

Flavor and Dark Matter via the one Higgs

Ernest Ma
Physics and Astronomy Department
University of California
Riverside, CA 92521, USA



With apology to J. R. R. Tolkien:

Three families of quarks and leptons,

one Higgs to rule them all,

and in the darkness bind them.

With the recent discovery of the 126 GeV particle at the LHC, and the likelihood of it being the one physical neutral Higgs boson h of the SM, it may be a good time to reflect on what it means as to some of the other outstanding problems in particle physics.

At this workshop, two main topics of discussion are **flavor** and **dark matter**, so I am linking them in this talk via the **one Higgs** of the SM.

I will show in eight easy steps how this may be achieved [Ma, PRL 112, 091801 (2014)].

Step 1

Let there be a **dark sector**, distinguished from the observable sector by a discrete Z_2 symmetry which may or may not be the remnant of an $U(1)_D$ gauge symmetry. The particles of this **dark sector** consist of Dirac fermions: $N_{1,2,3}$, and scalars:

$$(\eta^+, \eta^0), \zeta^{-1/3} \sim \underline{5}, (\xi^{2/3}, \xi^{-1/3}), (\zeta^{2/3})^*, \chi^+ \sim \underline{10},$$

which are complete $SU(5)$ multiplets, analogous to the scalar quarks and leptons of supersymmetry.

The lightest N is stable and a possible candidate for the observed **dark matter** of the Universe.

Step 2

Impose a non-Abelian discrete symmetry, under which $N_{1,2,3}$ as well as the three families of quarks and leptons transform nontrivially.

Take for example (my favorite) A_4 which is the symmetry of the perfect tetrahedron (Plato's fire). It has four irreducible representations $\underline{1}, \underline{1}', \underline{1}'', \underline{3}$, with the multiplication rule

$$\underline{3} \times \underline{3} = \underline{1} + \underline{1}' + \underline{1}'' + \underline{3} + \underline{3}.$$

Step 3

Assign

$$L_{iL} = (\nu, l)_{iL}, \quad Q_{iL} = (u, d)_{iL} \sim \underline{1}, \underline{1}', \underline{1}'', \\ l_{iR}, \quad d_{iR}, \quad u_{iR} \sim \underline{3},$$

but with only **one Higgs** doublet, i.e.

$$\Phi = (\phi^+, \phi^0) \sim \underline{1}.$$

Hence the usual SM Yukawa couplings

$\bar{L}_{iL} l_{jR} \Phi$, $\bar{Q}_{iL} d_{jR} \Phi$, $\bar{Q}_{iL} u_{jR} \tilde{\Phi}$ are forbidden.

The nonzero vacuum expectation value of ϕ^0 generates W and Z masses but **not** fermion masses.

Step 4

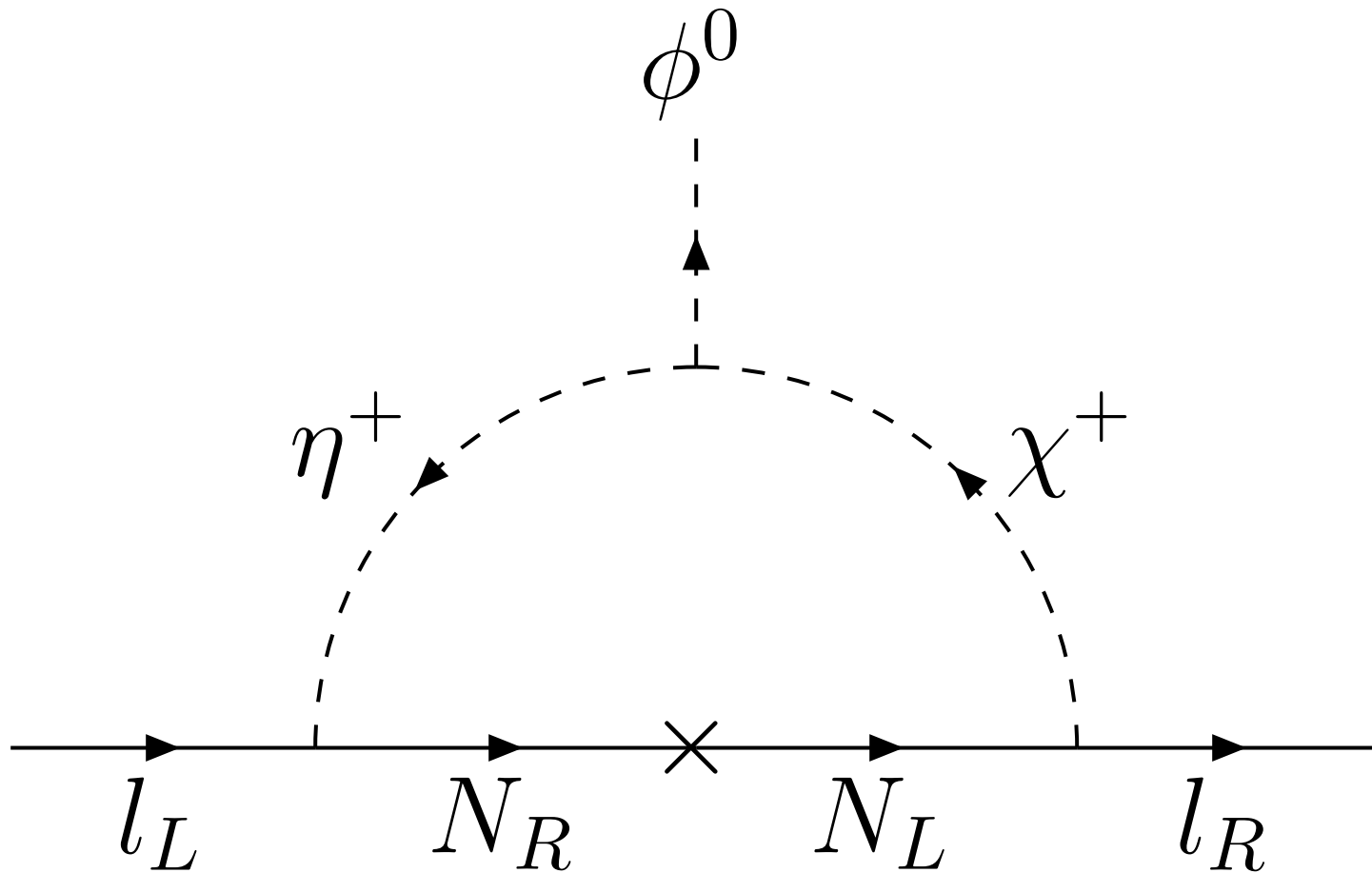
Consider now the particles of the **dark sector**. Let

