Neutrino Theory Impacts

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Contents

Questions and Answers

Neutrinos are different from other known particles. Neutrinos are the only fundamental fermions which may be their own antiparticles (Majorana). To study them theoretically, I adopt the following steps:

(1) Neutrino Theory Questions

(2) Possible Neutrino Theory Answers

(3) Impacts on Other Issues of Particles and Astrophysics

(4) Possible Experimental Verification?

Question: What is the origin of neutrino mass?

Usual assumption: The new physics responsible for neutrino mass is above the scale of electroweak symmetry breaking. [This excludes light singlet neutral (right-handed) fermions which may pair up with the known (left-handed) neutrinos to form Dirac neutrinos.] Hence the starting point of a neutrino theory **answer** is the unique dimension-five Weinberg operator (1979) for Majorana neutrino mass:

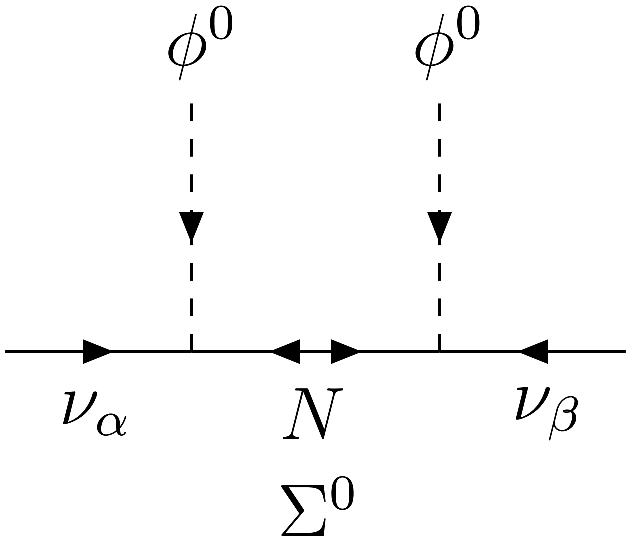
$$\frac{f_{\alpha\beta}}{2\Lambda}(\nu_\alpha\phi^0 - l_\alpha\phi^+)(\nu_\beta\phi^0 - l_\beta\phi^+) \Rightarrow \mathcal{M}_\nu = \frac{f_{\alpha\beta}v^2}{\Lambda}.$$

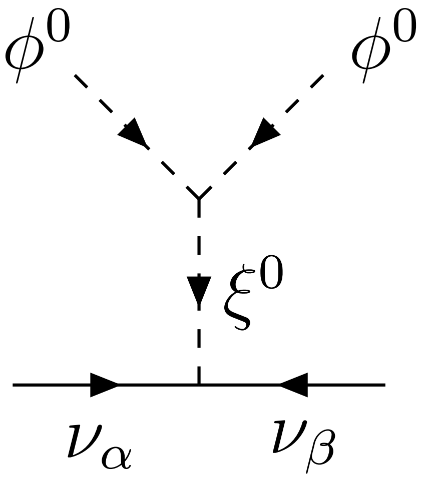
Ma (April, 1998): [PRL 81, 1171 (1998)]
Three tree-level realizations:
(I) fermion singlet N (1979),
(II) scalar triplet $(\xi^{++}, \xi^{+}, \xi^{0})$ (1980),
(III) fermion triplet $(\Sigma^{+}, \Sigma^{0}, \Sigma^{-})$ (1989);
and three generic one-loop realizations:
(IV) (Zee, 1980), (V) (Ma, 2006), (VI) (?).

