Fermion and scalar phenomenology of a 2-Higgs doublet model with S_3.

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Introduction and Motivation

The origin of fermion masses and mixings cannot be understood within the Standard Model.

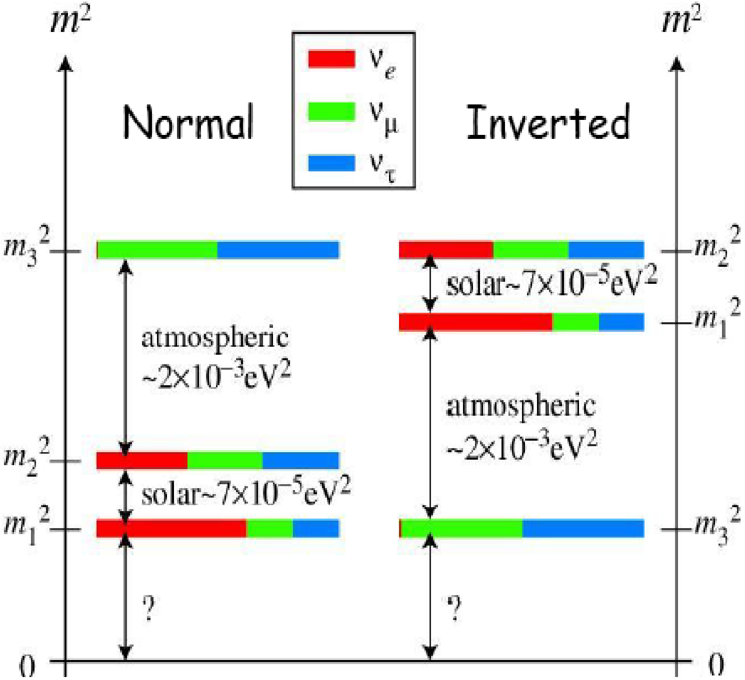
FERMIONS matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3


m^2
Normal
ν_e
ν_μ
ν_τ
Inverted
m^2
$m_3{}^2$
$m_2{}^2$
solar~7×10^{-5}eV^2
$m_1{}^2$
atmospheric
~2×10^{-3}eV^2
$m_2{}^2$
atmospheric
~2×10^{-3}eV^2
solar~7×10^{-5}eV^2
$m_1{}^2$
$m_3{}^2$
?
?
0
0

The popular tribimaximal (TBM) ansatz for the leptonic mixing matrix

$$U_{TBM}=\begin{pmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$, predicts $\left(\sin^2\theta_{12}\right)_{TBM}=\frac{1}{3}$,
$\left(\sin^2\theta_{23}\right)_{TBM}=\frac{1}{2}$, and $\left(\sin^2\theta_{13}\right)_{TBM}=0$.

Parameter	$\Delta m_{21}^2(10^{-5}\mathrm{eV}^2)$	$\Delta m_{31}^2(10^{-3}\mathrm{eV}^2)$	$\left(\sin^2\theta_{12}\right)_{\exp}$	$\left(\sin^2\theta_{23}\right)_{\exp}$	$\left(\sin^2\theta_{13}\right)_{\exp}$
Best fit	7.60	2.48	0.323	0.567	0.0234
1σ range	7.42 – 7.79	2.41 – 2.53	0.307 – 0.339	0.439 – 0.599	0.0214 – 0.0254
2σ range	7.26 – 7.99	2.35 – 2.59	0.292 – 0.357	0.413 – 0.623	0.0195 – 0.0274
3σ range	7.11 – 8.11	2.30 – 2.65	0.278 – 0.375	0.392 – 0.643	0.0183 – 0.0297

Table 1: Range for experimental values of neutrino mass squared splittings and leptonic mixing parameters taken from Forero et al, 2014 for the case of normal hierarchy.

Parameter	$\Delta m_{21}^2(10^{-5}\mathrm{eV}^2)$	$\Delta m_{13}^2(10^{-3}\mathrm{eV}^2)$	$\left(\sin^2\theta_{12}\right)_{\exp}$	$\left(\sin^2\theta_{23}\right)_{\exp}$	$\left(\sin^2\theta_{13}\right)_{\exp}$
Best fit	7.60	2.38	0.323	0.573	0.0240
1σ range	7.42 – 7.79	2.32 – 2.43	0.307 – 0.339	0.530 – 0.598	0.0221 – 0.0259
2σ range	7.26 – 7.99	2.26 – 2.48	0.292 – 0.357	0.432 – 0.621	0.0202 – 0.0278
3σ range	7.11 – 8.11	2.20 – 2.54	0.278 – 0.375	0.403 – 0.640	0.0183 – 0.0297

Table 2: Range for experimental values of neutrino mass squared splittings and leptonic mixing parameters taken from Forero et al, 2014 for the case of inverted hierarchy.