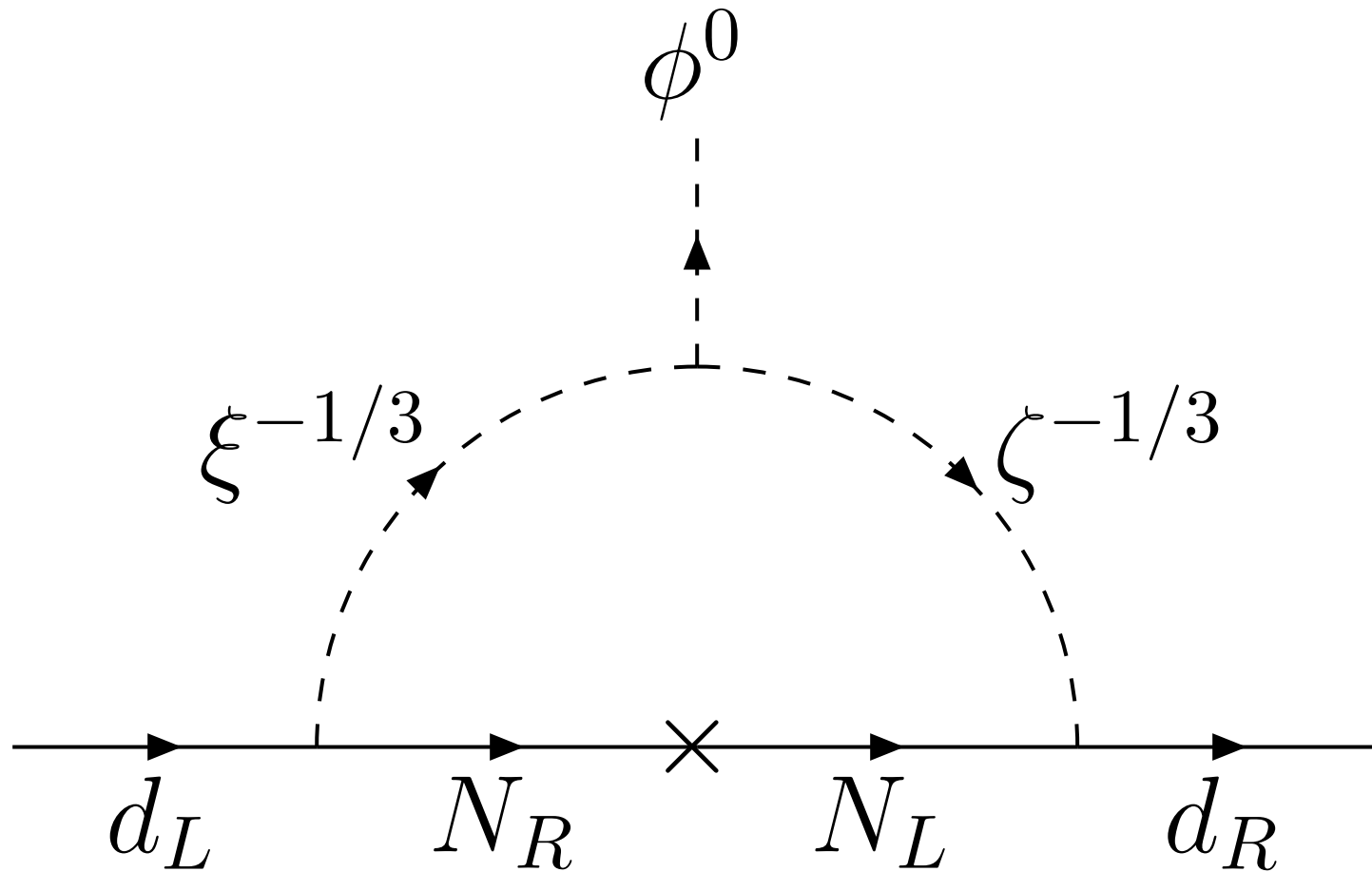
$$(\eta^+, \eta^0), \quad \chi^+ \sim \underline{1}, \quad N_{iL} \sim \underline{3}, \quad N_{iR} \sim \underline{1}, \underline{1}', \underline{1}''.$$

