MonoHiggsology

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Contents

Standard Model Deficiencies

particle	$SU(3)$	$SU(2)$	$U(1)$
$(u, d)_L$	3	2	1/6
u_R, d_R	3	1	$2/3, -1/3$
$(\nu, e)_L$	1	2	$-1/2$
e_R	1	1	-1
(ϕ^+, ϕ^0)	1	2	1/2

Should there be particles beyond this list?

- Yes for neutrino mass.
- Yes for dark matter.
- Yes for matter-antimatter asymmetry.
- Yes for strong CP conservation.
- Yes for flavor symmetry.

All may be accomplished in a renormalizable field theory with only additions in the dark sector, and just the one SM Higgs doublet.

With apology to Leon Lederman:

There is only one God.

There is only one God particle.

There is only one goddamn particle.

There is only one Higgs boson.

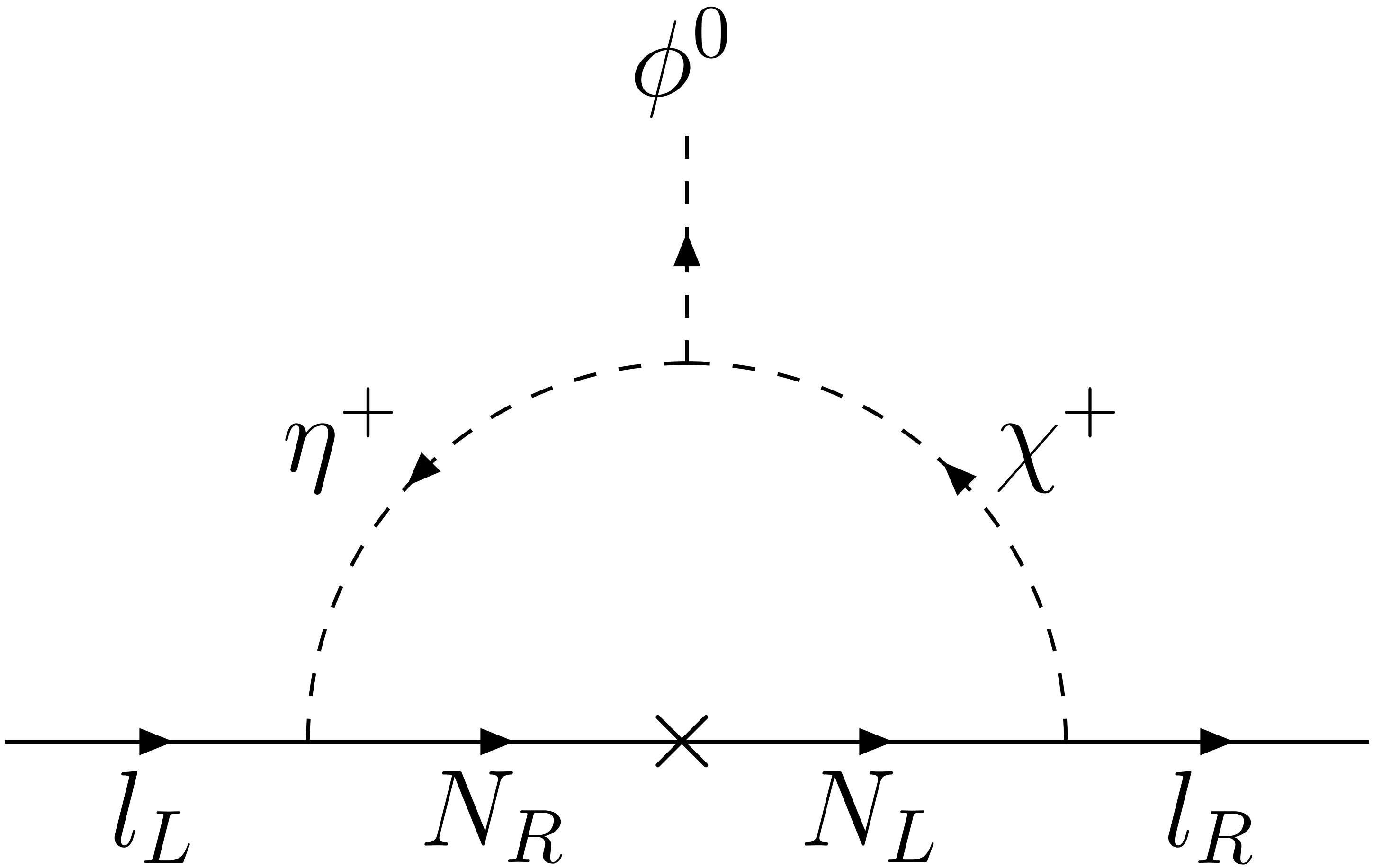
E. Ma, Phys. Rev. Lett. **112**, 091801 (2014).

With apology to J. R. R. Tokien:

Three families of quarks and leptons,

one Higgs to rule them all,

and in the darkness bind them.



ϕ^0
η^+
χ^+
l_L
N_R
N_L
l_R

Scotogenic Froggatt-Nielsen

Instead of using neutral fermion singlets N as the universal scotogenic links, I now advocate scalars η and as always, only consider renormalizable theories.

