

THE 126 GeV HIGGS BOSON AND ITS NATURAL RELATIVES*

ERNEST MA

Physics and Astronomy Department, University of California
Riverside, California 92521, USA

(Received October 8, 2013)

Assuming that the observed 126 GeV particle at the Large Hadron Collider (LHC) is very close to being the Standard-Model Higgs boson, three examples of extra scalar doublets are discussed where they are set apart from the 126 GeV Higgs boson naturally because of symmetries.

DOI:10.5506/APhysPolB.44.2113

PACS numbers: 12.60.Fr, 14.80.Cp, 11.30.Hv

1. What has the LHC discovery taught us?

Last year (2012) was the year of the Higgs boson. We now know that there is a particle at 126 GeV which looks very much like the one Higgs boson of the Standard Model (SM). What has it taught us?

There are two possibilities: (1) The SM is it, and we can just clean up the details and go home. (2) There is new physics lurking, but it should naturally give us the 126 GeV particle as observed!

An example of (2) is supersymmetry (SUSY) where there are two Higgs doublets. In general, the lightest neutral physical scalar is not a linear combination equaling that of the SM, unless the SUSY breaking scale M_{SUSY} is rather high, say 10 TeV. However, $m_H = 126 \text{ GeV} > m_Z$ requires not only large M_{SUSY} but also very fine tuning in the Minimal Supersymmetric Standard Model (MSSM) between the parameters $m_{H_u}^2$ and μ^2 . The new hope of *natural* SUSY is NMSSM or a gauge extension, *i.e.* Z' or more.

2. Dark scalar doublet(s) and neutrino mass

A second scalar doublet (η^+, η^0) with an exactly conserved odd Z_2 symmetry [1] is good, because it does not mix with the SM Higgs and is a possible dark-matter candidate. In 2006, I proposed [2] the scotogenic (from

* Presented at the XXXVII International Conference of Theoretical Physics “Matter to the Deepest” Ustroń, Poland, September 1–6, 2013.

the Greek *scotos* meaning darkness) model of radiative neutrino mass, using the addition of N_i which are also odd under Z_2 together with (η^+, η^0) , thereby linking neutrino mass to the existence of dark matter.

Let $\eta^0 = (\eta_R + i\eta_I)/\sqrt{2}$, then η_R could be (cold) dark matter [2], or N_i of the order of 10 keV could be (warm) dark matter [3]. Two months after my 2006 paper, Barbieri *et al.* [4] proposed (η^+, η^0) by itself and called it the *inert* Higgs doublet, but it is neither inert (because it has gauge interactions) nor Higgs (because it has no vacuum expectation value).

Note that $\eta_{R,I}$ are split in mass by the Z_2 allowed term $(\lambda_5/2)(\Phi^\dagger\eta)^2 + \text{H.c.}$ as ϕ^0 acquires a v.e.v. This is important: (1) the one-loop diagram for Majorana neutrino mass is nonzero, and (2) the elastic scattering of η_R off nuclei through Z exchange is kinematically forbidden if η_I is a few hundred keV heavier than η_R .

Recently, it has been proposed [5] that Z_2 be promoted to a local gauge $U(1)_D$ symmetry with two dark scalar doublets $(\eta_{1,2}^+, \eta_{1,2}^0)$ transforming as ± 1 under $U(1)_D$, together with three Dirac N s. The Majorana neutrino mass is then generated by m_N without breaking $U(1)_D$. Such a massless dark photon is consistent with astrophysical observations for Dirac fermion dark matter at the TeV scale. If $U(1)_D$ is broken by a scalar with two units of dark charge, the Z_2 symmetry is recovered. The dark photon is then massive, together with a scalar particle which is also a force carrier for dark matter.

3. Lepton (and quark) flavor triality

Extra scalar doublets are also present in models of flavor symmetry based on non-Abelian discrete symmetries. In the case of A_4 , T_7 , or $\Delta(27)$, a residual Z_3 symmetry is obtained [6, 7] in the charged-lepton sector, allowing the natural separation of the SM Higgs from two others which carry no v.e.v.

