$h \to \mu\tau$ as an indication for S_4 flavor symmetry

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Motivation

Could lepton flavor be violated?

- $2.4\,\sigma$ anomaly in $h \to \mu\tau$

  CMS: $\mathrm{Br}(h \to \mu\tau) = (0.84 \pm 0.39)\%$
  [CMS Collaboration, Phys.Lett. B749 (2015)]

  ATLAS: $\mathrm{Br}(h \to \mu\tau) = (0.77 \pm 0.62)\%$
  [ATLAS Collaboration, ArXiv:1508.03372 (2015)]

- A typical signature of Multi-Higgs models

Objective

- Build a Multi-Higgs model (here: 3HDM) that predicts $h \to \mu\tau$ avoiding FCNC constraints

Main tool: Lepton Flavor Triality

- Global symmetry group (e.g., S_4) is broken down to a residual Z_3 subgroup in the lepton sector

  [Cao, Damanik, Ma, Wegman, Phys.Rev. D83, 093012 (2011)]

$$U_l = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 1 & 1 \\ 1 & \omega^2 & \omega \\ 1 & \omega & \omega^2 \end{pmatrix}, \quad \omega = e^{2i\pi/3}$$

$$(e, \mu, \tau) \sim (1, \omega^2, \omega) \qquad (\phi_a, \phi_b, \phi_c) \sim (1, \omega, \omega^2)$$

- Preserved Z_3 quantum numbers forbid certain interactions, among them the $l \to l'\gamma$ decays $\to$ FCNCs suppressed!
- Additional scalar doublets can decay into LFV final states

Why S_4?

Requirements:
Correct mixing, Triality, Z_3 symmetry, 3 Higgs doublets, ...

- S_4 naturally leads to TBM mixing, perturbations account for $\theta_{13} \approx 9^\circ$
- The global minimum $v(1,1,1)$ of the S_4 potential preserves a Z_3 subgroup

$$U_{\text{PMNS}} \approx \begin{pmatrix} \frac{2}{\sqrt{6}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

S_4 is (together with A_4 and $\Delta(27)$) the smallest group that fulfills our requirements

The Model (charged leptons)

Ingredients:

- $L = (L_e, L_\mu, L_\tau) \, : \, \mathbf{3}, \quad \tau_R \, : \, \mathbf{1}, \quad (e_R, \mu_R) \, : \, \mathbf{2}$
- Three $SU(2)$ doublets to induce LFV $\phi = (\phi_1, \phi_2, \phi_3) \, : \, \mathbf{3}$
- VEV alignment $\frac{v}{\sqrt{3}}(1,1,1)$ of the ϕ_i breaks S_4 down to Z_3

Result:

$$M_l = \frac{v_{\mathrm{SM}}}{\sqrt{6}} \begin{pmatrix} 1 & 1 & 1 \\ \omega^2 & \omega & 1 \\ \omega & \omega^2 & 1 \end{pmatrix} \mathrm{diag}(y_e, y_\mu, y_\tau)$$

$\Rightarrow$ Charged lepton and scalar mass bases coincide with Z_3 basis

$$(e,\ \mu,\ \tau) \sim (\omega,\ \omega^2,\ 1), \quad (\phi_a,\ \phi_b,\ \phi_c) \sim (\omega^2,\ \omega,\ 1)$$

Yukawa Couplings

In the mass bases (of scalars and leptons) the charged lepton Yukawa couplings are:

$$\phi_{(a)b}: \quad Y^0_{(a)b} = (i)\frac{1}{v\sqrt{2}} \begin{pmatrix} 0 & m_\mu\omega^2 & (-)m_\tau\omega \\ (-)m_e\omega & 0 & m_\tau\omega^2 \\ m_e\omega^2 & (-)m_\mu\omega & 0 \end{pmatrix}$$

$$\phi_c: \quad Y^0_c = \frac{1}{v} \begin{pmatrix} m_e & 0 & 0 \\ 0 & m_\mu & 0 \\ 0 & 0 & m_\tau \end{pmatrix}$$

$\Rightarrow$ ϕ^0_c couplings are SM Higgs-like $\Rightarrow \phi^0_c \equiv h_{\text{SM}}$

$\Rightarrow$ $\phi^0_{a,b}$ can decay into LFV final states, but $\phi^0_c \equiv h_{\text{SM}}$ cannot!

$\Rightarrow$ Since $\phi_{a,b}$ and ϕ_c are distinct Z_3 states, they do not mix

How do we explain $h \to \mu\tau$?

$\Rightarrow$ **Triality needs to be broken!**

Breaking Z_3

What about quarks and neutrinos?