The S_3 group has three irreducible representations: $\mathbf{1}$, $\mathbf{1}'$ and $\mathbf{2}$. Denoting the basis vectors for two S_3 doublets as $(x_1, x_2)^T$ and $(y_1, y_2)^T$ and y' a non trivial S_3 singlet, the S_3 multiplication rules are (Ishimori, et al, Prog. Theor. Phys. Suppl 2010)::

$$\begin{pmatrix} x_1 \\ x_2 \end{pmatrix}_{\mathbf{2}} \otimes \begin{pmatrix} y_1 \\ y_2 \end{pmatrix}_{\mathbf{2}} = (x_1 y_1 + x_2 y_2)_{\mathbf{1}} + (x_1 y_2 - x_2 y_1)_{\mathbf{1}'} + \begin{pmatrix} x_2 y_2 - x_1 y_1 \\ x_1 y_2 + x_2 y_1 \end{pmatrix}_{\mathbf{2}}, \tag{1}$$

$$\begin{pmatrix} x_1 \\ x_2 \end{pmatrix}_{\mathbf{2}} \otimes (y')_{\mathbf{1}'} = \begin{pmatrix} -x_2 y' \\ x_1 y' \end{pmatrix}_{\mathbf{2}}, \qquad (x')_{\mathbf{1}'} \otimes (y')_{\mathbf{1}'} = (x' y')_{\mathbf{1}}. \tag{2}$$

The Model

We consider a 2HDM with its full symmetry $\mathcal{G}$ broken spontaneously in two steps:

$$\mathcal{G} = SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \otimes S_3 \otimes Z_3 \otimes Z_3' \otimes Z_{14} \tag{3}$$

$$\Downarrow \Lambda$$

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \otimes Z_3$$

$$\Downarrow \Lambda_{EW}$$

$$SU(3)_C \otimes U(1)_{em},$$

where the different symmetry breaking scales satisfy the following hierarchy $\Lambda \gg \Lambda_{EW}$, where $\Lambda_{EW} = 246$ GeV is the electroweak symmetry breaking scale. We use the S_3 discrete group since it is the smallest non-Abelian group, having a doublet and two singlets as irreducible representations.

	q_{1L}	q_{2L}	q_{3L}	U_R	u_{3R}	d_{1R}	d_{2R}	d_{3R}	l_{1L}	l_{2L}	l_{3L}	l_{1R}	l_{2R}	l_{3R}	ν_{1R}	ν_{2R}
S_3	1	1	1	2	1	1	1	1	1	1	1	1'	1	1	1	1
Z_3	0	0	1	0	1	2	2	1	2	0	0	1	0	0	0	0
Z_3'	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0
Z_{14}	-3	-2	0	1	0	4	3	3	-3	0	0	4	5	3	0	0

Table: Assignments of the SM fermions under the flavor symmetries.

A field ψ transforms under the Z_N symmetry with a corresponding Q_n charge as: $\psi \to e^{\frac{2\pi i Q_n}{N}}\psi,\ n = 0, 1, 2, 3 \cdots N-1.$

Field	ϕ_1	ϕ_2	ξ	χ	ζ
$SU(2)_L$	2	2	1	1	1
S_3	1	1	2	1	1'
Z_3	0	1	0	0	0
Z_3'	0	0	0	0	1
Z_{14}	0	0	0	-1	0

Table: Assignments of the scalars under $SU(2)_L$ and the flavor symmetries.

The VEV of ξ is aligned as $(1,0)$ in the S_3 direction.

The relevant quark Yukawa terms are

$$\begin{aligned} \mathcal{L}_Y^U &= \varepsilon_{33}^{(u)}\overline{q}_{3L}\widetilde{\phi}_1 u_{3R} + \varepsilon_{23}^{(u)}\overline{q}_{2L}\widetilde{\phi}_2 u_{3R}\frac{\chi^2}{\Lambda^2} + \varepsilon_{13}^{(u)}\overline{q}_{1L}\widetilde{\phi}_2 u_{3R}\frac{\chi^3}{\Lambda^3} \\ &+ \varepsilon_{22}^{(u)}\overline{q}_{2L}\widetilde{\phi}_1 U_R\frac{\xi\chi^3}{\Lambda^4} + \varepsilon_{11}^{(u)}\overline{q}_{1L}\widetilde{\phi}_1 U_R\frac{\xi\chi^4\zeta^3}{\Lambda^8} + h.c. \end{aligned} \quad (4)$$

$$\begin{aligned} \mathcal{L}_Y^D &= \varepsilon_{33}^{(d)}\overline{q}_{3L}\phi_1 d_{3R}\frac{\chi^3}{\Lambda^3} + \varepsilon_{22}^{(d)}\overline{q}_{2L}\phi_2 d_{2R}\frac{\chi^5}{\Lambda^5} + \varepsilon_{12}^{(d)}\overline{q}_{1L}\phi_2 d_{2R}\frac{\chi^6}{\Lambda^6} \\ &+ \varepsilon_{21}^{(d)}\overline{q}_{2L}\phi_2 d_{1R}\frac{\chi^6}{\Lambda^6} + \varepsilon_{11}^{(d)}\overline{q}_{1L}\phi_2 d_{1R}\frac{\chi^7}{\Lambda^7} + h.c. \end{aligned} \quad (5)$$

The invariant Yukawa terms for charged leptons and neutrinos are

$$\mathcal{L}_Y^l = \varepsilon_{33}^{(l)}\bar{l}_{3L}\phi_1 l_{3R}\frac{\chi^3}{\Lambda^3} + \varepsilon_{23}^{(l)}\bar{l}_{2L}\phi_1 l_{3R}\frac{\chi^3}{\Lambda^3} + \varepsilon_{22}^{(l)}\bar{l}_{2L}\phi_1 l_{2R}\frac{\chi^5}{\Lambda^5} + \varepsilon_{32}^{(l)}\bar{l}_{3L}\phi_1 l_{2R}\frac{\chi^5}{\Lambda^5} + \varepsilon_{11}^{(l)}\bar{l}_{1L}\phi_2 l_{1R}\frac{\chi^7\zeta}{\Lambda^8} + h.c. \quad (6)$$