Let $L_i = (\nu_i, l_i) \sim \underline{3}$, $l_i^c \sim \underline{1}_i (i = 1, 2, 3)$, and $\Phi_i = (\phi_i^+, \phi_i^0) \sim \underline{3}$, then $L_i l_j^c \tilde{\Phi}_k$, where $\tilde{\Phi} = (\tilde{\phi}^0, -\phi^-)$, yields

$$\mathcal{M}_l = \begin{pmatrix} v_1^* & 0 & 0 \\ 0 & v_2^* & 0 \\ 0 & 0 & v_3^* \end{pmatrix} \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 1 & 1 \\ 1 & \omega^2 & \omega \\ 1 & \omega & \omega^2 \end{pmatrix} \begin{pmatrix} f_e & 0 & 0 \\ 0 & f_\mu & 0 \\ 0 & 0 & f_\tau \end{pmatrix}. \quad (1)$$

If $v_1 = v_2 = v_3$, then a residual Z_3 symmetry persists in the lepton Yukawa sector

$$\begin{aligned} \mathcal{L}_{\text{int}} = & v^{-1} [m_\tau \bar{L}_\tau \tau_R + m_\mu \bar{L}_\mu \mu_R + m_e \bar{L}_e e_R] \phi_0 \\ & + v^{-1} [m_\tau \bar{L}_\mu \tau_R + m_\mu \bar{L}_e \mu_R + m_e \bar{L}_\tau e_R] \phi_1 \\ & + v^{-1} [m_\tau \bar{L}_e \tau_R + m_\mu \bar{L}_\tau \mu_R + m_e \bar{L}_\mu e_R] \phi_2 + \text{H.c.}, \end{aligned} \quad (2)$$

where $v = \langle \phi_0^0 \rangle$ and

$$\begin{pmatrix} \Phi_1 \\ \Phi_2 \\ \Phi_3 \end{pmatrix} = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 1 & 1 \\ 1 & \omega^2 & \omega \\ 1 & \omega & \omega^2 \end{pmatrix} \begin{pmatrix} \phi_0 \\ \phi_1 \\ \phi_2 \end{pmatrix}. \tag{3}$$

Thus $e, \mu, \tau \sim 1, \omega^2, \omega$ and $\phi_{0,1,2} \sim 1, \omega, \omega^2$ under Z_3 , with $\phi_0 = \bar{\Phi}_{SM}$.

This flavor triality symmetry allows $\tau^+ \rightarrow \mu^+ \mu^+ e^-$ and $\tau^+ \rightarrow e^+ e^+ \mu^-$ but no others (including $l_1 \rightarrow l_2 \gamma$ and $\mu \rightarrow eee$.) From $B(\tau^+ \rightarrow \mu^+ \mu^+ e^-) < 2.3 \times 10^{-8}$, it is obtained

$$\frac{m_1 m_2}{\sqrt{m_1^2 + m_2^2}} > 22 \text{ GeV} \left(\frac{174 \text{ GeV}}{v} \right), \tag{4}$$

where $m_{1,2}$ are the masses of the mass eigenstates $\psi_{1,2}^0 = (\phi_1^0 \pm \bar{\phi}_2^0)/\sqrt{2}$.

4. S₃ model (2004)

In 2004, a flavor model of quarks and leptons was proposed [8] using the non-Abelian discrete symmetry S_3 . This is the permutation group of 3 objects, which is also the symmetry group of the equilateral triangle. It has 6 elements divided into 3 equivalence classes. It has 3 irreducible representations $\underline{1}, \underline{1}'$, and $\underline{2}$, and the multiplication rule $\underline{2} \times \underline{2} = \underline{1} + \underline{1}' + \underline{2}$.