Application to Froggatt-Nielsen: Consider

$$(c,s)_L, c_R \sim 0, \quad (u,d)_L \sim 1, \quad u_R \sim -1, \quad \eta \sim 1.$$

Allowed Yukawa couplings are then

$$\bar{c}_L c_R \bar{\phi}^0, \bar{c}_L u_R \bar{\phi}^0 (\eta/\Lambda), \bar{u}_L c_R \bar{\phi}^0 (\eta/\Lambda), \bar{u}_L u_R \bar{\phi}^0 (\eta/\Lambda)^2.$$

The scalar flavon η must then have a VEV and a possible renormalizable version of this mechanism is achieved with two heavy quarks x, y of the same charge as u, c. Let their FN charges be $x_{L,R} \sim 1$, $y_{L,R} \sim 0$, then

$$\mathcal{M}_{ucxy} = \begin{pmatrix} 0 & 0 & m_{ux} & 0 \\ 0 & m_c & 0 & m_{cy} \\ 0 & \epsilon_{xc} & M_x & \epsilon_{xy} \\ \epsilon_{yu} & 0 & \epsilon_{yx} & M_y \end{pmatrix},$$

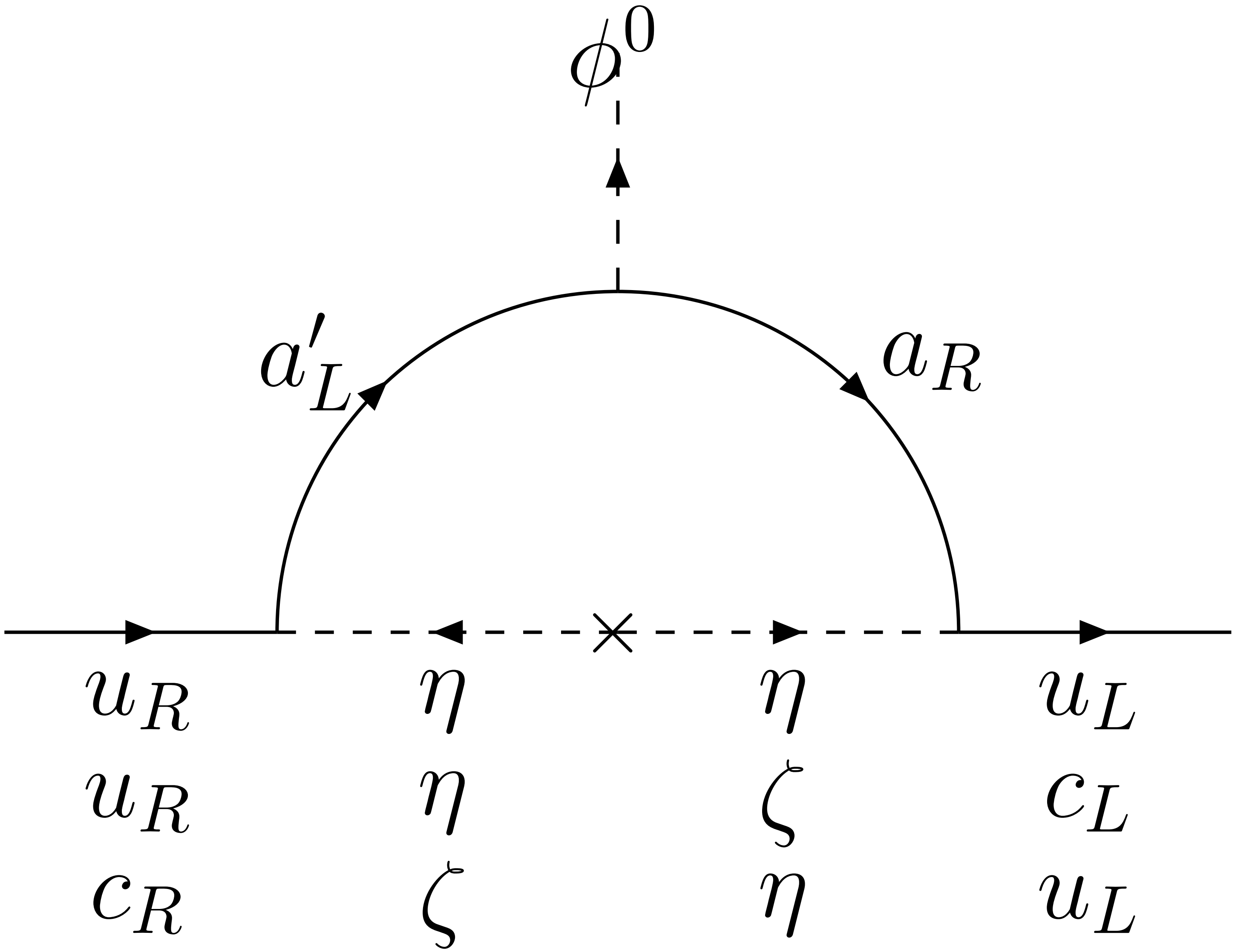
resulting in $m_{uc} = -m_{ux}\epsilon_{xc}/M_x$, $m_{cu} = -m_{cy}\epsilon_{yu}/M_y$, $m_{uu} = m_{ux}\epsilon_{xy}\epsilon_{yu}/M_xM_y - m_{uc}m_{cu}/m_c$.

Since the mass terms in $\mathcal{M}_{ucxy}$ come from three different sources, there will be flavor changing neutral interactions, which must be suppressed.

