} \) to be produced on mass shell or almost on mass shell which seems not coinciding with the L3 events. The situation with \( Z^{' \prime} \) on mass shell while \( H^2 \) off mass shell is very unfavorable because the width of \( Z^{' \prime} \) is much larger than that of \( H^2 \), which is
\[
\Gamma_{H^2} \approx 1.6 \sin^2 \beta \text{ keV}.
\]
In our above parameterization, \( \sin^2 \beta \sim 0.1 \). This process is dominated by the \( W^\pm \) loop. The same virtual \( W^\pm \) pair may also transfer into a fermion pair. However its total width is about five times smaller than this.

It seems that the \( ZAH_2 \) and the \( ZZH_2 \) vertices can also produce \( f\bar{f}\gamma\gamma \) events, where \( A \) is the physical pseudoscalar Higgs boson. Both modes can be made comfortable by introducing a large \( \sin^2 \beta \) and smaller \( g' \) (or neglecting \( Z' \) completely\([3]\)). However the first one will be dominated by heavy fermions such as \( b\bar{b} \). The second one, as we know, will produce too many \( q\bar{q} \) and \( \nu\bar{\nu} \). These modes look more unlikely to be relevant.

A \( Z' \) so light can be produced on-shell in some processes, in particular

\[
Z \rightarrow l\bar{l} \rightarrow l\bar{l}Z'.
\] (18)

where one of the lepton (or anti-lepton) in the intermediate step is off mass shell. With the same parameterization to obtain Eq. (16), we find that this mode has a reasonably large total branching ratio which is

\[
B(Z \rightarrow l\bar{l}Z') \sim 2.1 \times 10^{-6}.
\] (19)

The ratios of different final particles can be easily obtained from the leptonic branching ratios of the \( Z \), and the \( Z' \)

\[
2\mu^+2\mu^- : \mu^+\mu^-\nu\bar{\nu} : 2\nu2\bar{\nu} : \tau\bar{\tau} + \text{any} = 7.5 : 42 : 33 : 18.
\] (20)

The most interesting channel is a \( Z' \) produced from neutrinos decays to \( \mu^+\mu^- \) which has a probability of 35\%. The signal is characterized by a \( \mu^+\mu^- \) pair with a fixed invariant mass which is smaller than \( m_Z \). The residual energy is all missing.

In conclusion, when taking the L3 events seriously, we feel that both \( l^+l^- \) and \( \gamma\gamma \) of the \( l^+l^-\gamma\gamma \) events need new physics to explain.

The authors would like to thank Han-qing Zheng at CERN for drawing our attention to the new LEP events as well as discussions, and Yue-kuan Li at KEK for assistance in
understanding the TRISTAN data, Tao Han and T. Kumita for reading the primary draft of this paper and giving very useful comments. The High Energy Physics Group of the Prairie View A & M University is operated by the Particle Detector Research Center, Texas National Research Laboratory Commissions under Contract No. RCFY 9208. Superconducting Super Collider Laboratory is operated by the University Research Association, In., for the U.S. Department of Energy under Contract No. DE-AC35-89ER40486. The research of C.K. was supported in part by the U. S. Department of Energy and in part by the Texas National Research Laboratory Commissions.
Figure Captions

1. The total branching ratio of the new events in Eq. (14) as a function of $m_{Z'}$ for $m_{H_2} = 55$ GeV (dashed), 59.7 GeV (solid) and 65 GeV (dash-dotted).
References

[1] S. L. Glashow, Nucl. Phys. 22, 579 (1961); S. Weinberg, Phys. Rev. Lett. 19, 1264 (1967); A. Salam, in Elementary Particle Theory: Relativistic Groups and Analyticity (Nobel Symposium No. 8), edited by N. Svartholm (Almqvist and Wiksell, Stockholm), 367 (1968); S. Glashow, J. Iliopoulos and L. Maiani, Phys. Rev D2, 1285 (1970).

[2] K. Kang and J. E. Kim, Lett. Nuovo Cimento 16, 252 (1976); Phys Rev. D14, 1903 (1976); V. Barger and R. J. Phillips, ibid, 18, 775 (1978); M. Yasue, Prog. Theor. Phys. 61, 269 (1978); M. Chanowitz et al., Nucl. Phys. B128, 506 (1979); G. G. Ross and T. Weiler, J. Phys. G5, 733 (1979); J. de Groot et al., Phys. Lett. 85B, 399 (1979); A. Zee and J. E. Kim, Phys. Rev. D21, 1939 (1980); N. G. Deshpande and D. Iskandar, Nucl. Phys. B167, 223 (1980); C. S. Gao and D. D. Wu, Phys. Rev. D23, 2686 (1981).

[3] X. G. He, J. Joshi, H. Lew and R. Volkas, Phys. Rev. D43, R22 (1991).

[4] H. Haber, G. Kane, and T. Sterling, Nucl. Phys. B161, 493; J-L. Basdevant, E. L. Berger, D. Dicus, C. Kao and S. Willenbrock, FERMILAB–PUB–92/27–T, (1992); C. Kao, D. D. Wu and H. Q. Zheng, in preparation. These are two Higgs doublet models with one doublet decouples from fermions.

[5] When this research was in progress, a theoretical work by V. Barger N. G. Deshpande, J. L. Hewett and T. G. Rizzo, ANL-HEP-PR-92-102 (1992), was distributed which approaches the question differently from us.

[6] S. C. C. Ting, talk given at the 1992 Meeting of the Division of Particle and Fields (DPF92) of the American Physical Society, Fermilab, Batavia, Illinois, (1992); B. Wyslouch, talk at the DPF92, Fermilab, Batavia, Illinois; L3 Collaboration, CERN-PPE/92-152 (1992).
[7] J. Marco, DELPHI report given at the DPF92, Fermilab, Batavia, Illinois, (1992).

[8] S. L. Wu, private communications.

[9] K. Hikasa et al., Particle Data Group, Phys. Rev. D45, No. 11, V.7 (1992). T. Kumita, Ph. D. Dissertation(1992), University of Rochester.

[10] For constraints on heavy $Z'$ bosons, with normal coupling constants, see e. g. M. Cvetič, P. Langacker and B. Kayser, Phys. Rev. Lett. 68, 2871 (1992); L. S. Durkin and P. Langacker, Phys. Lett. 166B, 436 (1986); W. J. Marciano, talk at the DPF92, Fermilab, Batavia, Illinois, (1992).

[11] J. D. Bjorken, Weak Interaction Theory and Neutral Currents, SLAC Publication SLAC-198(1976).

[12] J. Gunion, H. Haber, G. Kane and S. Dawson, The Higgs Hunter’s Guide, (Addison-Wesley Publishing Company, Redwood City, CA, 1990).