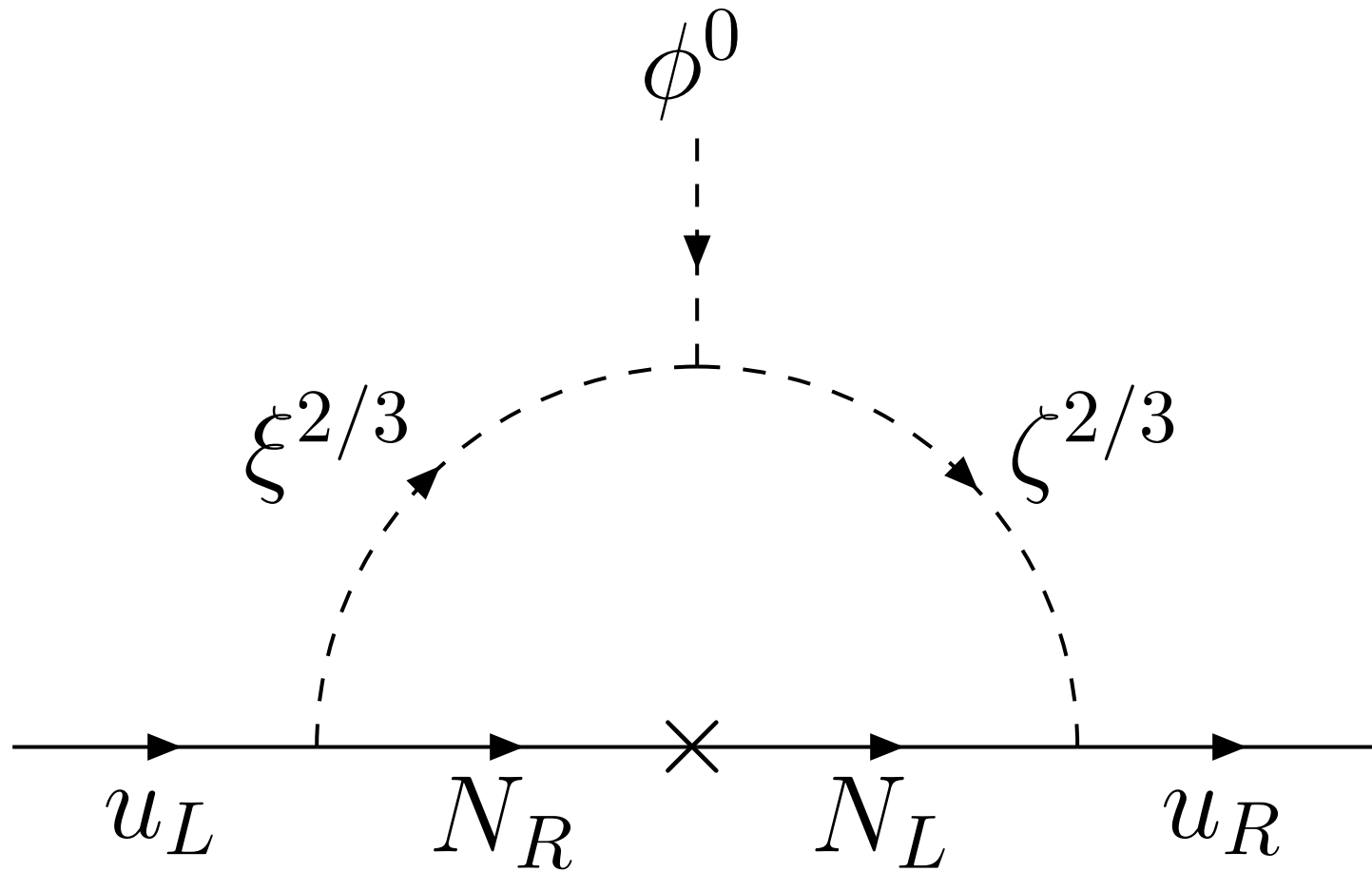
Hence the Yukawa couplings $\bar{N}_R l_L \eta^+$ and $\bar{l}_R N_L \chi^-$ are allowed. To connect \bar{l}_R with l_L , soft breaking of A_4 to Z_3 is assumed, i.e.

$$\mathcal{M}_N = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 1 & 1 \\ 1 & \omega & \omega^2 \\ 1 & \omega^2 & \omega \end{pmatrix} \begin{pmatrix} M_1 & 0 & 0 \\ 0 & M_2 & 0 \\ 0 & 0 & M_3 \end{pmatrix},$$

where $\omega = \exp 2\pi i/3 = -1/2 + \sqrt{3}/2$.







Thus all quarks and leptons owe their masses to **dark matter** in conjunction with Φ . Note that Z_2 remains unbroken. In the case of gauge $U(1)_D$, it may also remain unbroken, or broken to global $U(1)_D$ or discrete Z_2 .

Step 5

The residual Z_3 flavor (triality) symmetry maintains diagonal mass matrices for d and u quarks as well as charged leptons. This is an explanation of why the quark mixing matrix V_{CKM} is nearly diagonal. At this stage, the three families transform under Z_3 as $\underline{1}, \underline{1}', \underline{1}''$ in both L and R chiralities.

Step 6

To obtain a realistic quark mixing matrix V_{CKM} , soft breaking of Z_3 is required. The $\bar{q}_{iL}q_{jR}$ mass matrix is of the form

$$\mathcal{M}_q = \begin{pmatrix} f_1 & 0 & 0 \\ 0 & f_2 & 0 \\ 0 & 0 & f_3 \end{pmatrix} U_M^L \begin{pmatrix} M_1 & 0 & 0 \\ 0 & M_2 & 0 \\ 0 & 0 & M_3 \end{pmatrix} (U_M^R)^\dagger.$$

If the unitary matrices $U_M^{L,R}$ are the identity, then Z_3 is not broken and V_{CKM} is also the identity. Let U_M^L be

approximately given by

$$U_M^L \simeq \begin{pmatrix} 1 & -\epsilon_{12} & -\epsilon_{13} \\ \epsilon_{12}^* & 1 & -\epsilon_{23} \\ \epsilon_{13}^* & \epsilon_{23}^* & 1 \end{pmatrix},$$

then $\mathcal{M}_q \mathcal{M}_q^\dagger$ is given by

$$\begin{pmatrix} f_1^2 M_1^2 & f_1 f_2 \epsilon_{12} (M_1^2 - M_2^2) & f_1 f_3 \epsilon_{13} (M_1^2 - M_3^2) \\ f_1 f_2 \epsilon_{12}^* (M_1^2 - M_2^2) & f_2^2 M_2^2 & f_2 f_3 \epsilon_{23} (M_2^2 - M_3^2) \\ f_1 f_3 \epsilon_{13}^* (M_1^2 - M_3^2) & f_2 f_3 \epsilon_{23}^* (M_2^2 - M_3^2) & f_3^2 M_3^2 \end{pmatrix}.$$