$$\mathcal{L}_Y^\nu = \varepsilon_{11}^{(\nu)}\bar{l}_{1L}\widetilde{\phi}_2\nu_{1R}\frac{\chi^3}{\Lambda^3} + \varepsilon_{12}^{(\nu)}\bar{l}_{1L}\widetilde{\phi}_2\nu_{2R}\frac{\chi^3}{\Lambda^3} + \varepsilon_{21}^{(\nu)}\bar{l}_{2L}\widetilde{\phi}_1\nu_{1R} + \varepsilon_{22}^{(\nu)}\bar{l}_{2L}\widetilde{\phi}_1\nu_{2R} + \varepsilon_{31}^{(\nu)}\bar{l}_{3L}\widetilde{\phi}_1\nu_{1R} + \varepsilon_{32}^{(\nu)}\bar{l}_{3L}\widetilde{\phi}_1\nu_{2R} + M_1\bar{\nu}_{1R}\nu_{1R}^c + M_2\bar{\nu}_{2R}\nu_{2R}^c + M_{12}\bar{\nu}_{1R}\nu_{2R}^c + h.c. \quad (7)$$

Note that the breaking of the Z_3 symmetry at the EW scale generates the masses for the electron, down and strange quarks as well as a non trivial quark mixing.

The roles of the discrete symmetries are:

- S_3: Reduces the number of parameters in the Yukawa sector of this 2HDM making it more predictive.
- Z_3: Completely decouples the bottom quark from the remaining down and strange quarks.
- Z_3' and Z_{14}: Shapes the charged fermion mass and quark mixing hierarchy.

The Z_{14} symmetry is the smallest cyclic symmetry that allows $\frac{\chi^7}{\Lambda^7}$ in the Yukawa terms responsible for the down quark and electron masses. The Z_3' helps to explain the smallness of the up quark and electron masses.

Since the charged fermion mass and quark mixing pattern arises from the $Z_3' \otimes Z_{14}$ symmetry breaking, we set

$$v_\xi \sim v_\zeta \sim v_\chi = \lambda\Lambda. \tag{8}$$

where $\lambda = 0.225$.

Quark masses and mixing.

The mass matrices for up and down-type quarks are:

$$M_U = \frac{v}{\sqrt{2}} \left(\begin{array}{ccc} c_1\lambda^8 & 0 & a_1\lambda^3 \\ 0 & b_1\lambda^4 & a_2\lambda^2 \\ 0 & 0 & a_3 \end{array} \right), \quad M_D = \frac{v}{\sqrt{2}} \left(\begin{array}{ccc} e_1\lambda^7 & f_1\lambda^6 & 0 \\ e_2\lambda^6 & f_2\lambda^5 & 0 \\ 0 & 0 & g_1\lambda^3 \end{array} \right), \tag{9}$$

Setting $e_2 \approx f_2$ and fitting $|a_1|$, a_2, a_3, b_1, c_1, e_1, f_1, f_2, g_1 and $\arg(a_1)$, we get:

$$\begin{aligned} a_3 &\simeq 1, \qquad a_2 \simeq 0.81, \qquad a_1 \simeq -0.3e^{i\delta}, \\ \delta &= 67^\circ, \qquad b_1 \simeq \frac{m_c}{\lambda^4 m_t} \simeq 1.43, \qquad c_1 \simeq \frac{m_u}{\lambda^8 m_t} \simeq 1.27, \\ e_1 &\simeq 0.84, \qquad f_1 \simeq 0.4, \qquad f_2 \simeq 0.57, \qquad g_1 \simeq 1.42. \end{aligned} \tag{10}$$

Observable	Model value	Experimental value
$m_u(MeV)$	1.47	$1.45^{+0.56}_{-0.45}$
$m_c(MeV)$	641	635 ± 86
$m_t(GeV)$	172.2	$172.1 \pm 0.6 \pm 0.9$
$m_d(MeV)$	3.00	$2.9^{+0.5}_{-0.4}$
$m_s(MeV)$	59.2	$57.7^{+16.8}_{-15.7}$
$m_b(GeV)$	2.82	$2.82^{+0.09}_{-0.04}$

Table: Model and experimental values of the quark masses.

Observable	Model value	Experimental value
$\sin\theta_{12}$	0.2257	0.2254
$\sin\theta_{23}$	0.0412	0.0413
$\sin\theta_{13}$	0.00352	0.00350
δ	68°	68°

Table: Model and experimental values of CKM parameters.

Lepton masses and mixing.

The charged lepton mass matrix is:

$$M_l = \frac{v}{\sqrt{2}} \begin{pmatrix} x_1\lambda^8 & 0 & 0 \\ 0 & y_1\lambda^5 & z_1\lambda^3 \\ 0 & y_2\lambda^5 & z_2\lambda^3 \end{pmatrix}. \tag{11}$$

The neutrino mass matrix is

$$M_\nu = \begin{pmatrix} 0_{3\times 3} & M_\nu^D \\ \left(M_\nu^D\right)^T & M_R \end{pmatrix}, \tag{12}$$

where:

$$M_\nu^D = \begin{pmatrix} \lambda^3 \varepsilon_{11}^{(\nu)} \frac{v_2}{\sqrt{2}} & \lambda^3 \varepsilon_{12}^{(\nu)} \frac{v_2}{\sqrt{2}} \\ \varepsilon_{21}^{(\nu)} \frac{v_1}{\sqrt{2}} & \varepsilon_{22}^{(\nu)} \frac{v_3}{\sqrt{2}} \\ \varepsilon_{31}^{(\nu)} \frac{v_1}{\sqrt{2}} & \varepsilon_{33}^{(\nu)} \frac{v_3}{\sqrt{2}} \end{pmatrix} = \begin{pmatrix} A & F \\ B & E \\ C & D \end{pmatrix}, M_R = \begin{pmatrix} M_1 & \frac{1}{2}M_{12} \\ \frac{1}{2}M_{12} & M_2 \end{pmatrix} \tag{13}$$