Quark and lepton assignments are:

$$L_e = (\nu_e, e), \quad Q_1 = (u, d), \quad \Phi_3 = (\phi_3^0, \phi_3^-) \sim \underline{1}, \tag{5}$$

$$e^c, \mu^c, u^c, c^c, d^c, s^c \sim \underline{1}, \quad \tau^c, t^c, b^c \sim \underline{1}', \tag{6}$$

$$(L_\mu, L_\tau), (Q_2, Q_3), (\Phi_1, \Phi_2) \sim \underline{2}. \tag{7}$$

Using the Yukawa invariants $\underline{2} \times \underline{1} \times \underline{2}, \underline{2} \times \underline{1}' \times \underline{2}, \underline{1} \times \underline{1} \times \underline{1}$, the mass matrices for the u and d quarks are given by

$$\mathcal{M}_{u,d} = \begin{pmatrix} g_3^u v_3^* & g_4^u v_3^* & 0 \\ 0 & g_1^u v_1^* & -g_2^u v_1^* \\ 0 & g_1^u v_2^* & g_2^u v_2^* \end{pmatrix}, \begin{pmatrix} g_3^d v_3 & g_4^d v_3 & 0 \\ 0 & g_1^d v_2 & -g_2^d v_2 \\ 0 & g_1^d v_1 & g_2^d v_1 \end{pmatrix}. \tag{8}$$

Note that (v_1, v_2) in \mathcal{M}_d is replaced by (v_2^*, v_1^*) in \mathcal{M}_u . This is important in getting a realistic V_{CKM} .

Let $v_3 = 0$ and $v_1 = v_2$ (*i.e.* $S_3 \rightarrow Z_2$), the $\mathcal{M}_{u,d}$ are both rotated by $\pi/4$, so their mismatch is zero, *i.e.* perfect alignment with $\theta_{23} = 0$. Hence this residual symmetry is a good explanation of why V_{CKM} is almost diagonal. Its breaking occurs when $v_3 \neq 0$ and $v_1 \neq v_2$, which may be assumed to be small naturally. In the lepton sector, \mathcal{M}_l is just like \mathcal{M}_d , but \mathcal{M}_ν may be chosen to be diagonal if it is Majorana. Hence $\nu_\mu - \nu_\tau$ mixing is predicted to be maximal, *i.e.* $\theta_{23} = \pi/4$, in agreement with experiment.

5. Update (2013)

The original 2004 model mainly dealt with the lepton sector and predicted very small θ_{13} , in disagreement with present data. However, it neglected $e-\mu$ mixing which is generally present, so the model is still viable. Here the quark sector is studied instead [9].

Consider first only the 2 heavy quark families with (Φ_1, Φ_2) . Let

$$V_{12} = \mu_1^2 (\Phi_1^\dagger \Phi_1 + \Phi_2^\dagger \Phi_2) + \frac{1}{2} \lambda_1 (\Phi_1^\dagger \Phi_1 + \Phi_2^\dagger \Phi_2)^2 + \frac{1}{2} \lambda_2 (\Phi_1^\dagger \Phi_1 - \Phi_2^\dagger \Phi_2)^2 - \mu_2^2 (\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1) + \lambda_3 (\Phi_1^\dagger \Phi_2) (\Phi_2^\dagger \Phi_1). \tag{9}$$

This is invariant under S_3 except for the soft μ_2^2 term which breaks S_3 to Z_2 ($\Phi_1 \leftrightarrow \Phi_2$). The Z_2 symmetry enforces $\langle \phi_1^0 \rangle = \langle \phi_2^0 \rangle = v = 123 \text{ GeV}$, resulting in the mass eigenstates:

$$h^0 = \phi_{1R} + \phi_{2R}, \quad m^2 = 2(2\lambda_1 + \lambda_3)v^2, \tag{10}$$

$$H^0 = \phi_{1R} - \phi_{2R}, \quad m^2 = 2\mu_2^2 + 2(2\lambda_2 - \lambda_3)v^2, \tag{11}$$

$$A = \phi_{1I} - \phi_{2I}, \quad m^2 = 2\mu_2^2, \tag{12}$$

$$H^\pm = (\phi_1^\pm - \phi_2^\pm) / \sqrt{2}, \quad m^2 = 2\mu_2^2 - 2\lambda_3 v^2. \tag{13}$$

At this level, h^0 is even under Z_2 and is naturally identified with the SM Higgs. The other scalars are odd under Z_2 . Note that if $\mu_2^2 = 0$, then A would be massless.