- Z_3 actually broken by extra (not Z_3-symmetric) terms required to generate quark and neutrino mixings
- Global minimum not exactly $(1, 1, 1)$ but $(1 + 2\epsilon, 1 - \epsilon, 1 - \epsilon)$
- In scalar mass basis $\langle(\phi_a, \phi_b, \phi_c)\rangle = v(0, \sin\theta, \cos\theta)$
  [Heeck et al, Nucl. Phys. B896 (2015) 281-310]

$\Rightarrow$ θ accounts for deviation from triality

$\Rightarrow$ Deviation leads to new mixing of ϕ_b and ϕ_c

$\Rightarrow$ New mass eigenstates h (SM Higgs) and H

$\Rightarrow$ Small fraction of h decays into $\mu\tau$ depending on θ

Flavor violation

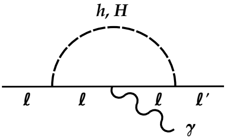
Problem: With flavor violation also come FCNCs . . .

- Dominant LFV Yukawa Higgs couplings ($y_{ll'} h l l'$)

$$y_{e\tau}, y_{\mu\tau} \propto \frac{m_\tau}{v_{\mathrm{SM}}} \sin(\theta), \qquad y_{e\mu} \propto \frac{m_\mu}{v_{\mathrm{SM}}} \cdot f(\theta)$$

- $y_{\mu\tau}$ decisive for $\mathrm{Br}(h \to \mu\tau)$ and $y_{e\mu}$ tightly constrained by $\mathrm{Br}(\mu \to e\gamma) < 5.7 \times 10^{-13}$

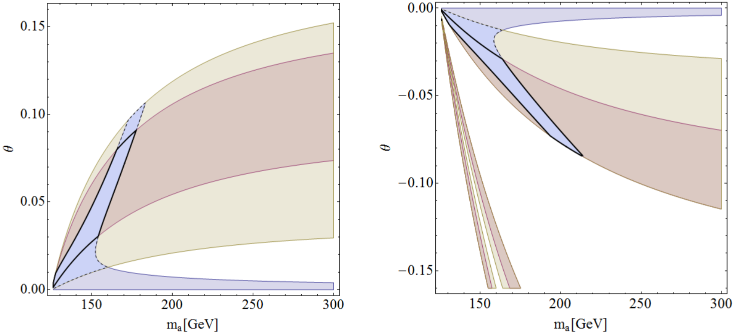
[MEG, Phys.Rev.Lett. 110 (2013)]



Objective: Find regions in the θ parameter space that explain $\mathrm{Br}(h \to \mu\tau)$ and at the same time comply with $\mathrm{Br}(\mu \to e\gamma)$ data!

Experimental constraints

1. $\text{Br}(h \to \mu\tau)_{\text{CMS}} \Leftrightarrow 0.0019 < \sqrt{|y_{\mu\tau}|^2 + |y_{\tau\mu}|^2} < 0.0032$ (@1σ)
   [I. Dorsner et al.,1502.07784]
2. $\text{Br}(\mu \to e\gamma) = \frac{\tau_\mu \alpha_{\text{EM}} m_\mu^5}{64\pi^4} \left(|c_L|^2 + |c_R|^2\right) < 5.7 \times 10^{-13}$ (MEG)



Predictions

@1σ and $m_\eta = 200\,\text{GeV}$

$$\begin{array}{ccccc} 0.002 & < & \theta & < & 0.090\,, \\ 126\ \text{GeV} & < & m_H & < & 204\,\text{GeV} \end{array}$$

- With these parameters we predict

$$\begin{array}{lll} \text{Br}(\tau \to \mu\gamma) & \in (0.3 - 1.3) \times 10^{-8}, & < 4.4 \times 10^{-8} \\ \text{Br}(\tau \to e\gamma) & \in (0.3 - 1.3) \times 10^{-8}, & < 1.2 \times 10^{-7} \\ \text{Br}(\tau \to 3\mu) & \in (1.9 - 8.1) \times 10^{-10}, & < 2.1 \times 10^{-8} \\ \text{Br}(\tau \to 3e) & \in (0.9 - 4.1) \times 10^{-9}, & < 2.7 \times 10^{-8} \\ \text{Br}(h \to e\tau) & \in (0.4 - 1.2) \times 10^{-2} & \\ \text{Br}(h \to e\mu) & \in (1.5 - 4.2) \times 10^{-5} & \end{array}$$

$\Rightarrow$ Large LFV also expected in $h \to e\tau$ channel

Conclusion

- We have investigated a flavor model based on the discrete S_4 symmetry that can give rise to LFV Higgs decays
- Lepton Flavor Triality is employed to suppress the constrained radiative decays $l \to l'\gamma$
- A small breaking of triality can explain the $2.4\,\sigma$ anomaly in $h \to \mu\tau$ reported by CMS if the extra neutral scalars are light
- Large branching fractions are also expected for $h \to e\mu$ and $h \to e\tau$ in this framework

Thank you!