Let $m_d \simeq f_1^d M_1$, $m_s \simeq f_2^d M_2$, $m_b \simeq f_3^d M_3$, $m_u \simeq f_1^u M_1$,

$m_c \simeq f_2^u M_2$, $m_t \simeq f_3^u M_3$, then V_{CKM} becomes

$$V_{ud} \simeq V_{cs} \simeq V_{tb} \simeq 1, \quad V_{us} \simeq \left(\frac{m_d}{m_s} - \frac{m_u}{m_c} \right) \epsilon_{12} \left(\frac{M_2}{M_1} - \frac{M_1}{M_2} \right),$$

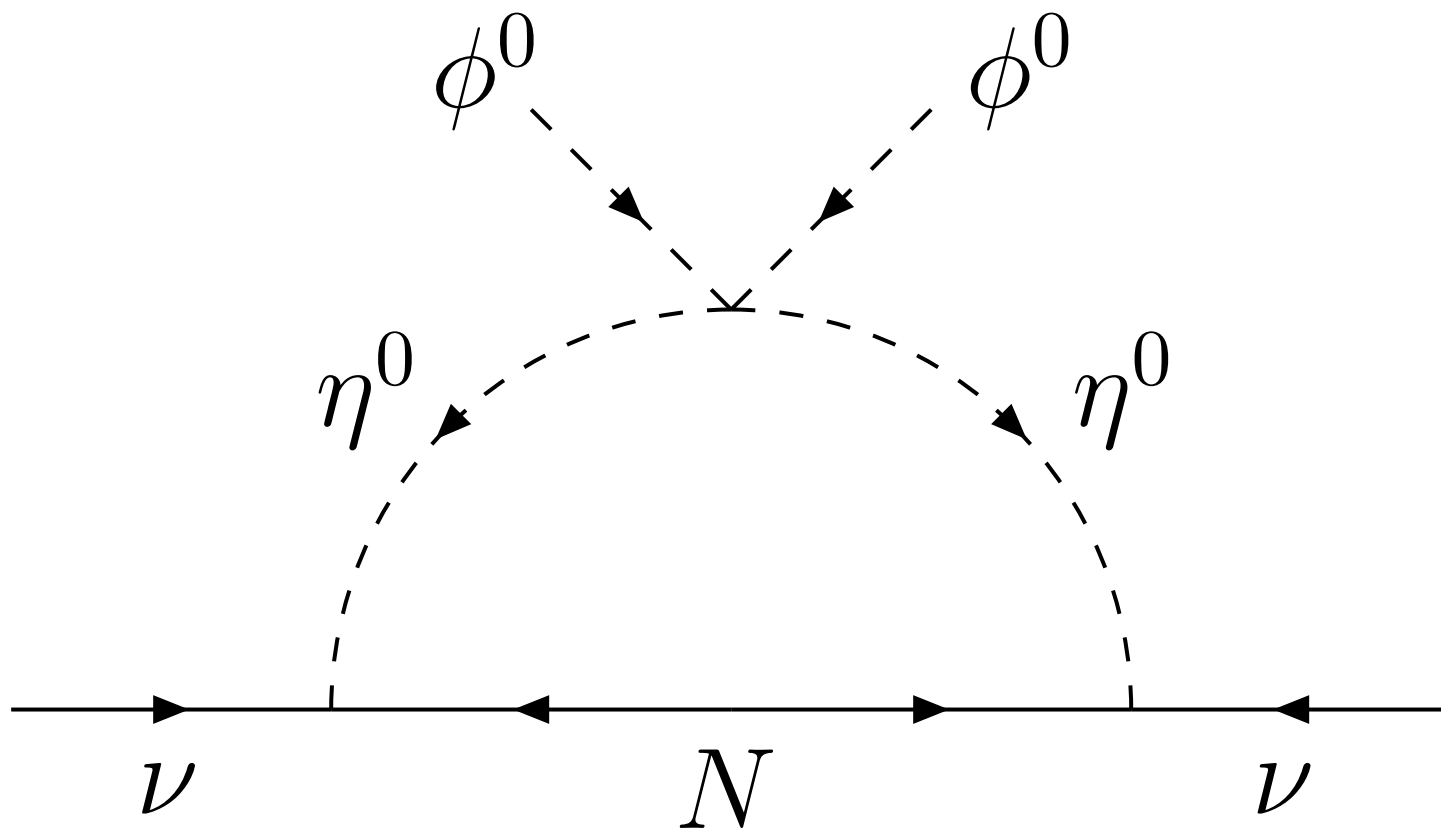
$$V_{ub} \simeq \left(\frac{m_d}{m_b} - \frac{m_u}{m_t} \right) \epsilon_{13} \left(\frac{M_3}{M_1} - \frac{M_1}{M_3} \right),$$