The $c - t$ and $s - b$ mass matrices are both of the form

$$\mathcal{M} = \begin{pmatrix} f_1 v & -f_2 v \\ f_1 v & f_2 v \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & -1 \\ 1 & 1 \end{pmatrix} \begin{pmatrix} f_1 \sqrt{2} v & 0 \\ 0 & f_2 \sqrt{2} v \end{pmatrix}. \tag{14}$$

Consequently, the physical s, b quarks couple to h^0 according to $(m_s/2v)\bar{s}s + (m_b/2v)\bar{b}b$ as in the SM. The other scalar couplings are given by

$$\mathcal{L}_Y = \frac{m_s}{\sqrt{2}v} \left[H^+ \bar{t}_L + \left(\frac{H^0 + iA}{\sqrt{2}} \right) \bar{b}_L \right] s_R + \frac{m_b}{\sqrt{2}v} \left[H^+ \bar{c}_L + \left(\frac{H^0 + iA}{\sqrt{2}} \right) \bar{s}_L \right] b_R + \text{H.c.}, \tag{15}$$

which maintains the Z_2 symmetry with t, b odd and c, s even. This forbids $b \rightarrow s\gamma$ but allows $B_s - \bar{B}_s$ mixing. The coefficient of the $(\bar{s}_L b_R)^2$ operator is $(m_b^2/4v^2)(m_H^{-2} - m_A^{-2})$. The coefficient of the $(\bar{s}_L b_R)(\bar{s}_R b_L)$ operator is $(m_s m_b/4v^2)(m_H^{-2} + m_A^{-2})$. The hadronic matrix element of the former (latter) gives $-23.87 \times 10^{-6} \text{ GeV}^3$ and $1.20 \times 10^{-6} \text{ GeV}^3$. The experimental

value $\Delta m_{B_s} = 1.164 \pm 0.005 \times 10^{-11}$ GeV agrees with the SM prediction to within 10%, so $m_{H,A}$ are constrained by

$$|-23.87 (m_H^{-2} - m_A^{-2}) + 1.20 (m_H^{-2} + m_A^{-2})| < 1.16, \quad (16)$$

where $m_{H,A}$ are in units of TeV. If $m_H = m_A$, then $m_{H,A} > 1.44$ TeV. If $m_H = 0.7$ TeV, then $0.73 < m_A < 0.75$ TeV.

Add Φ_3 with $\langle \phi_3^0 \rangle = v_3 \ll v$, then $\mathcal{M}_{d,u}$ are diagonalized on the left by

$$V_d = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c' & -s' \\ 0 & s' & c' \end{pmatrix} \begin{pmatrix} c_d & -s_d & 0 \\ s_d & c_d & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad (17)$$

where $s'/c' = v_2/v_1$, and

$$V_u = \begin{pmatrix} 1 & 0 & 0 \\ 0 & s' & -c' \\ 0 & c' & s' \end{pmatrix} \begin{pmatrix} c_u & -s_u e^{i\delta} & 0 \\ s_u e^{-i\delta} & c_u & 0 \\ 0 & 0 & 1 \end{pmatrix}. \quad (18)$$