Since $(M_R)_{ii} >> v$, type I seesaw mechanism generates the light active neutrino mass matrix:

$$M_L = \begin{pmatrix} W^2 & \kappa WX & WY \\ \kappa WX & X^2 & \kappa XY \\ WY & \kappa XY & Y^2 \end{pmatrix}, \qquad \kappa = \cos\varphi. \tag{14}$$

We further simplify the analysis by considering

$$x_1 = y_2 = z_1, \tag{15}$$

Fitting x_1, y_1, z_2, κ, W, X and Y, we get:

$$\begin{aligned} \kappa &\simeq 0.45, \quad W \simeq 0.13 eV^{\frac{1}{2}}, \quad X \simeq 0.11 eV^{\frac{1}{2}}, \quad Y \simeq 0.18 eV^{\frac{1}{2}}, \\ x_1 &\simeq 0.42, \quad y_1 \simeq 1.39, \quad z_2 \simeq 0.77, \qquad \text{for NH} \end{aligned} \tag{16}$$

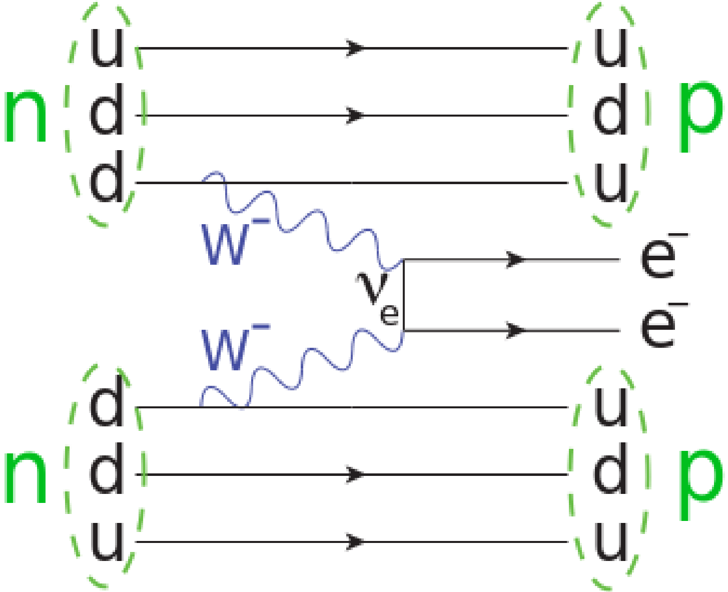
$$\begin{aligned} \kappa &\simeq 4.03 \times 10^{-3}, \quad W \simeq 0.18 eV^{\frac{1}{2}}, \quad X \simeq 0.22 eV^{\frac{1}{2}}, \quad Y \simeq 0.13 eV^{\frac{1}{2}}, \\ x_1 &\simeq 0.42, \quad y_1 \simeq 1.38, \quad z_2 \simeq 0.78, \qquad \text{for IH} \end{aligned} \tag{17}$$

$$m_1 = 0, \qquad m_2 \approx 9\text{meV}, \qquad m_3 \approx 50\text{meV}, \qquad \text{for NH} \tag{18}$$

$$m_1 \approx 49\text{meV}, \qquad m_2 \approx 50\text{meV}, \qquad m_3 = 0, \qquad \text{for IH} \tag{19}$$

Observable	Model value	Experimental value
$m_e(MeV)$	0.487	0.487
$m_\mu(MeV)$	102.8	102.8 ± 0.0003
$m_\tau(GeV)$	1.75	1.75 ± 0.0003
$\Delta m_{21}^2(10^{-5}\mathrm{eV}^2)$ (NH)	7.60	$7.60^{+0.19}_{-0.18}$
$\Delta m_{31}^2(10^{-3}\mathrm{eV}^2)$ (NH)	2.48	$2.48^{+0.05}_{-0.07}$
$\sin^2\theta_{12}$ (NH)	0.323	0.323 ± 0.016
$\sin^2\theta_{23}$ (NH)	0.567	$0.567^{+0.032}_{-0.128}$
$\sin^2\theta_{13}$ (NH)	0.0234	0.0234 ± 0.0020
$\Delta m_{21}^2(10^{-5}\mathrm{eV}^2)$ (IH)	7.60	$7.60^{+0.19}_{-0.18}$
$\Delta m_{13}^2(10^{-3}\mathrm{eV}^2)$ (IH)	2.48	$2.48^{+0.05}_{-0.06}$
$\sin^2\theta_{12}$ (IH)	0.323	0.323 ± 0.016
$\sin^2\theta_{23}$ (IH)	0.573	$0.573^{+0.025}_{-0.043}$
$\sin^2\theta_{13}$ (IH)	0.0240	0.0240 ± 0.0019

Table: Model and experimental values of the charged lepton masses, neutrino mass squared splittings and leptonic mixing parameters for thenormal (NH) and inverted (IH) mass hierarchies.


n
u
d
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W⁻
W⁻
ν_e
e⁻
e⁻
p
u
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n
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u

Furthermore, it is well known that the amplitude for neutrinoless double beta decay is proportional to the combination

$$m_{ee} = \sum_k U_{ek}^2 m_{\nu_k} \tag{20}$$

We predict the following effective neutrino mass for both hierarchies:

$$m_{\beta\beta} = \begin{cases} 4 \text{ meV} & \text{for} \quad \text{NH} \\ 50 \text{ meV} & \text{for} \quad \text{IH} \end{cases} \tag{21}$$

Therefore our predicted effective Majorana neutrino mass is consistent with its current experimental bound $|m_{ee}| < 0.3$ eV.