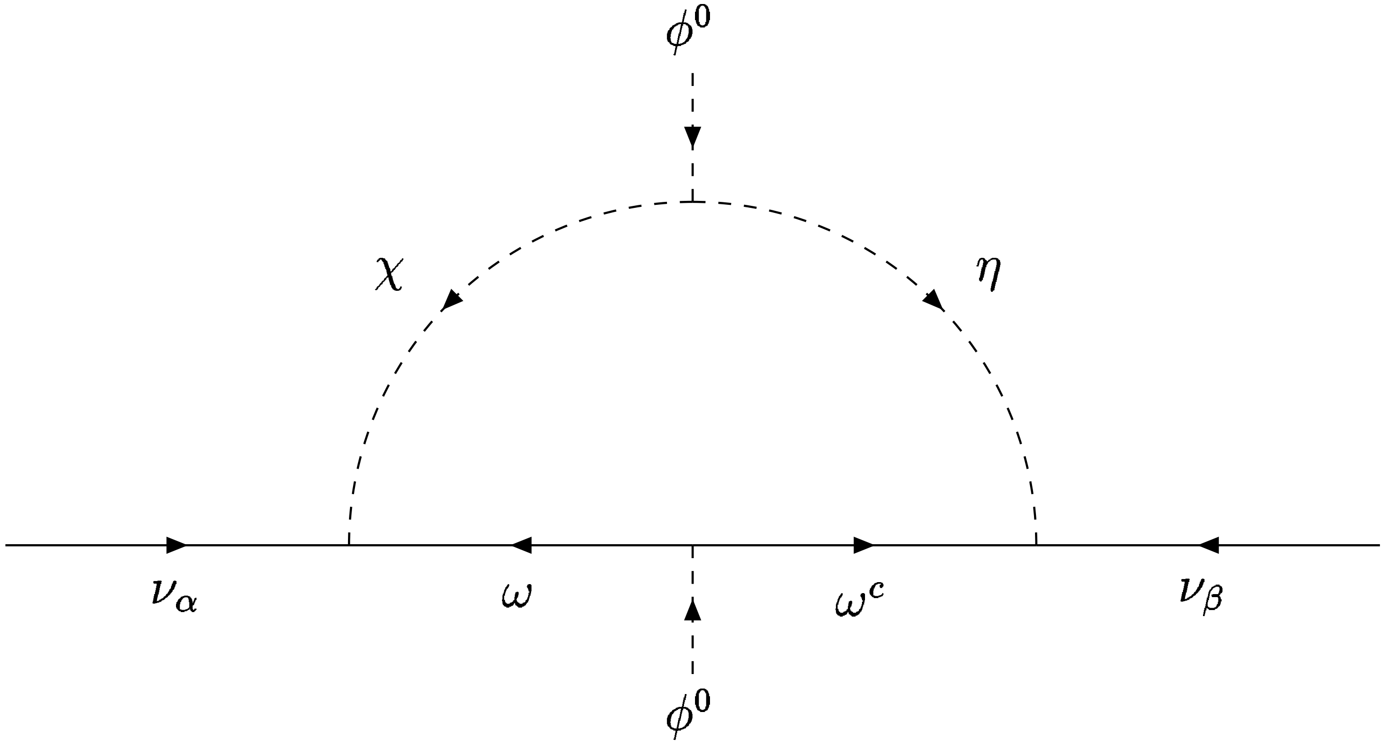
Super-K (June, 1998): [Neutrino 98 Conference, Japan]
Atmospheric neutrino oscillations established.

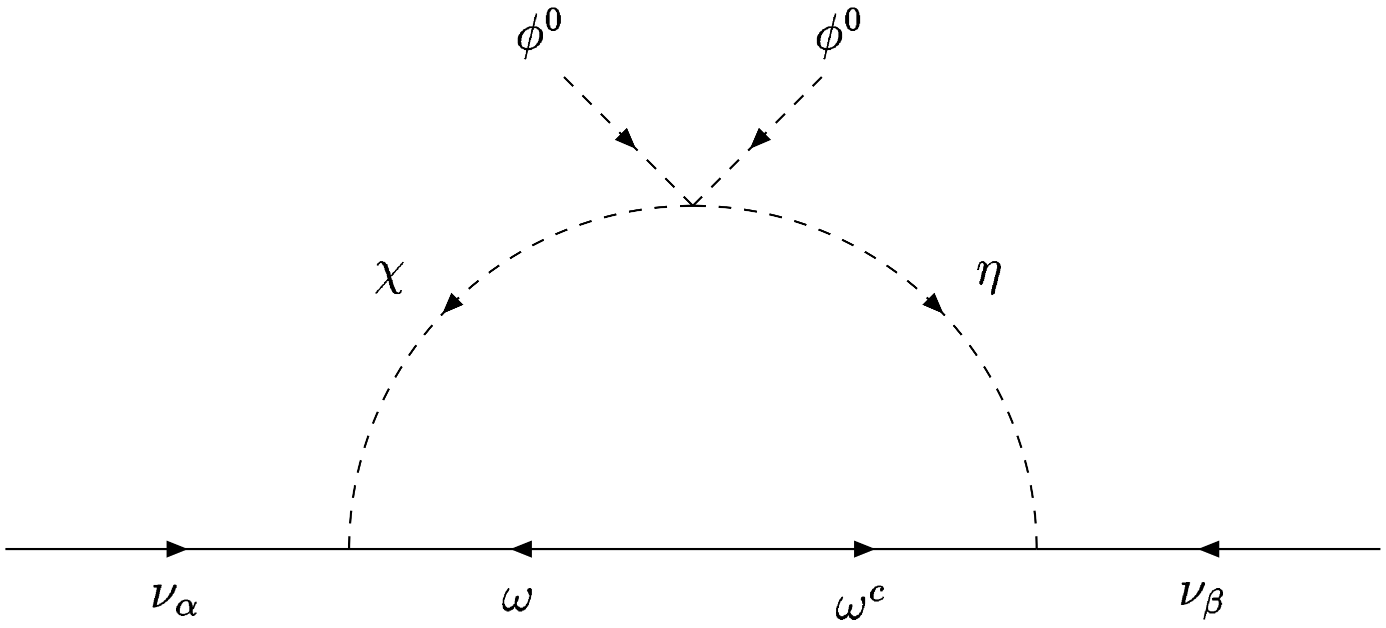
Headline news around the world: Neutrinos Have Mass!!