Hence

$$V_{\text{CKM}} = V_u^\dagger V_d = \begin{pmatrix} c_u c_d + c'' s_u s_d e^{i\delta} & -c_u s_d + c'' s_u c_d e^{i\delta} & s'' s_u e^{i\delta} \\ -s_u c_d e^{-i\delta} + c'' c_u s_d & s_u s_d e^{-i\delta} + c'' c_u c_d & s'' c_u \\ -s'' s_d & -s'' c_d & c'' \end{pmatrix}, \quad (19)$$

where $s''/c'' = (c'^2 - s'^2)/2s'c'$. Using the 2012 PDG values, the parameters of this model are given by

$$s'' = 0.04135, \quad s_u = 0.08489, \quad s_d = 0.20983, \quad \cos \delta = -5.47 \times 10^{-3}, \quad (20)$$

and

$$J_{\text{CP}} = s_u c_u s_d c_d (s'')^2 c'' \sin \delta = 2.96 \times 10^{-5}. \quad (21)$$

This scheme does not predict any precise value of the measured parameters, but it does provide an understanding of why $(s'')^2, (s_u)^2, (s_d)^2$ are small.

To obtain $v_1 \neq v_2$, the Z_2 symmetry must be broken: add $\mu_3^2 (\Phi_1^\dagger \Phi_1 - \Phi_2^\dagger \Phi_2)$. This changes h^0 . However, in the limit of large $\mu_2^2 > 0$,

$$h^0 - h_{\text{SM}}^0 \simeq \frac{(\lambda_1 - \lambda_2 + \lambda_3) (v_1^2 - v_2^2)}{2\mu_2^2} H^0. \quad (22)$$

Note that $v_1 = v_2$ implies $h^0 = h_{\text{SM}}^0$. Without the $(v_1^2 - v_2^2)/4v^2 = 0.0207$ suppression, μ_2 becomes much larger, say > 10 TeV.

Adding Φ_3 means the addition of 5 quartic terms invariant under S_3

$$\begin{aligned}
 & (\lambda_4/2) \left(\Phi_3^\dagger \Phi_3 \right)^2 + \lambda_5 \left(\Phi_3^\dagger \Phi_3 \right) \left(\Phi_1^\dagger \Phi_1 + \Phi_2^\dagger \Phi_2 \right) + \lambda_6 \Phi_3^\dagger \left(\Phi_1 \Phi_1^\dagger + \Phi_2 \Phi_2^\dagger \right) \Phi_3 \\
 & + \left[\lambda_7 \Phi_3^\dagger \Phi_1 \Phi_3^\dagger \Phi_2 + \lambda_8 \Phi_3^\dagger \left(\Phi_1 \Phi_2^\dagger \Phi_1 + \Phi_2 \Phi_1^\dagger \Phi_2 \right) + \text{H.c.} \right]. \tag{23}
 \end{aligned}$$

The λ_8 term may be eliminated by imposing an extra Z_2 symmetry under which Φ_3 and $(u, d)_L$ are odd, and all others even. This Z_2 symmetry is then allowed to be broken softly by the term $\mu_4^2 \Phi_3^\dagger (\Phi_1 + \Phi_2) + \text{H.c.}$ As a result, for large $m_3^2 > 0$, $v_3 \simeq -\mu_4^2 (v_1 + v_2) / m_3^2$. Hence ϕ_{3R} mixes with $(v_1 \phi_{1R} + v_2 \phi_{2R}) / \sqrt{v_1^2 + v_2^2}$ by $v_3 / \sqrt{v_1^2 + v_2^2}$. This means that

$$h^0 - h_{\text{SM}}^0 \simeq \frac{v_3 m_h^2}{2v m_3^2} \phi_{3R}. \tag{24}$$

If the λ_8 term is present, then $h^0 - h_{\text{SM}}^0 \simeq (2v_3/v) \phi_{3R}$ which means that h^0 exchange itself would contribute too much to $K^0 - \bar{K}^0$ mixing. With the extra Z_2 symmetry, this problem is alleviated.

The direct exchange of ϕ_3^0 to $K^0 - \bar{K}^0$ mixing is now dominant and it has the effective interaction

$$\frac{s_d^2 c_d^2 m_d m_s}{v_3^2 m_3^2} (\bar{d}_L s_R) (\bar{d}_R s_L). \tag{25}$$

Allowing this to be 20% of the experimental measurement $\Delta m_K = 3.483 \pm 0.006 \times 10^{-15}$ GeV, $v_3 m_3 > 6 \times 10^4$ GeV² is obtained. For example, if $v_3 = 10$ GeV, then $m_3 > 6$ TeV.