Backup

S_4 Symmetry

- Irreducible presentations of S_4

$$\mathbf{1}, \mathbf{1}', \mathbf{2}, \mathbf{3}, \mathbf{3}'$$

- The S_4 product rules

$$\mathbf{3}' \otimes \mathbf{3}' = \mathbf{1} \oplus \mathbf{2} \oplus \mathbf{3} \oplus \mathbf{3}', \qquad \mathbf{3} \otimes \mathbf{3}' = \mathbf{1}' \oplus \mathbf{2} \oplus \mathbf{3} \oplus \mathbf{3}',$$
$$\mathbf{2} \otimes \mathbf{2} = \mathbf{1} \oplus \mathbf{1}' \oplus \mathbf{2}, \qquad \mathbf{2} \otimes \mathbf{3} = \mathbf{3} \oplus \mathbf{3}', \qquad \mathbf{2} \otimes \mathbf{3}' = \mathbf{3}' \oplus \mathbf{3},$$
$$\mathbf{3} \otimes \mathbf{1}' = \mathbf{3}', \qquad \mathbf{3}' \otimes \mathbf{1}' = \mathbf{3}, \qquad \mathbf{2} \otimes \mathbf{1}' = \mathbf{2}.$$

Scalar Sector (Triality limit)

$$\phi_j = \left[\phi_j^+, \quad \frac{1}{\sqrt{2}}\left(\frac{v}{\sqrt{3}} + \phi_{jR}^0 + i\phi_{jI}^0\right)\right]^T$$

- 3 CP even neutral scalars ϕ_{jR}^0 ($j = 1, 2, 3$), 3 CP odd neutral scalars ϕ_{jI}^0, 3 complex charged scalars ϕ_j^+
- 3 degrees of freedom eaten by the SM gauge bosons

$\Rightarrow$ In total 9 massive (low-energy) scalars $\phi_{a,b,c}$

with $\langle\phi_a\rangle = \langle\phi_b\rangle = 0$ and $\langle\phi_c\rangle = v_{SM}$

Scalar Sector (Triality limit)

$$V(\phi) = -\mu_1^2 \sum_{i=1}^{3} \phi_i^\dagger \phi_i + \alpha(\sum_{i=1}^{3} \phi_i^\dagger \phi_i)^2 + \sum_{i,j=1,i\neq j}^{3} (\beta(\phi_i^\dagger \phi_i)(\phi_j^\dagger \phi_j) + \gamma|\phi_i^\dagger \phi_j|^2 + \delta(\phi_i^\dagger \phi_j)^2)$$

$$m^2_{\phi^0_{(a,b)R}} = -\frac{v^2}{3}\kappa, \qquad m^2_{\phi^0_{cR}} = \frac{v^2}{3}(3\alpha + 2\kappa),$$
$$m^2_{\phi^\pm_{a,b}} = -v^2(\kappa - \beta), \qquad m^2_{\phi^0_{cI}} = 0,$$
$$m^2_{\phi^0_{(a,b)I}} = -v^2\delta, \qquad m^2_{\phi^\pm_c} = 0.$$

with $\kappa := \beta + \gamma + \delta$.

Scalar Sector

- Mass eigenstates $\phi_{a,b,c}$

$$\begin{pmatrix} \phi_a \\ \phi_b \\ \phi_c \end{pmatrix} = \begin{pmatrix} 0 & -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{\sqrt{2}}{\sqrt{3}} & -\frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{6}} \\ \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \end{pmatrix} \cdot \begin{pmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \end{pmatrix}$$

- Comparing with the Z_3 eigenstates $\phi_{x,y,z} \sim 1, \omega, \omega^2$

$$\begin{pmatrix} \phi_x \\ \phi_y \\ \phi_z \end{pmatrix} = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 1 & 1 \\ 1 & \omega^2 & \omega \\ 1 & \omega & \omega^2 \end{pmatrix} \begin{pmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \end{pmatrix}$$

we find that Z_3 remains unbroken

$$\phi_c \equiv \phi_x, \quad \phi_b \equiv \frac{1}{\sqrt{2}}(\phi_y + \phi_z), \quad \phi_a \equiv \frac{1}{\sqrt{2}}(\phi_y - \phi_z)$$

$$\text{with} \quad \langle \phi_a \rangle = \langle \phi_b \rangle = 0 \quad \text{and} \quad \langle \phi_c \rangle = v_{\text{SM}}.$$