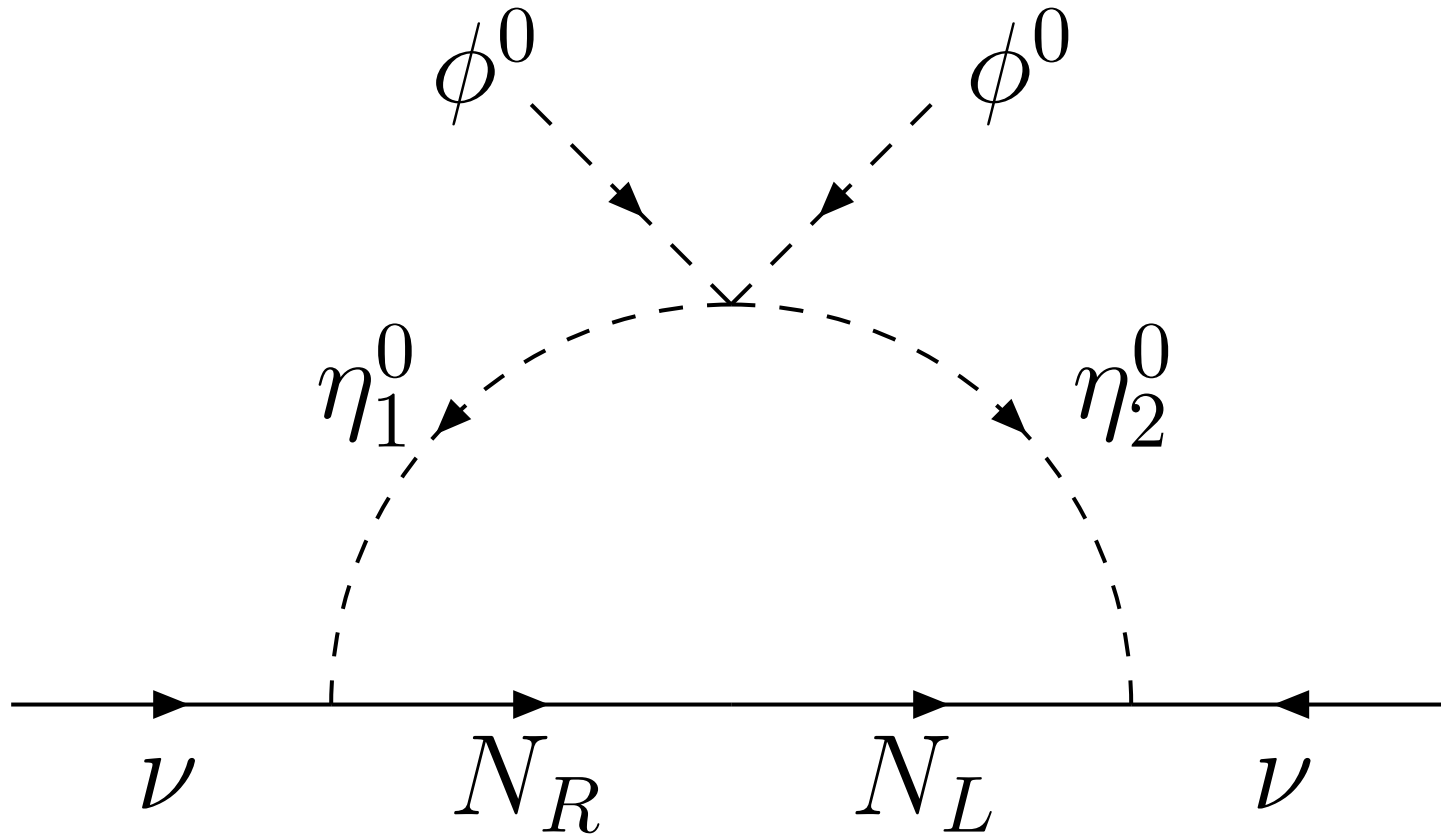
$$V_{cb} \simeq \left(\frac{m_s}{m_b} - \frac{m_c}{m_t} \right) \epsilon_{23} \left(\frac{M_3}{M_2} - \frac{M_2}{M_3} \right).$$

The soft breaking of \mathbf{Z}_3 which generates U_M^L is directly linked to the observed V_{CKM} . For example, if $f_1^d = f_2^d = f_3^d$, then $V_{CKM} \simeq (U_M^L)^\dagger$.

Step 7

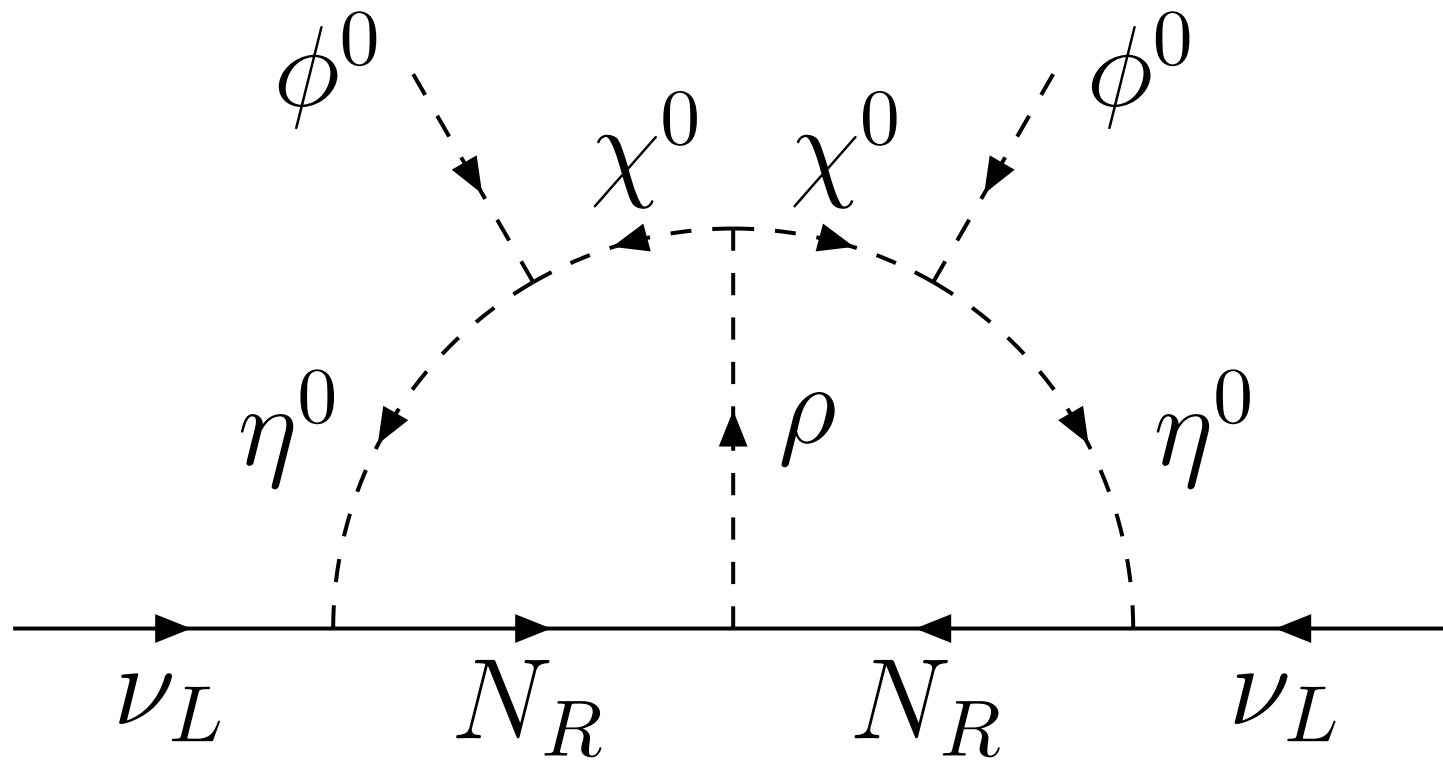
Neutrino mass may be generated in one loop using the well-studied scotogenic model [Ma/2006)] with Z_2 or the recently proposed version [Ma/Picek/Radovcic(2013)] with gauge $U(1)_D$. This requires two dark-matter scalar doublets $(\eta_{1,2}^+, \eta_{1,2}^0)$ transforming oppositely under $U(1)_D$. It implies self interacting dark matter (SIDM), which may be the key to understanding the dark-matter profile of dwarf galaxies. SIDM has become in recent years a very active area of research. The dark photon and the dark Higgs are now frequent buzz words.