The scalar spectrum of this model has only one light Higgs boson h^0 which coincides with the SM Higgs to a very good approximation. As for the other two scalar doublets, they are much heavier. The linear combination $\Phi_1 - \Phi_2$ is constrained by $B_s - \bar{B}_s$ mixing to be heavier than about 0.7 TeV, whereas Φ_3 is constrained by $K^0 - \bar{K}^0$ mixing to be heavier than about 6 TeV if $v_3 = 10$ GeV. With these masses, all rare processes involving only quarks but not leptons such as $b \rightarrow s\gamma$ are negligible. However, the $s - b$ sector is connected to the $\mu - \tau$ sector

$$\begin{aligned}
 \mathcal{L}_Y = & \frac{m_\mu}{\sqrt{2}v} \left[H^+ \bar{\nu}_{\tau L} + \left(\frac{H^0 + iA}{\sqrt{2}} \right) \bar{\tau}_L \right] \mu_R \\
 & + \frac{m_\tau}{\sqrt{2}v} \left[H^+ \bar{\nu}_{\mu L} + \left(\frac{H^0 + iA}{\sqrt{2}} \right) \bar{\mu}_L \right] \tau_R + \text{H.c.} \tag{26}
 \end{aligned}$$

This means that the decay $b \rightarrow s\tau^- \mu^+ (B_s \rightarrow \tau^+ \mu^-)$ proceeds through the exchange of $H^0 + iA$ with a possible branching fraction of 10^{-7} , but

$b \rightarrow s\tau^+\mu^-(B_s \rightarrow \tau^-\mu^+)$ will be suppressed by $(m_\mu/m_\tau)^2$. Given that $B(B_s \rightarrow \mu^+\mu^-) \simeq 3.2 \times 10^{-9}$ has been seen at the LHCb, this unique prediction is verifiable in the future.

6. Conclusion

In conclusion, the 126 GeV particle discovered at the LHC could very well be the SM Higgs boson or very close to it. Yet it may have some natural relatives, such as dark scalar doublets, or flavor triality partners, or the extra doublets in an S_3 model, where $h^0 \simeq h_{\text{SM}}^0$ because of the residual symmetry Z_2 from S_3 , and the extra Z_2 symmetry for Φ_3 and $(u, d)_L$. The unique prediction of this model is $b \rightarrow \tau^-\mu^+(B_s \rightarrow \tau^+\mu^-)$ which may be testable at the LHCb or Super KEKB.

I thank Janusz Gluza and all the other Organizers of the Ustroń 2013 Conference for their great hospitality. This work is supported in part by the U.S. Department of Energy under Grant No. DE-FG03-94ER40837.

REFERENCES

- [1] N.G. Deshpande, E. Ma, *Phys. Rev.* **D18**, 2574 (1978).
- [2] E. Ma, *Phys. Rev.* **D73**, 077301 (2006).
- [3] E. Ma, *Phys. Lett.* **B717**, 235 (2012).
- [4] R. Barbieri, L.J. Hall, V.S. Rychkov, *Phys. Rev.* **D74**, 015007 (2006).
- [5] E. Ma, I. Picek, B. Radovic, *Phys. Lett.* **B726**, 744 (2013) [arXiv:1308.5313 [hep-ph]].
- [6] E. Ma, *Phys. Rev.* **D82**, 037301 (2010).
- [7] Q.-H. Cao, A. Damanik, E. Ma, D. Wegman, *Phys. Rev.* **D83**, 093012 (2011).
- [8] S.-L. Chen, M. Frigerio, E. Ma, *Phys. Rev.* **D70**, 073008 (2004).
- [9] E. Ma, B. Melic, *Phys. Lett.* **B725**, 402 (2013).