However, it is possible to have all mass terms coming from the one SM Higgs doublet by putting the FN flavons in the dark sector as follows.

$$(a, v)_{L,R}, a'_{L,R}, v'_{L,R} \sim 0, \quad \eta \sim 1, \quad \zeta \sim 0.$$

The dark sector consists of the heavy a, v and a', v' quarks of the same charges as u, d and c, s, as well as η and ζ with the distinction now of having no VEV.



ϕ^0
a'_L
a_R
u_R
u_R
c_R
η
η
ζ
η
ζ
η
u_L
c_L
u_L

Scotogenic A_4 Model of Leptons

The fundamental shift of philosophy being advocated is the replacement of the spontaneous symmetry breaking of any imposed flavor symmetry to that of soft breaking in the dark sector.

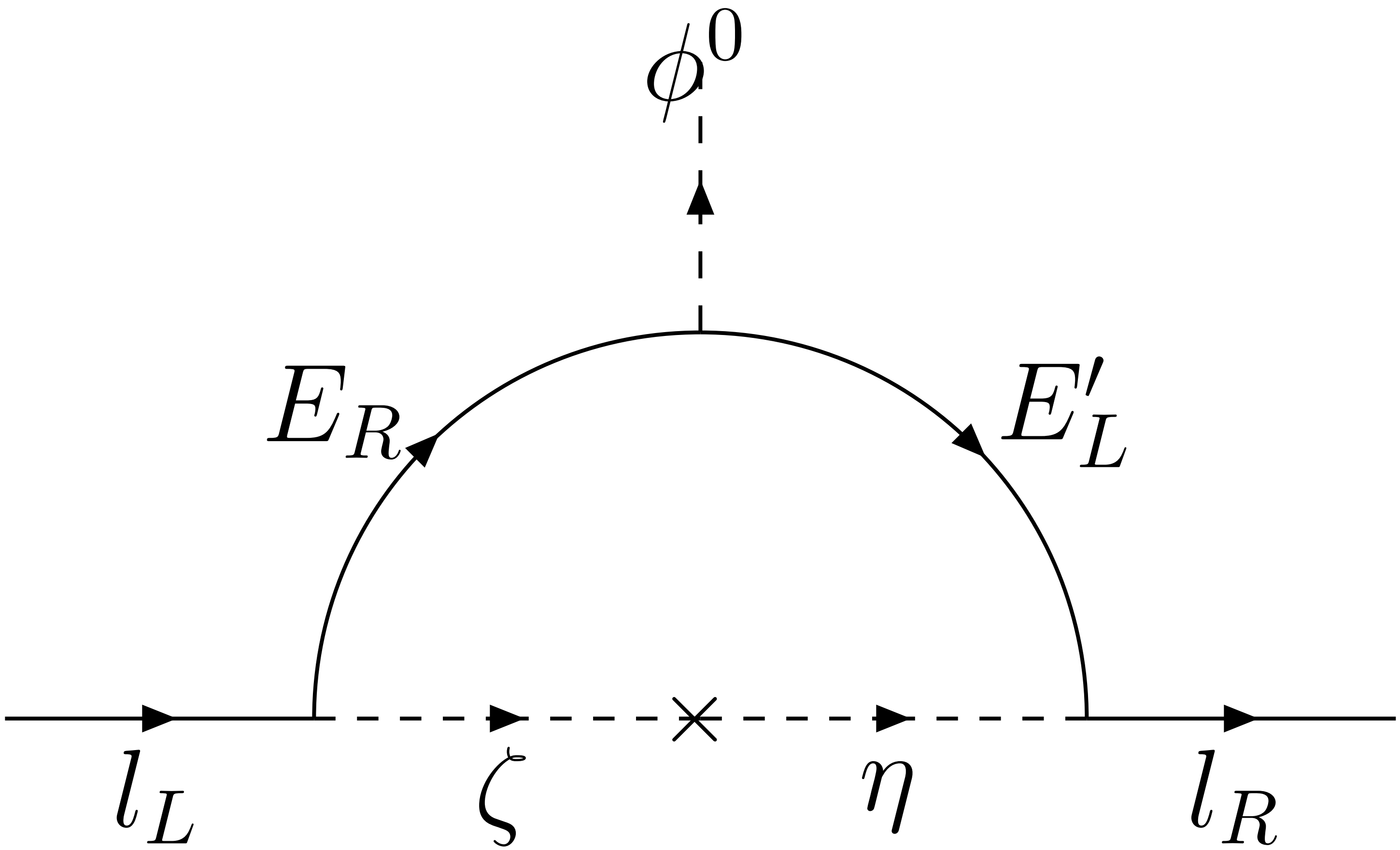
Consider now the original A_4 model of leptons [Ma/Rajasekaran(2001)].

$$L_{iL} = (\nu_i, l_i)_L \sim \underline{3}, \quad l_{iR} \sim \underline{1}, \underline{1}', \underline{1}'', \quad \Phi_i = (\phi_i^+, \phi_i^0) \sim \underline{3}.$$

As A_4 breaks to Z_3 through $\langle \phi_i^0 \rangle = v/\sqrt{3}$, independent m_e, m_μ, m_τ are obtained, and the unitary transformation linking them to the neutrino mass matrix is

$$U_\omega = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 1 & 1 \\ 1 & \omega & \omega^2 \\ 1 & \omega^2 & \omega \end{pmatrix},$$

where $\omega = \exp 2\pi i/3 = -1/2 + i\sqrt{3}/2$. The residual Z_3 forbids $\mu \to e\gamma$. The scotogenic realization needs just the SM Higgs doublet, with $(N, E)_{L,R} \sim \underline{1}$, $E'_{L,R} \sim \underline{1}$, $\eta_{1,2,3} \sim \underline{1}, \underline{1}', \underline{1}''$, $\zeta_{1,2,3} \sim \underline{3}$ in the dark sector.