Alternatively, a two-loop realization is also possible. Four extra singlet neutral scalar fields $\chi^0, \rho_{1,2,3}$ are needed. Under $U(1)_D$, $\chi^0 \sim 1$, $\rho_{1,2,3} \sim 2$. Under Z_3 , $\chi^0 \sim 1$, $\rho_{1,2,3} \sim 1, \omega, \omega^2$. The addition of χ^0 and ρ_1 completes the two loops without breaking $U(1)_D$ or Z_3 . This would result in a Majorana neutrino mass matrix in the basis $(\nu_e, \nu_\mu, \nu_\tau)$ of the form

$$\mathcal{M}_\nu = \begin{pmatrix} A & 0 & 0 \\ 0 & 0 & B \\ 0 & B & 0 \end{pmatrix}.$$



The further addition of $\rho_{2,3}$ together with the soft breaking of Z_3 using the trilinear $\chi^0 \chi^0 \rho_{1,2}^\dagger$ couplings allows \mathcal{M}_ν to become

$$\mathcal{M}_\nu = \begin{pmatrix} A & C & C^* \\ C & D^* & B \\ C^* & B & D \end{pmatrix},$$

where A and B are real. This form is protected by a symmetry [Grimus/Lavoura(2004)], i.e. $e \rightarrow e$ and $\mu - \tau$ interchange with CP conjugation. It is guaranteed to yield maximal $\nu_\mu - \nu_\tau$ mixing ($\theta_{23} = \pi/4$) and maximal CP violation, i.e. $\exp(-i\delta) = \pm i$, with nonzero θ_{13} .

θ_{13} and θ_{12} are determined by $s_{13}/c_{13} = -D_I/\sqrt{2}C_R$,
 $s_{13}c_{13}/(c_{13}^2 - s_{13}^2) = \sqrt{2}C_I/(A - B + D_R)$, and

$$\frac{s_{12}c_{12}}{c_{12}^2 - s_{12}^2} = \frac{-\sqrt{2}(c_{13}^2 - s_{13}^2)C_R}{c_{13}[c_{13}^2(A - B - D_R) + 2s_{13}^2D_R]}.$$

The three neutrino masses are determined by

$$m_2 + m_1 \simeq A + B + D_R + s_{13}^2(A - B + D_R),$$

$$(c_{12}^2 - s_{12}^2)(m_2 - m_1) \simeq -A + B + D_R - s_{13}^2(A - B + D_R),$$

$$m_3 \simeq -B + D_R + s_{13}^2(A - B + D_R).$$

Step 8

The predicted new scalars which connect the quarks and leptons to their common **dark-matter** antecedents, i.e.

$N_{1,2,3}$, are possibly observable at the LHC. They may also change significantly the SM couplings of the **one Higgs** [Fraser/Ma(2014)]. The doublet (η^+, η^0) and singlet χ^+ mix through the term $\mu(\eta^+ \phi^0 - \eta^0 \phi^+) \chi^-$, where $\langle \phi^0 \rangle = v/\sqrt{2}$. Thus

$$\mathcal{M}_{\eta\chi}^2 = \begin{pmatrix} m_\eta^2 & \mu v/\sqrt{2} \\ \mu v/\sqrt{2} & m_\chi^2 \end{pmatrix},$$