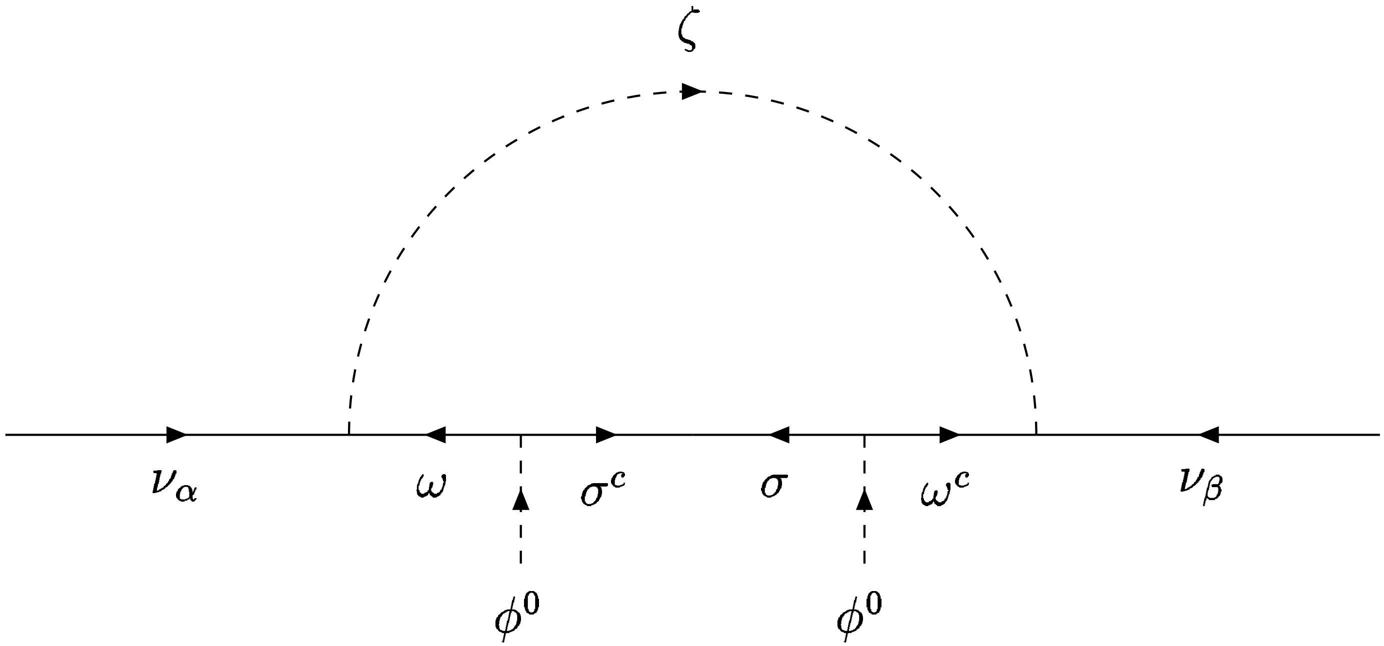
SNO (2002): Solar neutrino oscillations established.