Charged leptons

- The particle assignments in the notation $(S_4, SU(2), Z_{12})$ are

$$L = (L_e, L_\mu, L_\tau) \ : \ (3', 2, 1), \quad \tau_R \ : \ (1, 1, -i), \quad (e_R, \mu_R) \ : \ (2, 1, e^{\frac{7i\pi}{6}}),$$
$$\phi = (\phi_1, \phi_2, \phi_3) \ : \ (3', 2, 1), \quad \eta_1 \ : \ (1, 1, e^{\frac{i\pi}{6}}), \quad \eta_2 \ : \ (1', 1, e^{\frac{i\pi}{6}}).$$

- Three Higgs $SU(2)$ doublets ϕ_i induce LFV
- Z_{12} and $\eta_{1,2}$ necessary for a realistic lepton mass hierarchy

Charged leptons

Charged lepton Lagrangian

$$\mathcal{L} \supset y_1 [L\phi]_1 \, \tau_R \frac{\eta_1^3 + \varepsilon_0 \eta_1 \eta_2^2}{\Lambda^3} + y_2 [L\phi]_2 \begin{pmatrix} e_R \\ \mu_R \end{pmatrix} \frac{\eta_1^5 + \varepsilon_1 \eta_1^3 \eta_2^2 + \varepsilon_2 \eta_1 \eta_2^4}{\Lambda^5} + y_3 [L\phi]_2 \begin{pmatrix} e_R \\ \mu_R \end{pmatrix} \frac{\eta_2^5 + \varepsilon_3 \eta_2^3 \eta_1^2 + \varepsilon_4 \eta_2 \eta_1^4}{\Lambda^5}$$

leads to the following mass matrix for charged leptons:

$$M_l = \frac{1}{\sqrt{2}} \begin{pmatrix} v_1 (\widetilde{y}_2 - \widetilde{y}_3) \lambda^5 & v_1 (\widetilde{y}_2 + \widetilde{y}_3) \lambda^5 & v_1 \widetilde{y}_1 \lambda^3 \\ v_2 \omega^2 (\widetilde{y}_2 - \widetilde{y}_3) \lambda^5 & v_2 \omega (\widetilde{y}_2 + \widetilde{y}_3) \lambda^5 & v_2 \widetilde{y}_1 \lambda^3 \\ v_3 \omega (\widetilde{y}_2 - \widetilde{y}_3) \lambda^5 & v_3 \omega^2 (\widetilde{y}_2 + \widetilde{y}_3) \lambda^5 & v_3 \widetilde{y}_1 \lambda^3 \end{pmatrix} = v \frac{1}{\sqrt{6}} \begin{pmatrix} 1 & 1 & 1 \\ \omega^2 & \omega & 1 \\ \omega & \omega^2 & 1 \end{pmatrix} \mathrm{diag}((\widetilde{y}_2 - \widetilde{y}_3) \lambda^5, (\widetilde{y}_2 + \widetilde{y}_3) \lambda^5, \widetilde{y}_1 \lambda^3)$$

with $v_1 = v_2 = v_3 = \frac{v}{\sqrt{3}}$, $\omega = e^{2i\pi/3}$

$$\widetilde{y}_1 = (1 + \varepsilon_0) \, y_1, \quad \widetilde{y}_2 = (1 + \varepsilon_1 + \varepsilon_2) \, y_2, \quad \widetilde{y}_3 = (1 + \varepsilon_3 + \varepsilon_4) \, y_3$$

Neutrino sector

The $S_4 \otimes Z_2 \otimes Z_2' \otimes Z_{12}$ assignments are

$$N_{1R} \; : \; (1,-1,1,1)\,, \quad N_{2R} \; : \; (1,-1,-1,1),$$
$$\chi : \; (3',-1,1,1)\,, \quad \xi \; : \; (3,-1,1,1)\,, \quad \sigma : \; (3',-1,-1,1)\,, \quad \zeta : \; (3,-1,-1,1).$$

$$\begin{aligned}\mathcal{L} \quad & \supset y_1^{(\nu)}\,[L\phi]_{3'}\,N_{1R}\,\tfrac{\chi}{\Lambda} + y_2^{(\nu)}\,[L\phi]_3\,N_{1R}\,\tfrac{\xi}{\Lambda} + y_3^{(\nu)}\,[L\phi]_{3'}\,N_{2R}\,\tfrac{\sigma}{\Lambda} \\ & + y_4^{(\nu)}\,[L\phi]_3\,N_{2R}\,\tfrac{\zeta}{\Lambda} + \tfrac{y_5^{(\nu)}}{\Lambda}L\,[\phi\chi]_{3'}\,N_{1R} + \tfrac{y_6^{(\nu)}}{\Lambda}L\,[\phi\xi]_{3'}\,N_{1R} \\ & + \tfrac{y_7^{(\nu)}}{\Lambda}L\,[\phi\sigma]_{3'}\,N_{2R} + \tfrac{y_8^{(\nu)}}{\Lambda}L\,[\phi\zeta]_{3'}\,N_{2R} + M_1\overline{N}_{1R}N_{1R}^c + M_2\overline{N}_{2R}N_{2R}^c.\end{aligned}$$