Implications of flavour changing neutral Higgs couplings

The up-type Yukawa couplings $Y^{h,H}_{ut,ct}$, however, allow for the tree-level decays $t \to hq$ $(q = u, c)$, whose branching ratios are currently limited by ATLAS (2014) to $\mathrm{Br}(t \to ch) < 0.79\%$ @ 95% C.L. and by CMS to $\mathrm{Br}(t \to ch) < 0.56\%$ @ 95% C.L (observed limit) and $\mathrm{Br}(t \to ch) < 0.65^{+0.29}_{-0.19}\%$ (expected limit). We consider only the stronger CMS constraint which implies

$$\sqrt{|y^h_{ut}|^2 + |y^h_{ct}|^2} < 0.14\,. \left|\frac{c_{\alpha-\beta}}{c_\beta s_\beta}\right| \lesssim 3.40\,.$$

That bound translates to

$$\left|\frac{c_{\alpha-\beta}}{c_\beta s_\beta}\right| \lesssim 3.40\,.$$

The $t \to ch$ channel is particularly interesting since its branching ratio $\mathrm{Br}(t \to hc)_{\mathrm{SM}} \simeq 10^{-15}$ is extremely suppressed in the SM, but can be potentially large in our model allowing it to be probed at future collider experiments. Our model predictions can reach branching ratios of $\mathcal{O}(0.01\%)$ in some regions of the $\alpha - \beta$ parameter space.

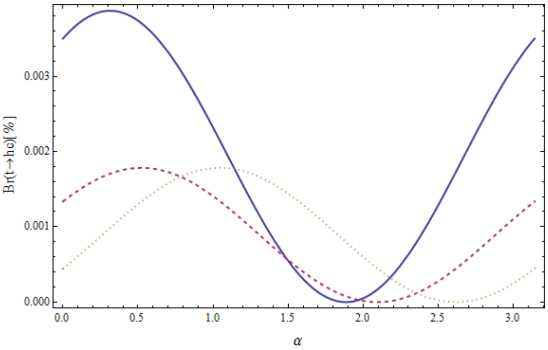

Figure: $\mathrm{Br}(t \to hc)$ as a function of α for $\beta = \pi/10$ (blue, solid), $\beta = \pi/6$ (red, dashed) and $\beta = \pi/3$ (yellow, dotted).

The charged leptons are also free of FCNCs due to the lack of off-diagonal Yukawa couplings. Consequently, the recently reported anomaly in $h \to \mu\tau$ decays cannot be explained in our present model.

Constraints from $h \to \gamma\gamma$

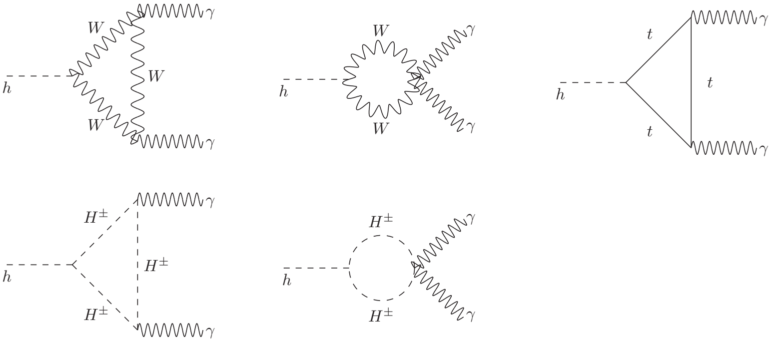

Figure: One-loop Feynman diagrams in the Unitary Gauge contributing to the $h \to \gamma\gamma$ decay.

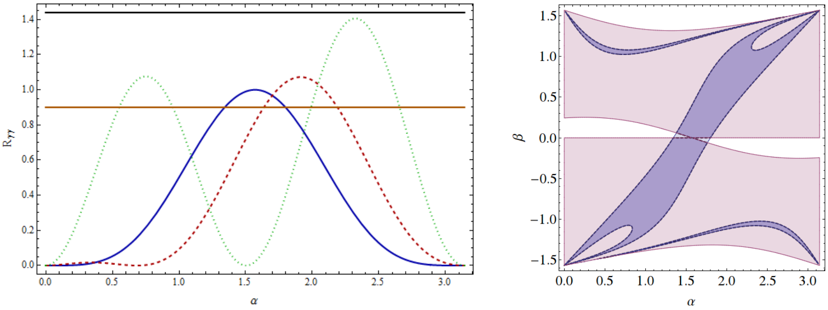

Figure: The constraints on the model imposed by keeping $R_{\gamma\gamma}$ inside the experimentally allowed 1σ range determined by CMS and ATLAS to be $1.14^{+0.26}_{-0.23}$ and 1.17 ± 0.27, respectively. Here $m_{H^\pm} = 500$ GeV, $\gamma_{12} + \kappa_{12} = 1$. The blue, red and green curves correspond β set to 0, $\frac{\pi}{6}$ and $\frac{\pi}{3}$, respectively, and the horizontal lines are the minimum and maximum values of the ratio $R_{\gamma\gamma}$. The Figure of the right panel shows the allowed region in the α-β plane consistent with the Higgs diphoton decay rate constraint at the LHC, superimposed with the constraint $Br(t \to qh) < 0.79\%$ at 95%CL.