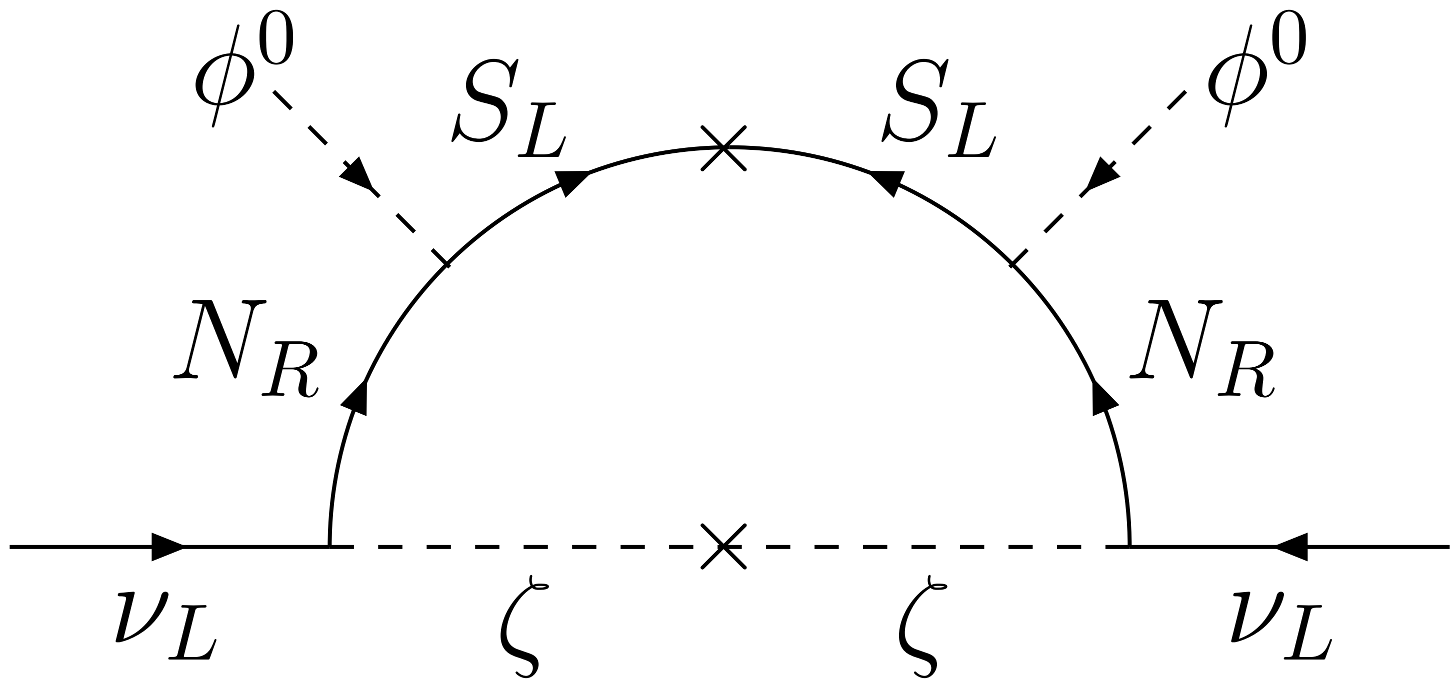

ϕ^0
E_R
E'_L
l_L
ζ
η
l_R

The soft breaking connecting ζ to η is assumed to be of the form U_ω times a diagonal matrix, thereby ensuring the residual Z_3 symmetry.

In the neutrino sector, a light dark fermion singlet S_L is added. The 3×3 mass matrix spanning$(\bar{N}_R, N_L, S_L)$ is

$$\mathcal{M}_N = \begin{pmatrix} 0 & m_N & m_1 \\ m_N & 0 & m_2 \\ m_1 & m_2 & m_S \end{pmatrix},$$

where m_N is a large invariant mass, m_1 comes from $\langle \bar{\phi}^0 \rangle$, m_2 comes from $\langle \phi^0 \rangle$,and m_S is assumed small.



ϕ^0
S_L
S_L
ϕ^0
N_R
N_R
ν_L
ζ
ζ
ν_L

2000: Fukuura/Miura/Takasugi/Yoshimura noted that if $U_{l\nu} = U_\omega{}^\dagger \mathcal{O}$, where $\mathcal{O}$ is orthogonal, then $U^*_{2i} = U_{3i}$ for $i = 1, 2, 3$. Compared this to the PDG form of $U_{l\nu}$, i.e.

$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix},$$

it is obvious that after rotating the phases of the third column and the second and third rows, the two matrices are identical if and only if $s_{23} = c_{23}$ and $\cos\delta = 0$, i.e. $\theta_{23} = \pi/4$ and $\delta_{CP} = \pm\pi/2$, i.e. cobimaximal mixing.

This is automatic if $\zeta_{1,2,3}$ are real.