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

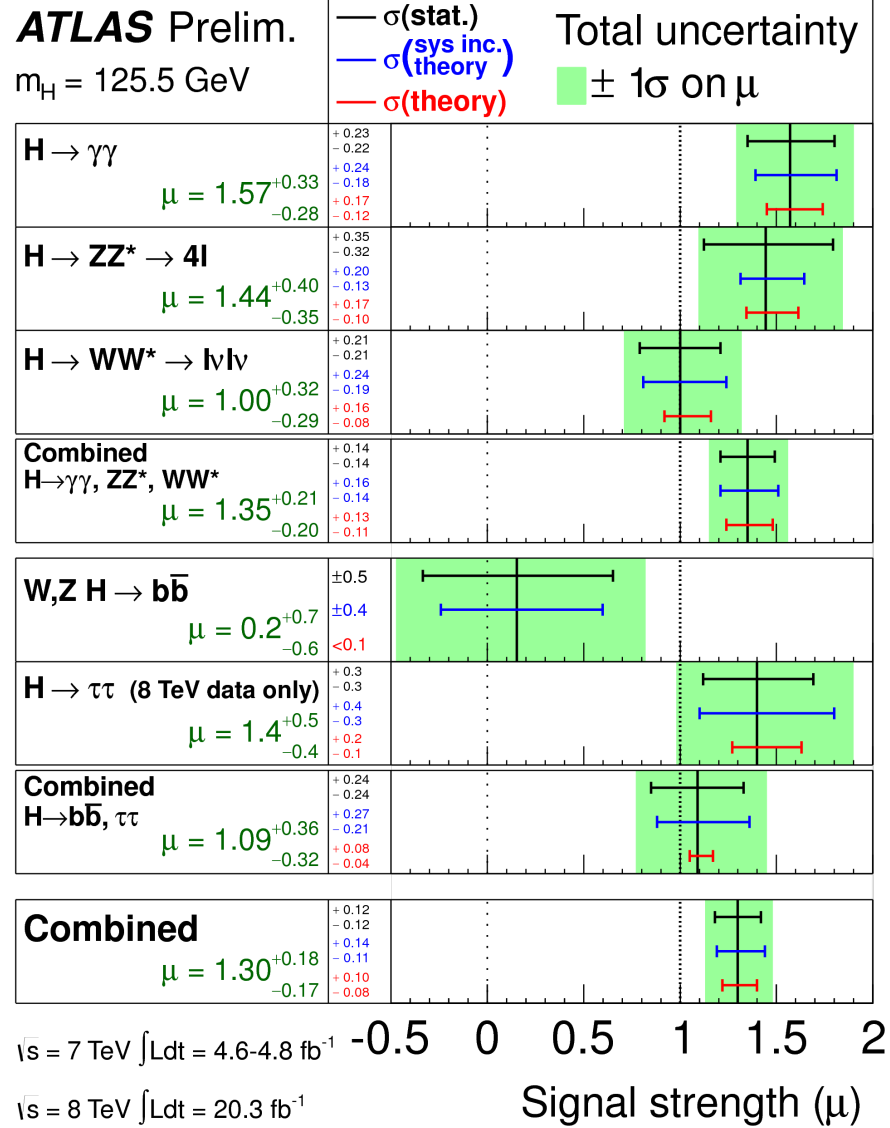
The Yukawa coupling of h to $\bar{l}l$ is now not exactly equal to m_l/v . It has three contributions, through $\eta^+ \eta^-$, $\chi^+ \chi^-$, and $\eta^\pm \chi^\mp$. Let $r_{\eta,\chi} = \lambda_{\eta,\chi} v^2 / m_N^2$, then

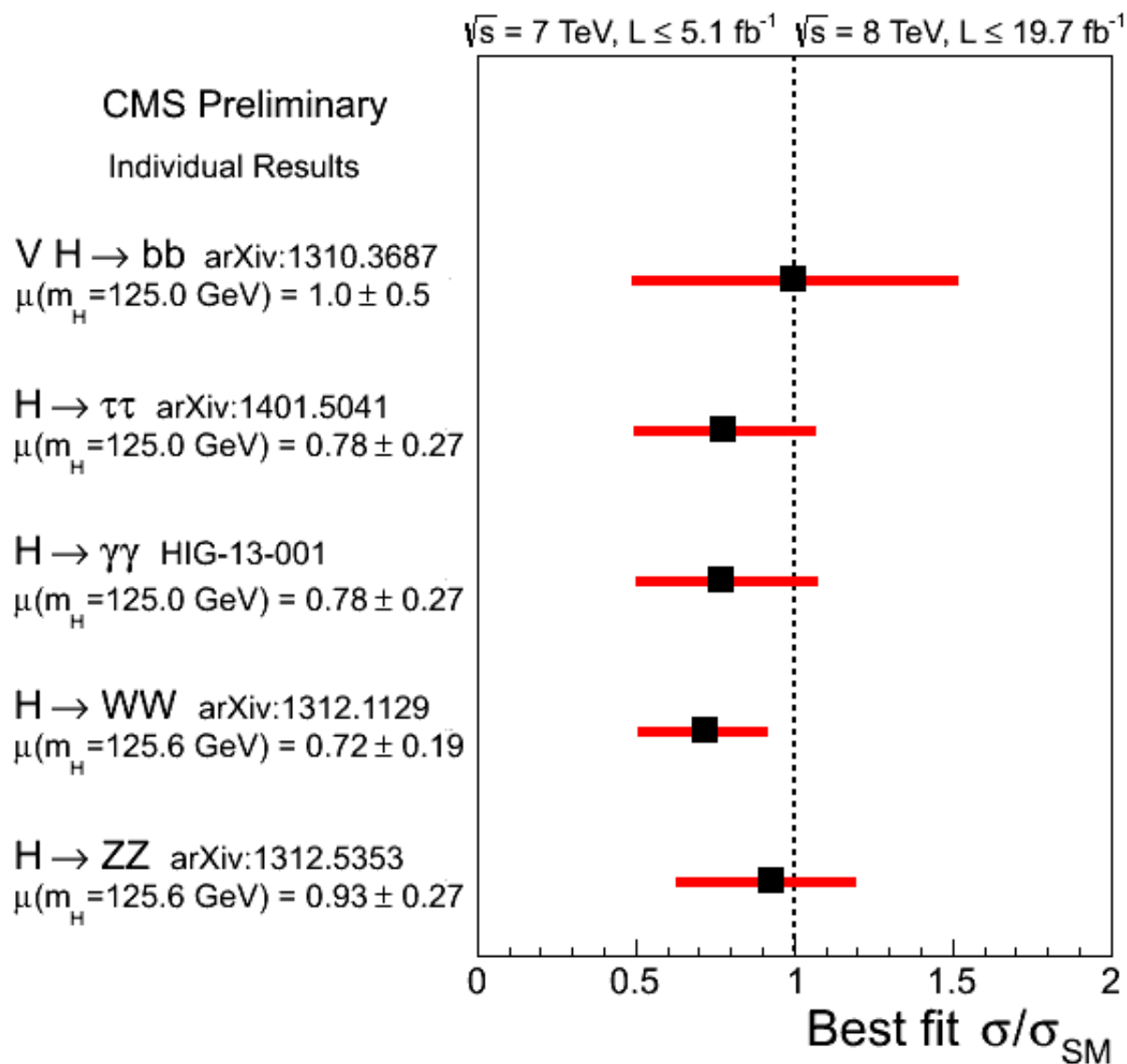
$$f_l v / m_l = 1 + a_+ F_+ + a_- F_-,$$