As the mixing angle β is increased, the range of α consistent with LHC observations of $h \to \gamma\gamma$ moves away from $\pi/2$.

The T and S parameters

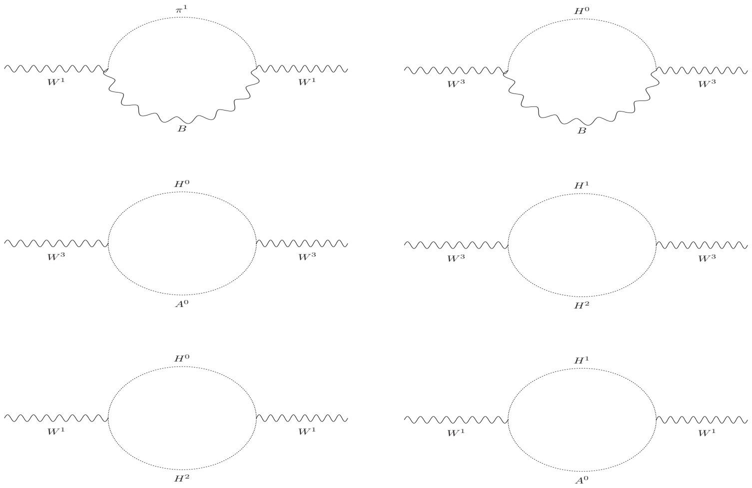

Figure: One-loop Feynman diagrams contributing to the T parameter.

The T and S parameters are defined as:

$$T=\frac{\Pi_{33}(0)-\Pi_{11}(0)}{M_W^2\,\alpha_{em}(m_Z)},\quad S=\frac{4\sin^2\theta_W}{\alpha_{em}(m_Z)}\frac{g}{g'}\frac{d\Pi_{30}(q^2)}{dq^2}\bigg|_{q^2=0}. \qquad (22)$$

We can write $T=T_{SM}+\Delta T$ and $S=S_{SM}+\Delta S$, where

$$T_{SM}=-\frac{3}{16\pi\cos^2\theta_W}\ln\left(\frac{m_h^2}{m_W^2}\right),\quad S_{SM}=\frac{1}{12\pi}\ln\left(\frac{m_h^2}{m_W^2}\right) \qquad (23)$$

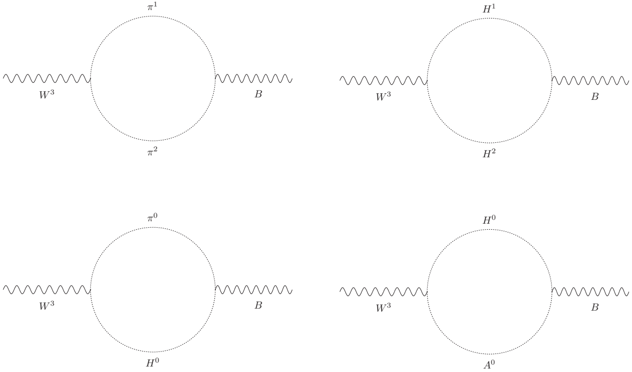

Figure: One-loop Feynman diagrams contributing to the S parameter.

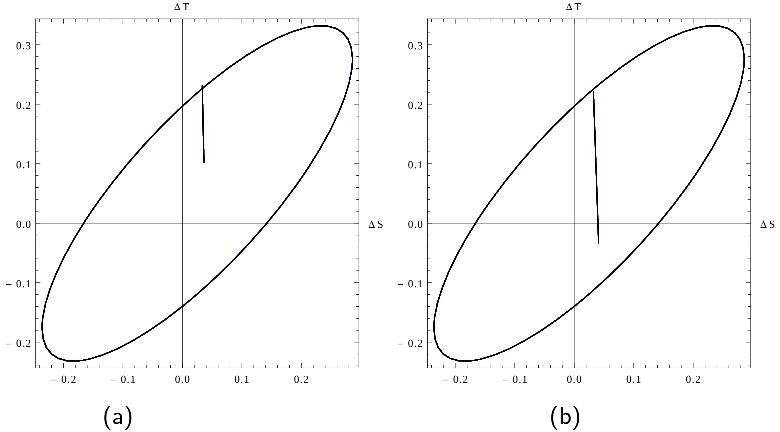

Figure: The $\Delta S - \Delta T$ plane, where the ellipses contain the experimentally allowed region at 95% confidence level. We set $\alpha - \beta = \frac{\pi}{5}$. Figures (a) and (b) correspond to $m_{A^0} = m_{H^0} = 500$ GeV and $m_{H^0} = m_{H^\pm} = 500$ GeV, respectively. Here 550 GeV $\leq m_{H^\pm} \leq$ 580 GeV (Fig. (a), 375 GeV $\leq m_{A^0} \leq$ 495 GeV (Fig. 1(b). The nearly vertical lines going up towards the ellipses correspond to ΔT and ΔS parameters in our model as masses are varied in the aforementioned ranges.