The coupling of SM Higgs boson to SS is

$$f_h = \frac{m_N}{v\sqrt{2}} \left(\frac{m_1}{m_N}\right) \left(\frac{m_2}{m_N}\right),$$

and its decay rate is

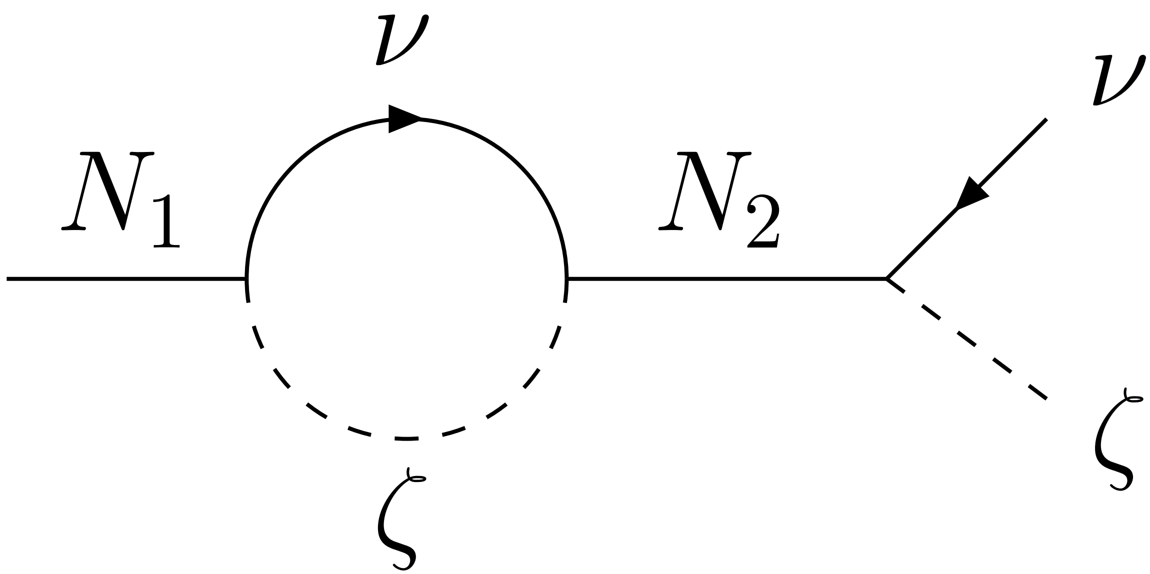
$$\Gamma_h = \frac{f_h^2 m_h}{8\pi} \sqrt{1 - 4r^2}(1 - 2r^2),$$

where $r = m_S/m_h$. If $f_h \sim 10^{-12} r^{-1/2}$, S may be freeze-in dark matter with the correct abundance. This implies $m_S m_1^2 m_2^2 / m_N^2 \sim 7.6 \times 10^{-18} (\mathrm{GeV})^3$. Let $m_N = 2$ TeV, $m_1 = m_2 = 30$ MeV, then $m_S \sim 38$ keV.

Scoto-Leptogenesis

As a rule, for every model of neutrino mass, there is a corresponding scenario of leptogenesis to explain the matter-antimatter asymmetry of the Universe.

In the new A_4 model, there are three Majorana fermions in the dark sector: N_1, N_2 and the light S. All couple to $\nu + \zeta$ and $\bar{\nu} + \zeta$. $N_{1,2}$ are heavy and for $m_{N_1} < m_{N_2}$, the decay of N_1 to $\nu + \zeta$ and $\bar{\nu} + \zeta$ generates a lepton asymmetry which gets converted to a baryon asymmetry through sphalerons. The subsequent decay of ζ conserves CP and does not contribute to the lepton asymmetry.