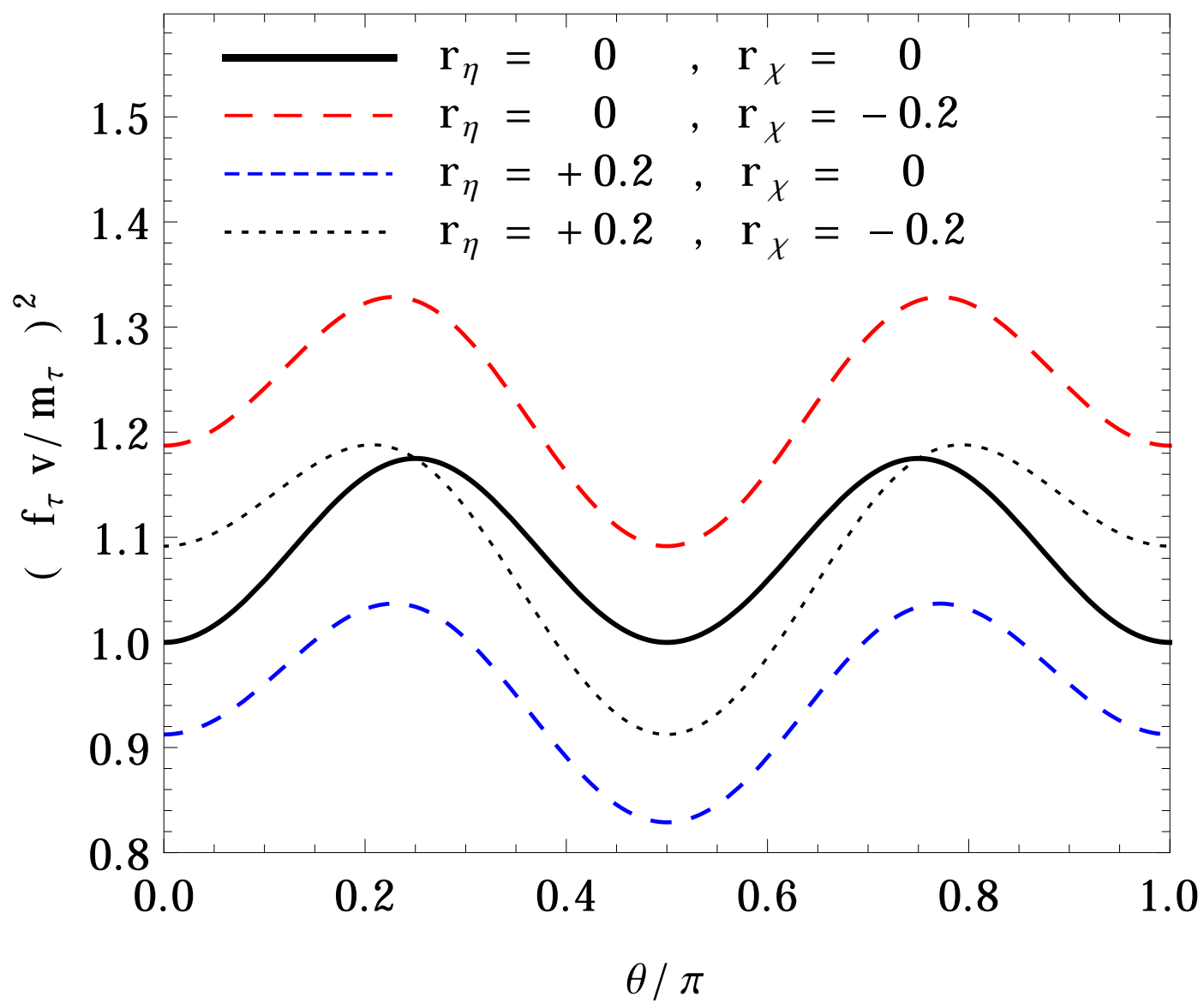
where $a_+ = (\sin 2\theta)^2/2 + \sin 4\theta(r_\eta - r_\chi)/4$,
 $a_- = \sin 2\theta(r_\eta + r_\chi)/2$, and
 $F_+ = [F(x_1, x_1) + F(x_2, x_2)]/2F(x_1, x_2) - 1$,
 $F_- = [F(x_1, x_1) - F(x_2, x_2)]/2F(x_1, x_2)$, with

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

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







Prognosis

The 126 GeV particle may hold secrets of physics beyond the SM. It could indeed be the **one Higgs**, but not exactly that of the SM. Its couplings to fermions may hold the key to understanding **flavor** and **dark matter**. Particles which look like scalar quarks and leptons are also predicted at the LHC, but with properties not exactly like those required by supersymmetry.

One possible signature is $\tilde{q} \rightarrow q N_{1,2}$, then $N_2 \rightarrow \mu \zeta$, then $\zeta \rightarrow N_1 e$, resulting in 2 quark jets, μ^\pm , e^\mp + missing energy