Neutrino sector

Mass matrices

$$M_\nu^D = \frac{v}{\sqrt{3}} = \begin{pmatrix} 0 & a e^{i\tau} \\ b & 0 \\ 0 & a e^{-i\tau} \end{pmatrix}, \quad M_R = \begin{pmatrix} M_1 & 0 \\ 0 & M_2 \end{pmatrix}$$

$$M_L^{(\nu)} = M_\nu^D M_R^{-1} \left(M_\nu^D\right)^T = \begin{pmatrix} a^2 e^{2i\tau} & 0 & a^2 \\ 0 & b^2 \frac{M_2}{M_1} & 0 \\ a^2 & 0 & a^2 e^{-2i\tau} \end{pmatrix} \frac{v^2}{3M_2}$$

$$= \begin{pmatrix} A e^{2i\tau} & 0 & A \\ 0 & B & 0 \\ A & 0 & A e^{-2i\tau} \end{pmatrix}$$

Mixing matrix:

$$V_\nu = \begin{pmatrix} \cos\psi & 0 & \sin\psi e^{-i\phi} \\ 0 & 1 & 0 \\ -\sin\psi e^{i\phi} & 0 & \cos\psi \end{pmatrix} \quad \text{with} \quad \psi = \pm\frac{\pi}{4}$$

Neutrino sector

$$J = Im\left(U_{e1}U_{\mu2}U^*_{e2}U^*_{\mu1}\right) = \frac{1}{6\sqrt{3}}\cos 2\psi, \quad \sin\delta = \frac{8J}{\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}}.$$

$$\begin{aligned}
\text{NH}: \quad & m_{\nu_1} = 0, \quad m_{\nu_2} = B = \sqrt{\Delta m^2_{21}} \approx 9\,\text{meV}, \\
& m_{\nu_3} = 2\,|A| = \sqrt{\Delta m^2_{31}} \approx 50\,\text{meV} \\
\text{IH}: \quad & m_{\nu_2} = B = \sqrt{\Delta m^2_{21} + \Delta m^2_{13}} \approx 50\,\text{meV}, \\
& m_{\nu_1} = 2\,|A| = \sqrt{\Delta m^2_{13}} \approx 49\,\text{meV}, \quad m_{\nu_3} = 0.
\end{aligned}$$

By varying ϕ we obtain the following best-fit result:

NH : $\phi = -0.453\pi, \quad \sin^2\theta_{12} \approx 0.34, \quad \sin^2\theta_{23} \approx 0.61, \quad \sin^2\theta_{13} \approx 0.0232$

IH : $\phi = 0.546\,\pi, \quad \sin^2\theta_{12} \approx 0.34, \quad \sin^2\theta_{23} \approx 0.61, \quad \sin^2\theta_{13} \approx 0.024.$

Quark sector

The $S_4 \otimes Z_2'' \otimes Z_6 \otimes Z_{12}$ assignments are:

$$\begin{array}{rcl} t_R & : & (1,1,1,1), \quad c_R:\ (1,1,1,1), \quad u_R:\ (1,1,1,-1), \\ b_R & : & (1,1,-1,1), \quad s_R:\ (1,1,-1,1), \quad d_R:\ (1,1,-1,-1), \\ Q & : & (3',-1,1,1), \quad \rho:\ (3',-1,1,1), \quad \varphi:\ (3,-1,1,1), \\ \Omega_1 & : & (1,1,1,i), \quad \Omega_2:\ (1,-1,1,\omega^{\frac{1}{2}}), \quad \Omega_3:\ (1,1,\omega^{\frac{1}{2}},1) \end{array}$$

with the VEV patterns

$$\langle\rho\rangle = v_\rho\,(i,0,0)\,, \quad \langle\varphi\rangle = v_\varphi\,(1,0,0)\ ,$$
$$\langle\Omega_1\rangle = v_{\Omega_1}, \quad \langle\Omega_2\rangle = v_{\Omega_2} e^{i\theta_\Omega}, \quad \langle\Omega_3\rangle = v_{\Omega_3}.$$