ν
N_1
N_2
ν
ζ
ζ

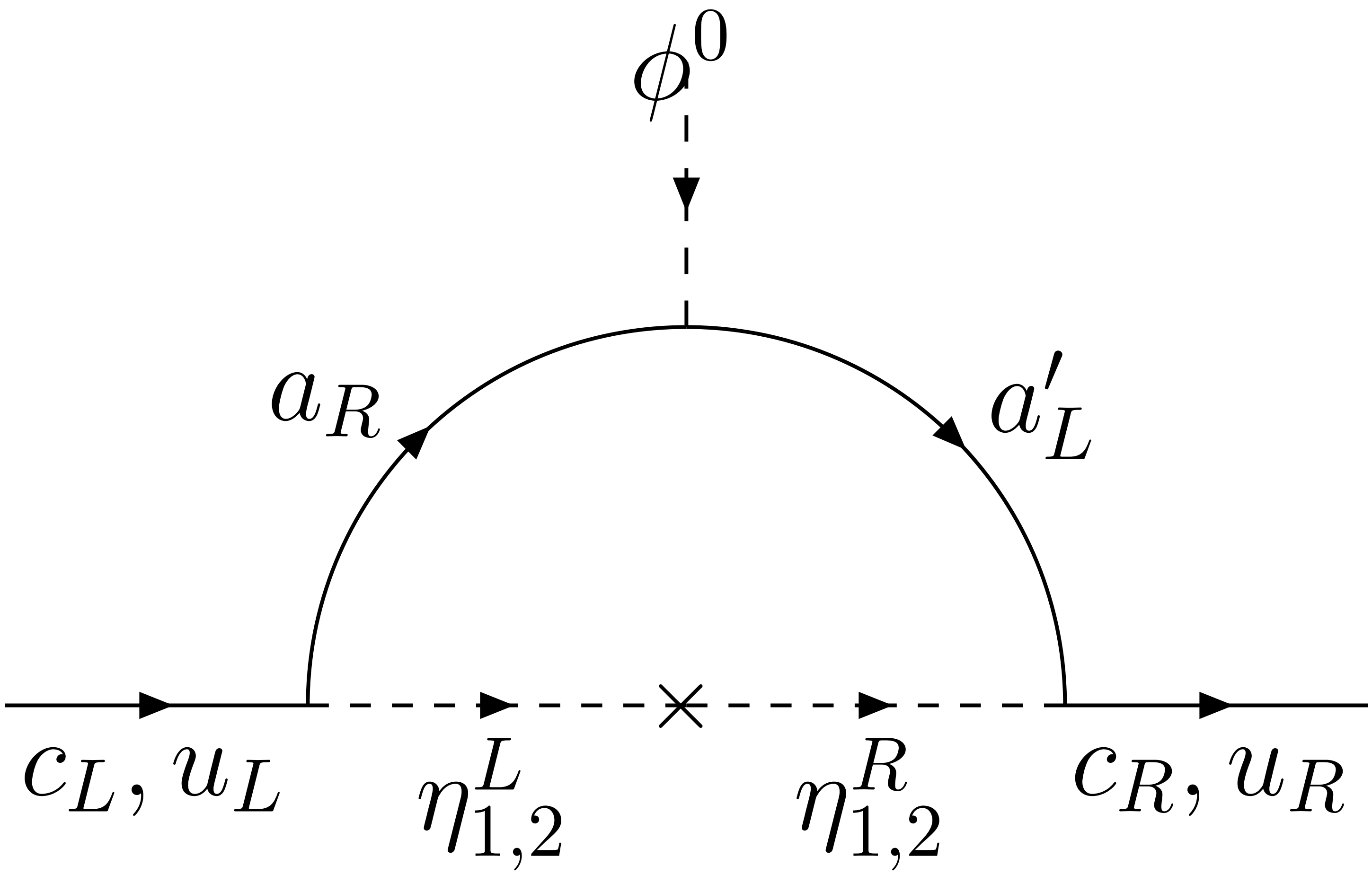
Scotogenic Peccei-Quinn

The strong CP phase of QCD may be dynamically set to zero through the Peccei-Quinn mechanism using an anomalous global U(1) symmetry coupled to color fermions such as quarks and gluinos. Here dark quarks are proposed: $\Psi \sim (8,1,0) \sim 1$,

$$(a,v)_L \sim 1, \quad (a,v)_R \sim -3, \qquad a'_R, v'_R \sim 1, \quad a'_L, v'_L \sim -3,$$

together with a scalar singlet $\sigma \sim 2$ which acquires a large VEV and whose dynamical phase becomes the axion. $\zeta \sim 4$, $\kappa \sim 6$ are added.

As such, they have no direct connection to the SM quarks which do not transform under this $U(1)_{PQ}$. Consider then the imposition of $Z_3 \times Z_3$ flavor symmetry on the SM quarks:
$(t,b)_L, t_R, b_R \sim (1,1), \quad (c,s)_L \sim (\omega,1), c_R, s_R \sim (1,\omega), \quad (u,d)_L \sim (\omega^2,1), u_R, d_R \sim (1,\omega^2)$. With also $(\phi^+,\phi^0) \sim (1,1)$, only t and b quarks obtain tree-level masses. The other entries of the two 3×3 quark mass matrices are then obtained in one loop from the addition of 5 neutral singlet flavons η with PQ charge 3 and matching the respective $Z_3 \times Z_3$ transformations.



ϕ^0
a_R
a'_L
c_L, u_L
$\eta^L_{1,2}$
$\eta^R_{1,2}$
c_R, u_R

If $Z_3 \times Z_3$ is exact, the 5×5 mass-squared matrix $\mathcal{M}_\eta^2$ is diagonal, and the depicted amplitude is zero.

Allowing soft $Z_3 \times Z_3$ breaking, $\mathcal{M}_\eta^2 = U^\dagger \mathcal{M}_{diag}^2 U$, so that the link between η_i and η_j in the diagram is $\sum_k U_{ik}^\dagger m_k^{-2} U_{kj}$ where m_k are the η mass eigenvalues. For $i \neq j$, $\sum_k U_{ik}^\dagger U_{kj} = 0$ which ensures the one-loop finiteness of the amplitude.

Let the soft breaking obey $\eta_i^L \leftrightarrow \eta_i^R$, then both $\mathcal{M}_u$ and $\mathcal{M}_d$ are Hermitian with parallel structures, which is the starting arbitrary assumption of many studies.