To explain the LHC diphoton excess at 750 GeV, we add to the fermion sector four $SU(2)_L$ singlet exotic quark fields with electric charge $\frac{5}{3}$, grouped into two S_3 doublets, as follows $T_L = (T_{1L}, T_{2L})$, $T_R = (T_{1R}, T_{2R})$. These exotic quarks fields are neutral under the $Z_3 \otimes Z_3'$ discrete symmetry but charged under the Z_{14} symmetry as:

$$T_L \to e^{-\frac{\pi i}{7}} T_L, \qquad T_R \to T_R. \tag{24}$$

The diphoton excess is attributed to the Z_{14} charged scalar χ, having the following Yukawa interaction with the exotic quarks:

$$y_T \overline{T}_L T_R \chi \tag{25}$$

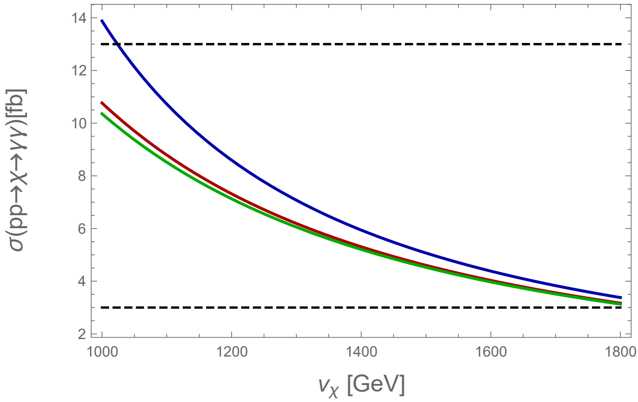

Figure: Total cross section $\sigma(pp \to \chi \to \gamma\gamma)$ as a function of v_χ for and different values of the exotic quark Yukawa couplings 1.5, 1 and 0.5 (in the curves from top to bottom, respectively), assuming $\sqrt{s} = 13\ TeV$ and $\alpha_s(m_\chi/2) \simeq 0.1$. The horizontal lines denote the experimentally allowed limits of the diphoton signal given by ATLAS and CMS, which amount to $10 \pm 3 fb$ and $6 \pm 3\ fb$, respectively. The limits require $v_\chi \lesssim 1.8\,\text{TeV}$ if natural order one exotic quark Yukawa couplings are assumed.

Conclusions

- Fermion masses and mixings are successfully accounted for.
- Light neutrino masses arise from type I seesaw mechanism with two heavy Majorana neutrinos.
- The observed charged fermion mass and quark mixing hierarchy arises from the $Z_3' \otimes Z_{14}$ symmetry breaking at a very high energy.
- The model has 17 effective free parameters in the Yukawa sector.
- The additional scalars mediate flavor changing neutral current processes that only in the up-type quark sector.
- The $h \to \gamma\gamma$ rate in our model can be distinguished from the SM prediction and places constraints on the mixing angles α and β.
- The model is compatible with the T and S parameter constraints.
- We predict an effective Majorana neutrino mass $m_{\beta\beta}$ equal to 4 meV and 48 meV for NH and IH neutrino spectrum, respectively.
- The 750 GeV diphoton excess constraints the exotic quark masses to be in the range $[1, 1.8]$ TeV, for $O(1)$ exotic quark Yukawa couplings.

Acknowledgements

Thank you very much to all of you for the attention.

Extra Slides

The Higgs doublets ϕ_j ($j = 1, 2$) acquire VEVs that break $SU(2)_L$

$$\phi_j = \begin{pmatrix} 0 \\ \frac{v_j}{\sqrt{2}} \end{pmatrix}, \qquad j = 1, 2. \tag{26}$$

We decompose the Higgs fields around this minimum as

$$\phi_l = \begin{pmatrix} \varphi_l^+ \\ \frac{1}{\sqrt{2}}\left(v_l + \rho_l + i\eta_l\right) \end{pmatrix} = \begin{pmatrix} \frac{1}{\sqrt{2}}\left(\omega_l + i\tau_l\right) \\ \frac{1}{\sqrt{2}}\left(v_l + \rho_l + i\eta_l\right) \end{pmatrix}, \tag{27}$$

where

$$\langle\rho_l\rangle = \langle\eta_l\rangle = \langle\omega_l\rangle = \langle\tau_l\rangle = 0, \qquad l = 1, 2. \tag{28}$$

From an analysis of the scalar potential, we obtain the following VEVs for the SM singlet scalars:

$$\langle\xi\rangle = v_\xi\left(1, 0\right), \qquad \langle\chi\rangle = v_\chi, \qquad \langle\zeta\rangle = v_\zeta, \tag{29}$$

i.e., the VEV of ξ is aligned as $(1, 0)$ in the S_3 direction.

The renormalizable low energy scalar potential is

$$\begin{aligned} V &= -\sum_{i=1}^{2}\mu_i^2(\phi_i^\dagger\phi_i)+\sum_{i=1}^{2}\kappa_i(\phi_i^\dagger\phi_i)^2 \\ &+ \gamma_{12}(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2)+\kappa_{12}(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) \\ &- \mu_{12}^2\left[\left(\phi_1^\dagger\phi_2\right)+\left(\phi_2^\dagger\phi_1\right)\right] \end{aligned} \tag{30}$$