lead to the quark mass matrices

$$M_q = \begin{pmatrix} C_q e^{i\theta_{1q}} & 0 & 0 \\ D_q e^{-i\theta_{2q}} & E_q e^{-i\theta_{3q}} & F_q e^{-i\theta_{4q}} \\ D_q e^{i\theta_{2q}} & E_q e^{i\theta_{3q}} & F_q e^{i\theta_{4q}} \end{pmatrix}, \qquad q = U, D.$$

which can be diagonalized in closed form

Breaking Z_3

- To generate the large leptonic mixing angles the S_4 symmetry has to be broken in a different direction in the neutrino sector
- Accommodating quarks and neutrinos requires extra scalars ($\mathbf{3} \in S_4$ and $\mathbf{1} \in SU(2)$) with Z_3 breaking VEV alignments
- Thanks to flavor symmetries the scalars communicate with each other only through portal-like interactions

Example: $\rho : \mathbf{3}$ with $\langle \rho \rangle = v_\rho(1, 0, 0)$

$$V_{\text{int}} \supset \sum_{i=\mathbf{1},\mathbf{2},\mathbf{3},\mathbf{3}'} \lambda_{\rho_i} (\phi^\dagger \phi)_i (\rho^\dagger \rho)_i$$

$$(\phi^\dagger \phi)_2 (\rho^\dagger \rho)_2 = \sum_{j,k=1, j\neq k}^{3} 2|\phi_j|^2 |\rho_j|^2 - |\phi_j|^2 |\rho_k|^2$$

$$\sim \quad 2 v_\rho^2 \lambda_\rho |\phi_1|^2 - v_\rho^2 \lambda_\rho |\phi_2|^2 - v_\rho^2 \lambda_\rho |\phi_3|^2$$

Breaking Z_3

- We can interpret this breaking as a perturbation of the ϕ VEVs [Heeck et al, Nucl. Phys. B896 (2015) 281-310]

$$\langle\phi\rangle = \langle(\phi_1, \phi_2, \phi_3)\rangle = v(1+2\epsilon, 1-\epsilon, 1-\epsilon)$$

$$\begin{pmatrix} \langle\phi_a\rangle \\ \langle\phi_b\rangle \\ \langle\phi_c\rangle \end{pmatrix} = \begin{pmatrix} 0 & -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{\sqrt{2}}{\sqrt{3}} & -\frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{6}} \\ \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \end{pmatrix} \begin{pmatrix} \frac{v}{\sqrt{3}}(1+2\epsilon) \\ \frac{v}{\sqrt{3}}(1-\epsilon) \\ \frac{v}{\sqrt{3}}(1-\epsilon) \end{pmatrix} = v \begin{pmatrix} 0 \\ \sqrt{2}\epsilon \\ 1 \end{pmatrix}$$

$\Rightarrow$ Choose parametrization

$$\langle(\phi_a, \phi_b, \phi_c)\rangle = v(0, \sin\theta, \cos\theta)$$

- θ accounts for the deviation from LFT (Triality limit $\theta \to 0$)

Breaking Z_3

- Z_3 breaking induces mixing of the scalars ϕ_b and ϕ_c ($\cos\theta := c_\theta,\ \sin\theta := s_\theta$)

$$\begin{pmatrix} H^\pm \\ \pi^\pm \end{pmatrix} = \begin{pmatrix} c_\theta & s_\theta \\ -s_\theta & c_\theta \end{pmatrix} \begin{pmatrix} \phi_b^\pm \\ \phi_c^\pm \end{pmatrix}$$

$$\begin{pmatrix} \eta_I^0 \\ \pi_I^0 \end{pmatrix} = \begin{pmatrix} c_\theta & s_\theta \\ -s_\theta & c_\theta \end{pmatrix} \begin{pmatrix} \phi_{b,I}^0 \\ \phi_{c,I}^0 \end{pmatrix}$$

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} c_\vartheta & s_\vartheta \\ -s_\vartheta & c_\vartheta \end{pmatrix} \begin{pmatrix} \phi_{b,R}^0 \\ \phi_{c,R}^0 \end{pmatrix}$$

- Result: FCNCs, but also LFV from Higgs decays that can be controlled with the θ parameter

- Triality limit $\theta \to 0$ (also $\vartheta \to 0$) yields original masses

$$m_h^2 \to m_{\phi_{c,R}^0}^2, \qquad m_H^2 \to m_{\phi_{b,R}^0}^2 = m_{\phi_{a,R}^0}^2$$