Observable Consequences

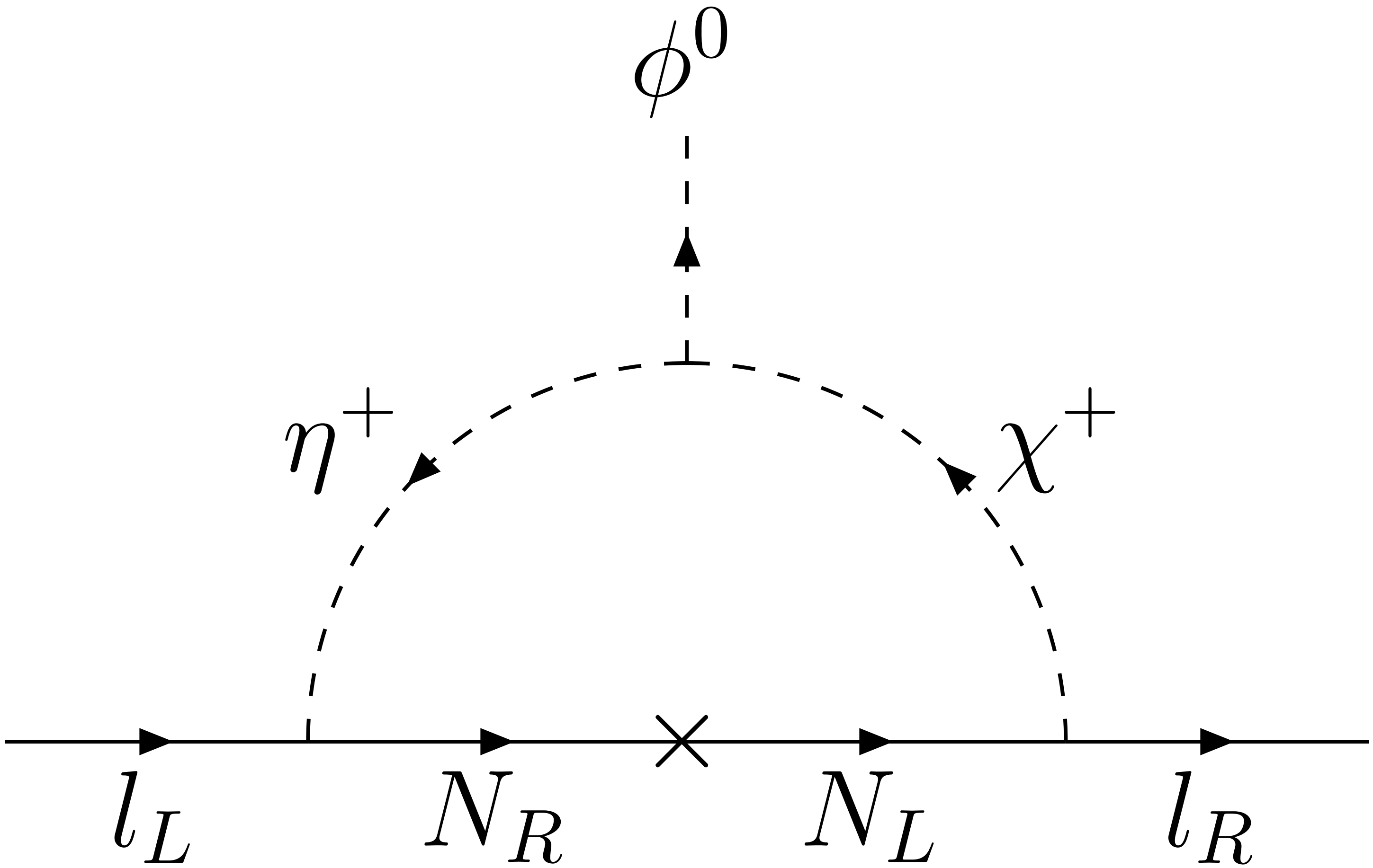
Even though there is only one Higgs boson, its coupling to SM fermions is now not $(m_f/v\sqrt{2})$ as in the SM. [Fraser/Ma(2014)]

Consider the 2×2 mass matrix spanning (a, a'):

$$\mathcal{M}_a = \begin{pmatrix} M_a & m_a \\ m'_a & M'_a \end{pmatrix}.$$

If $m_a, m'_a << M_a, M'_a$, the Higgs quark couplings are proportional to the corresponding entries of the quark mass matrix as in the SM. However, there are now additional Higgs couplings, such as $\lambda_{01}(v + h/\sqrt{2})^2 \eta_1^* \eta_1$. This implies an anomalous $h\bar{t}_L c_R$ coupling given by $\sqrt{2} v \lambda_{01} m_{tc}/m_{eff}^2$, where m_{eff} is an effective combination of η masses.

To explore further the anomalous Higgs couplings, consider the one-loop lepton masses with $N_{1,2,3}$ dark matter shown earlier. The doublet (η^+, η^0) and singlet χ^+ mix through the term $\mu(\eta^+ \phi^0 - \eta^0 \phi^+)\chi^-$, where $\langle \phi^0 \rangle = v/\sqrt{2}$.


ϕ^0
η^+
χ^+
l_L
N_R
N_L
l_R

Let the mass eigenstates be $\zeta_1 = \eta\cos\theta + \chi\sin\theta$, and $\zeta_2 = \chi\cos\theta - \eta\sin\theta$ with masses m_1 and m_2, then $\mu v/\sqrt{2} = \sin\theta\cos\theta(m_1^2 - m_2^2)$. The one-loop mass is

$$m_l = \frac{f_\eta f_\chi \sin\theta\cos\theta m_N}{16\pi^2}\left(\frac{x_1\ln x_1}{x_1 - 1} - \frac{x_2\ln x_2}{x_2 - 1}\right),$$

where $x_{1,2} = m_{1,2}^2/m_N^2$.