The scalar mass eigenstates are:

$$\begin{pmatrix} h \\ H^0 \end{pmatrix} = \begin{pmatrix} \sin\alpha & -\cos\alpha \\ -\cos\alpha & -\sin\alpha \end{pmatrix}\begin{pmatrix} \rho_1 \\ \rho_2 \end{pmatrix}, \tag{31}$$

$$\begin{pmatrix} \pi^0 \\ A^0 \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ \sin\beta & -\cos\beta \end{pmatrix}\begin{pmatrix} \eta_1 \\ \eta_2 \end{pmatrix},$$

$$\begin{pmatrix} \pi^\pm \\ H^\pm \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ \sin\beta & -\cos\beta \end{pmatrix}\begin{pmatrix} \varphi_1^\pm \\ \varphi_2^\pm \end{pmatrix}, \qquad \tan\beta = \frac{v_2}{v_1}$$

$$\tan 2\alpha = \frac{2\left(\gamma v_1 v_2 - \mu_{12}^2\right)}{2\left(\kappa_1 v_1^2 - \kappa_2 v_2^2\right) + \mu_{12}^2\left(\frac{v_2}{v_1} - \frac{v_1}{v_2}\right)}, \tag{32}$$

$$Y_h^d = \begin{pmatrix} y_{dd}^h & y_{ds}^h & y_{db}^h \\ y_{sd}^h & y_{ss}^h & y_{sb}^h \\ y_{bd}^h & y_{bs}^h & y_{bb}^h \end{pmatrix} = \sqrt{2} \begin{pmatrix} -\frac{c_\alpha m_d}{v s_\beta} & 0 & 0 \\ 0 & -\frac{c_\alpha m_s}{v s_\beta} & 0 \\ 0 & 0 & \frac{m_b s_\alpha}{v c_\beta} \end{pmatrix},$$

$$Y_H^d = \begin{pmatrix} y_{dd}^H & y_{ds}^H & y_{db}^H \\ y_{sd}^H & y_{ss}^H & y_{sb}^H \\ y_{bd}^H & y_{bs}^H & y_{bb}^H \end{pmatrix} = \sqrt{2} \begin{pmatrix} -\frac{m_d s_\alpha}{v s_\beta} & 0 & 0 \\ 0 & -\frac{m_s s_\alpha}{v s_\beta} & 0 \\ 0 & 0 & -\frac{c_\alpha m_b}{v c_\beta} \end{pmatrix},$$

$$Y_h^u = \begin{pmatrix} y_{uu}^h & y_{uc}^h & y_{ut}^h \\ y_{cu}^h & y_{cc}^h & y_{ct}^h \\ y_{tu}^h & y_{tc}^h & y_{tt}^h \end{pmatrix} \simeq \sqrt{2} \begin{pmatrix} \frac{m_u s_\alpha}{v c_\beta} & 0 & \frac{m_t}{v} V_{tb} V_{ub} \left(\frac{c_\alpha}{s_\beta} + \frac{s_\alpha}{c_\beta} \right) \\ 0 & \frac{m_c s_\alpha}{v c_\beta} & \frac{m_t}{v} V_{tb} V_{cb} \left(\frac{c_\alpha}{s_\beta} + \frac{s_\alpha}{c_\beta} \right) \\ 0 & 0 & \frac{m_t}{v} V_{tb}^2 \frac{s_\alpha}{c_\beta} \end{pmatrix},$$

$$Y_H^u = \begin{pmatrix} y_{uu}^H & y_{uc}^H & y_{ut}^H \\ y_{cu}^H & y_{cc}^H & y_{ct}^H \\ y_{tu}^H & y_{tc}^H & y_{tt}^H \end{pmatrix} \simeq \sqrt{2} \begin{pmatrix} -\frac{c_\alpha m_u}{v c_\beta} & 0 & \frac{m_t}{v} V_{tb} V_{ub} \left(\frac{s_\alpha}{s_\beta} - \frac{c_\alpha}{c_\beta} \right) \\ 0 & -\frac{c_\alpha m_c}{v c_\beta} & \frac{m_t}{v} V_{tb} V_{cb} \left(\frac{s_\alpha}{s_\beta} - \frac{c_\alpha}{c_\beta} \right) \\ 0 & 0 & -\frac{m_t}{v} V_{tb}^2 \frac{c_\alpha}{c_\beta} \end{pmatrix}$$

In the charged lepton sector we obtain

$$Y_h^l = \sqrt{2}\begin{pmatrix} y_{ee}^h & y_{e\mu}^h & y_{e\tau}^h \\ y_{\mu e}^h & y_{\mu\mu}^h & y_{\mu\tau}^h \\ y_{\tau e}^h & y_{\tau\mu}^h & y_{\tau\tau}^h \end{pmatrix} = \sqrt{2}\begin{pmatrix} -\frac{c_\alpha m_e}{v s_\beta} & 0 & 0 \\ 0 & \frac{m_\mu s_\alpha}{v c_\beta} & 0 \\ 0 & 0 & \frac{m_\tau s_\alpha}{v c_\beta} \end{pmatrix}, \quad (33)$$

$$Y_H^l = \sqrt{2}\begin{pmatrix} y_{ee}^H & y_{e\mu}^H & y_{e\tau}^H \\ y_{\mu e}^H & y_{\mu\mu}^H & y_{\mu\tau}^H \\ y_{\tau e}^H & y_{\tau\mu}^H & y_{\tau\tau}^H \end{pmatrix} = \sqrt{2}\begin{pmatrix} -\frac{m_e s_\alpha}{v s_\beta} & 0 & 0 \\ 0 & -\frac{c_\alpha m_\mu}{v c_\beta} & 0 \\ 0 & 0 & -\frac{c_\alpha m_\tau}{v c_\beta} \end{pmatrix}. \quad (34)$$

The charged leptons are also free of FCNCs due to the lack of off-diagonal Yukawa couplings. Consequently, the recently reported anomaly in $h \to \mu\tau$ decays cannot be explained in our present model.