$\Rightarrow$ Consider h the SM like Higgs with $m_h \approx 125\,\text{GeV}$

Corrections to charged lepton mixing

Because of the perturbed alignment $v(0, s_\theta, c_\theta)$ the charged leptons mass matrix is no longer diagonal in the Z_3 basis of the charged leptons

$$M_l = \frac{v}{\sqrt{2}} \underbrace{\frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 1 & 1 \\ \omega^2 & \omega & 1 \\ \omega & \omega^2 & 1 \end{pmatrix}}_{U_\omega} \begin{pmatrix} c_\theta(\widetilde{y}_2 - \widetilde{y}_3)\lambda^5 & \frac{s_\theta(\widetilde{y}_2+\widetilde{y}_3)\lambda^5}{\sqrt{2}} & \frac{s_\theta \widetilde{y}_1 \lambda^3}{\sqrt{2}} \\ \frac{s_\theta(\widetilde{y}_2-\widetilde{y}_3)\lambda^5}{\sqrt{2}} & c_\theta(\widetilde{y}_2 + \widetilde{y}_3)\lambda^5 & \frac{s_\theta \widetilde{y}_1 \lambda^3}{\sqrt{2}} \\ \frac{s_\theta(\widetilde{y}_2-\widetilde{y}_3)\lambda^5}{\sqrt{2}} & \frac{s_\theta(\widetilde{y}_2+\widetilde{y}_3)\lambda^5}{\sqrt{2}} & c_\theta \widetilde{y}_1 \lambda^3 \end{pmatrix}.$$

The correction to V_L is approximately

$$V_L = U_\omega W_L \quad \text{with} \quad W_L \simeq \begin{pmatrix} 1 & \frac{\theta}{\sqrt{2}} - \frac{3\theta^2}{4} & \frac{\theta}{\sqrt{2}} \\ -\frac{\theta}{\sqrt{2}} + \frac{3\theta^2}{4} & 1 & \frac{\theta}{\sqrt{2}} \\ -\frac{\theta}{\sqrt{2}} & -\frac{\theta}{\sqrt{2}} & 1 \end{pmatrix}.$$

The deviations are the largest in θ_{12} but are within 3σ for $\theta < 0.08$. The breaking also affects the Jarlskog invariant

$$J \approx \frac{\cos(2\psi)}{6\sqrt{3}} + \frac{1}{12}\theta\left(\sqrt{6}\sin(2\psi)\cos(\phi) - \sqrt{2}\sin(2\psi)\sin(\phi)\right) + \mathcal{O}(\theta^2)$$

For $\theta \approx 0.07$ we can obtain CP violation of up to $\delta_{CP} \approx 0.3$

Z3 Breaking details

In leading order ($m_e \ll m_\mu \ll m_\tau$) the dominant flavor violating couplings are

$$y_{e\tau} \simeq -\frac{m_\tau}{v}(c_{\alpha_L} - s_{\alpha_L})s_{\vartheta+\theta},$$
$$y_{\mu\tau} \simeq -\frac{m_\tau}{v}(c_{\alpha_L} + s_{\alpha_L})s_{\vartheta+\theta},$$
$$y_{e\mu} \simeq \frac{m_\mu}{4v}\left(2c_\vartheta\left(c_{\alpha_L}\left(c_\theta - 2{s_\theta}^2 - 1\right) - s_{\alpha_L}\left(c_\theta - 2{s_\theta}^2 + 1\right)\right)\right.$$
$$- \; s_\vartheta\left(c_{\alpha_L}\left(c_\theta\left(4s_\theta + \sqrt{2}\right) - 2s_\theta + \sqrt{2}\right)\right.$$
$$\left.\left. + \; s_{\alpha_L}\left(-c_\theta\left(4s_\theta + \sqrt{2}\right) + 2s_\theta + \sqrt{2}\right)\right).$$

$$\tan 2\vartheta = -\frac{4s_\theta(\sqrt{2}\kappa s_\theta - 2c_\theta(3\alpha + \kappa))}{6(-1 + 2s_\theta^2)\alpha + (-6 - 2\sqrt{2}c_\theta s_\theta + 11s_\theta^2)\kappa}$$

$$\tan 2\alpha_L = \frac{s_\theta\left(4\sqrt{2}c_{3\theta} + 12\sqrt{2}c_\theta - 7s_{3\theta} - 3s_\theta\right)}{10c_{3\theta} + 6c_\theta + 8\sqrt{2}{s_\theta}^3}.$$

Mass spectrum after Z_3 breaking

$$m^2_{\phi^0_{a,I}} = m^2_{\eta^0_I} = -v^2\delta, \qquad m^2_{\pi^0_I} = 0,$$

$$m^2_{\phi^\pm_a} = m^2_{H^\pm} = -v^2(\kappa - \beta), \qquad m^2_{\pi^\pm} = 0,$$

$$m^2_{\phi^0_{a,R}} = \frac{1}{6}v^2(-2 + 2\sqrt{2}c_\theta s_\theta + s^2_\theta)\kappa,$$

$$m^2_h = \frac{1}{2}(v^2\alpha - m^2_{\phi^0_{a,R}}) + \Delta(\theta), \qquad m^2_H = \frac{1}{2}(v^2\alpha - m^2_{\phi^0_{a,R}}) - \Delta(\theta)$$