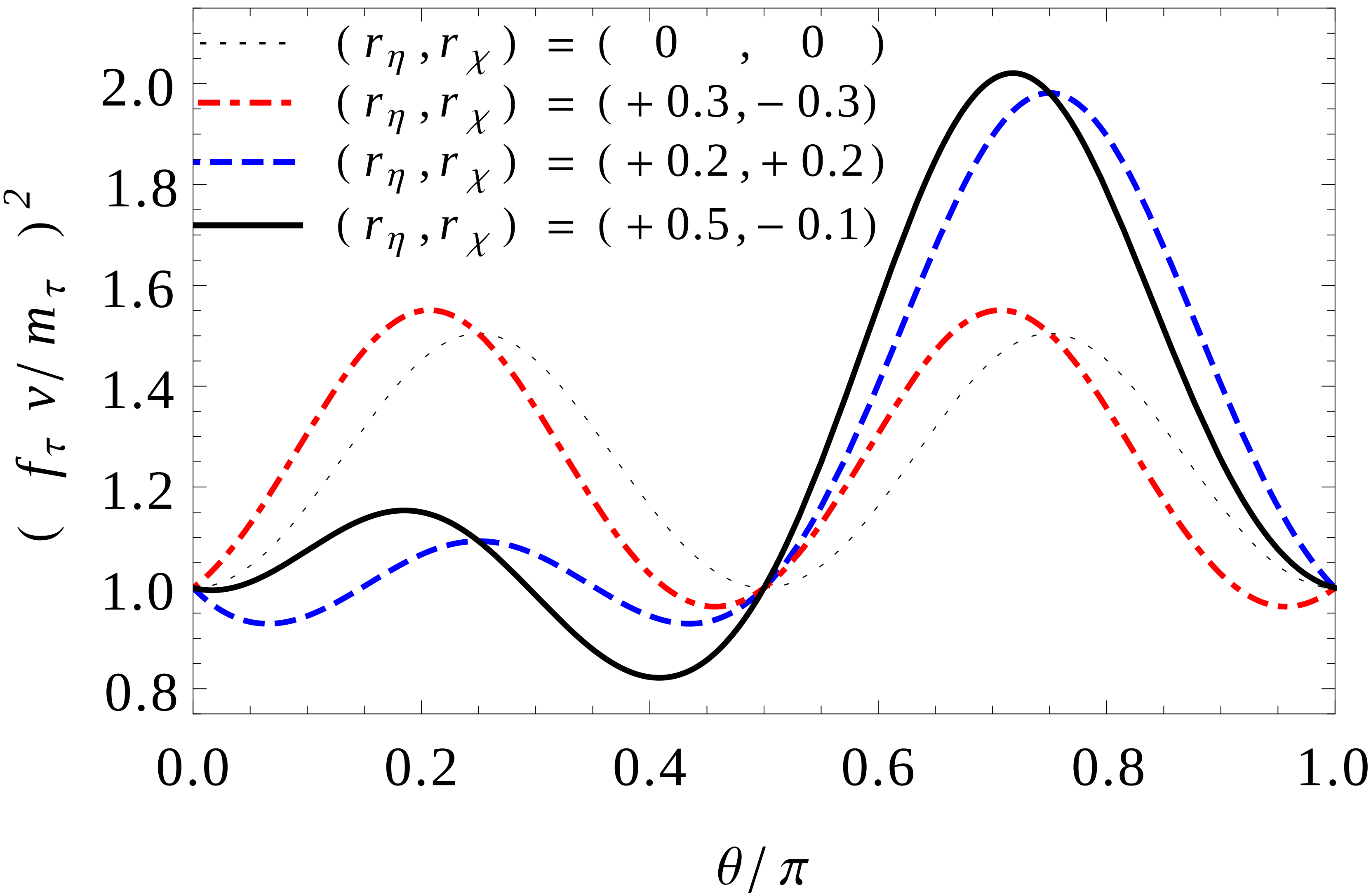
The Yukawa coupling of h to $\bar{l}l$ is now not exactly equal to m_l/v. It has three contributions, through $\eta^+\eta^-$, $\chi^+\chi^-$, and $\eta^\pm\chi^\mp$. Let $r_{\eta,\chi} = \lambda_{\eta,\chi}v\sqrt{2}/\mu$, then

$$f_l v/m_l = 1 + a_+F_+ + a_-F_-,$$

where $a_+ = (\sin 2\theta)^2/2 + \sin 4\theta(r_\eta - r_\chi)/4$,
$a_- = \sin 2\theta(r_\eta + r_\chi)/2$, and
$F_+ = [F(x_1, x_1) + F(x_2, x_2)]/2F(x_1, x_2) - 1$,
$F_- = [F(x_1, x_1) - F(x_2, x_2)]/2F(x_1, x_2)$, with

$$F(x_1, x_2) = \frac{1}{x_1 - x_2}\left(\frac{x_1 \ln x_1}{x_1 - 1} - \frac{x_2 \ln x_2}{x_2 - 1}\right).$$

$$F(x, x) = \frac{1}{x - 1} - \frac{\ln x}{(x - 1)^2}.$$


$(r_\eta, r_\chi) = (0, 0)$
$(r_\eta, r_\chi) = (+0.3, -0.3)$
$(r_\eta, r_\chi) = (+0.2, +0.2)$
$(r_\eta, r_\chi) = (+0.5, -0.1)$
$(f_\tau v/m_\tau)^2$
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.0
0.2
0.4
0.6
0.8
1.0
θ/π

To conclude, the SM may be complete as it is.
The rest is in the dark sector.

MonoHiggsology is the future!