Observations:

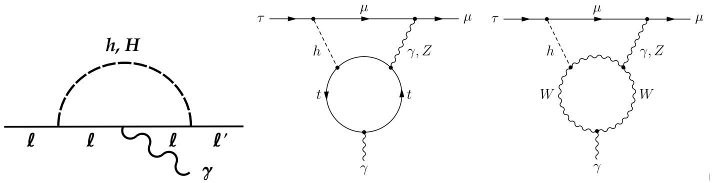
- Only the CP even scalar masses depend on θ
- Nonzero θ causes a mass splitting between h and H
- Triality limit $\theta \to 0$ yields original masses

$$m^2_h \to m^2_{\phi^0_{c,R}}, \qquad m^2_H \to m^2_{\phi^0_{b,R}} = m^2_{\phi^0_{a,R}}$$

$\Rightarrow$ Consider h the SM like Higgs with $m_h \approx 125\,\text{GeV}$

Experimental constraints

Strongest constraints from radiative decays $l \to l'\gamma$

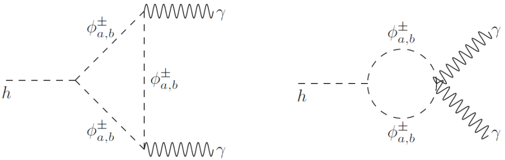


[R. Harnik, J. Kopp, J. Zupan.,10.1007/JHEP03(2013)026]

Objective:

Find regions in the θ parameter space that explain Br($h \to \mu\tau$) and at the same time comply with Br($\mu \to e\gamma$) data!

$h \to \gamma\gamma$



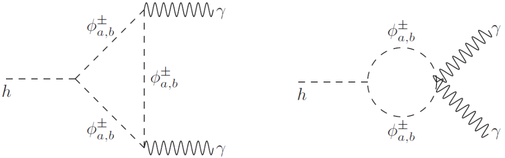
$$\Gamma\left(h \to \gamma\gamma\right) = \frac{\alpha_{em}^2 m_h^3}{256\pi^3 v^2}\left|\sum_f a_{hff} N_c Q_f^2 F_{1/2}\left(\beta_f\right) + F_1\left(\beta_W\right) + \sum_{s=a,b}\frac{\lambda_{h\phi_s^\pm\phi_s^\mp} v}{2m^2_{\phi_s^\pm}} F_0\left(\beta_{\phi_s^\pm}\right)\right|^2$$

$$\text{with} \quad \lambda_{h\phi_s^\pm\phi_s^\mp} = \frac{2}{v}\left(m_h^2 - m^2_{\phi_s^\pm}\right)$$

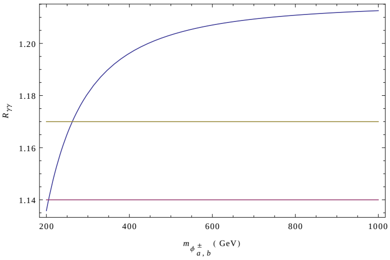
$$R_{\gamma\gamma} = \frac{\sigma\left(pp \to h\right)\Gamma\left(h \to \gamma\gamma\right)}{\sigma\left(pp \to h\right)_{SM}\Gamma\left(h \to \gamma\gamma\right)_{SM}} \simeq a_{htt}^2 \frac{\Gamma\left(h \to \gamma\gamma\right)}{\Gamma\left(h \to \gamma\gamma\right)_{SM}},$$

$$R_{\gamma\gamma}^{\text{CMS}} = 1.14^{+0.26}_{-0.23} \qquad \text{and} \qquad R_{\gamma\gamma}^{\text{ATLAS}} = 1.17 \pm 0.27,$$

$h \to \gamma\gamma$



$$R_{\gamma\gamma} = \frac{\sigma(pp \to h)\,\Gamma(h \to \gamma\gamma)}{\sigma(pp \to h)_{SM}\,\Gamma(h \to \gamma\gamma)_{SM}} \simeq a^2_{htt} \frac{\Gamma(h \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)_{SM}},$$



$R^{\text{CMS}}_{\gamma\gamma} = 1.14^{+0.26}_{-0.23}$

$R^{\text{ATLAS}}_{\gamma\gamma} = 1.17 \pm 0.27$

$h \to \gamma\gamma$ measurement favors charged Higgses between $200 - 205$ GeV