ϕ^0
ϕ^0
ν_α
N
Σ^0
ν_β


ϕ^0
ϕ^0
ξ^0
ν_α
ν_β


ϕ^0
χ
η
ν_α
ω
ω^c
ν_β
ϕ^0


ϕ^0
ϕ^0
χ
η
ν_α
ω
ω^c
ν_β


ζ
ν_α
ω
σ^c
σ
ω^c
ν_β
ϕ^0
ϕ^0

Seesaw Variants

In this talk, I assume m_ν is Majorana and $(-)^L$ is conserved.

Next Question: What is the mass scale of the new physics? Could there be 2 or more scales?

$$m_\nu \sim \frac{f^2 v^2}{\Lambda} \sim 1 \text{ eV}$$

$$\Rightarrow \frac{\Lambda}{f^2} \sim \frac{(100 \text{ GeV})^2}{1 \text{ eV}} \sim 10^{13} \text{ GeV}.$$

If $f \sim 1$, then $\Lambda \sim 10^{13}$ GeV. This high scale is suitable for leptogenesis:

Type (I) [Fukugita/Yanagida(1986)] $N_1 \to l^\pm \phi^\mp$ at tree level interfering with one-loop (vertex and self-energy) amplitudes involving N_2 with CP violation.

Type (II) [Ma/Sarkar(1998)] $\xi_1^{\pm\pm} \to l^\pm l^\pm, \phi^\pm \phi^\pm$ at tree level interfering with a one-loop (self-energy) amplitude involving ξ_2 with CP violation.

The lepton asymmetry generated is converted by sphalerons during the electroweak phase transition to the present observed baryon asymmetry of the Universe.

On the other hand, $\Lambda \sim 1$ TeV is often arbitrarily chosen so that it may have a chance of being observed experimentally.

Impacts on seesaw variants: (I) $\nu - N$ mixing $\sim \sqrt{m_\nu/m_N} \sim 10^{-6}$ is too small to be detectable;

(II) $\xi^{++} \to l_i^+ l_j^+$ is a great signature at the Large Hadron Collider LHC and its decay branching fractions map out the relative entries of the neutrino mass matrix. [Ma/Raidal/Sarkar(2000)];

(III) $\Sigma^\pm$ has some detectable signatures as well.

(I) extended to include two neutral singlet fermions N, S:

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_2 & 0 \\ m_2 & m_N & m_1 \\ 0 & m_1 & m_S \end{pmatrix}.$$

If $m_S, m_N << m_1$, then

$$m_\nu \sim \frac{m_2^2 m_S}{m_1^2}.$$

This assumes a second mass scale for m_S, so that m_ν is small because m_S and m_2/m_1 are both small.

The above is known as the inverse seesaw [Mohapata/valle(1986)]. It is supported by the consideration of lepton number L, under which $\nu, S \sim +1$ and $N \sim -1$. Thus $m_{1,2}$ conserve L, but m_S breaks it softly by 2 units.

In this case, $\nu - N$ mixing is even smaller, i.e. $m_\nu/m_2 \sim 10^{-11}$, whereas $\nu - S$ mixing is much larger, i.e. m_2/m_1 which could be of order 0.1, and render S observable through its mixing with ν. However, the assumptions that $m_1 \sim 1$ TeV and $m_S \sim 100$ eV remain arbitrary.

The mass scale of m_1 may be associated with a gauge $U(1)$ extension of the SM, and m_S is a two-loop radiative effect [Ma(2009)]. Since that first proposal, there are now several models of radiative inverse seesaw neutrino mass.

Another approach [Fraser/Ma/Popov(2014)] is to consider the one-loop mechanism (VI), using a heavy Dirac fermion doublet $(E^0, E^-)_{L,R}$, a light Majorana fermion singlet N_L and three neutral scalar singlets $s_{1,2,3}$, all of which are odd under an exactly conserved Z_2 symmetry (more in the next section).

Radiative Seesaw from Dark Matter

Deshpande/Ma(1978): Add to the SM a second scalar doublet (η^+, η^0) which is odd under a new exactly conserved Z_2 discrete symmetry, then η^0_R or η^0_I is absolutely stable. This simple idea lay dormant for almost thirty years until Ma, Phys. Rev. D 73, 077301 (2006). It was then studied seriously in
Barbieri/Hall/Rychkov(2006),
Lopez Honorez/Nezri/Oliver/Tytgat(2007),
Gustafsson/Lundstrom/Bergstrom/Edsjo(2007), and
Cao/Ma/Rajasekaran, Phys. Rev. D 76, 095011 (2007).

Radiative Neutrino Mass:

Zee(1980): (IV)

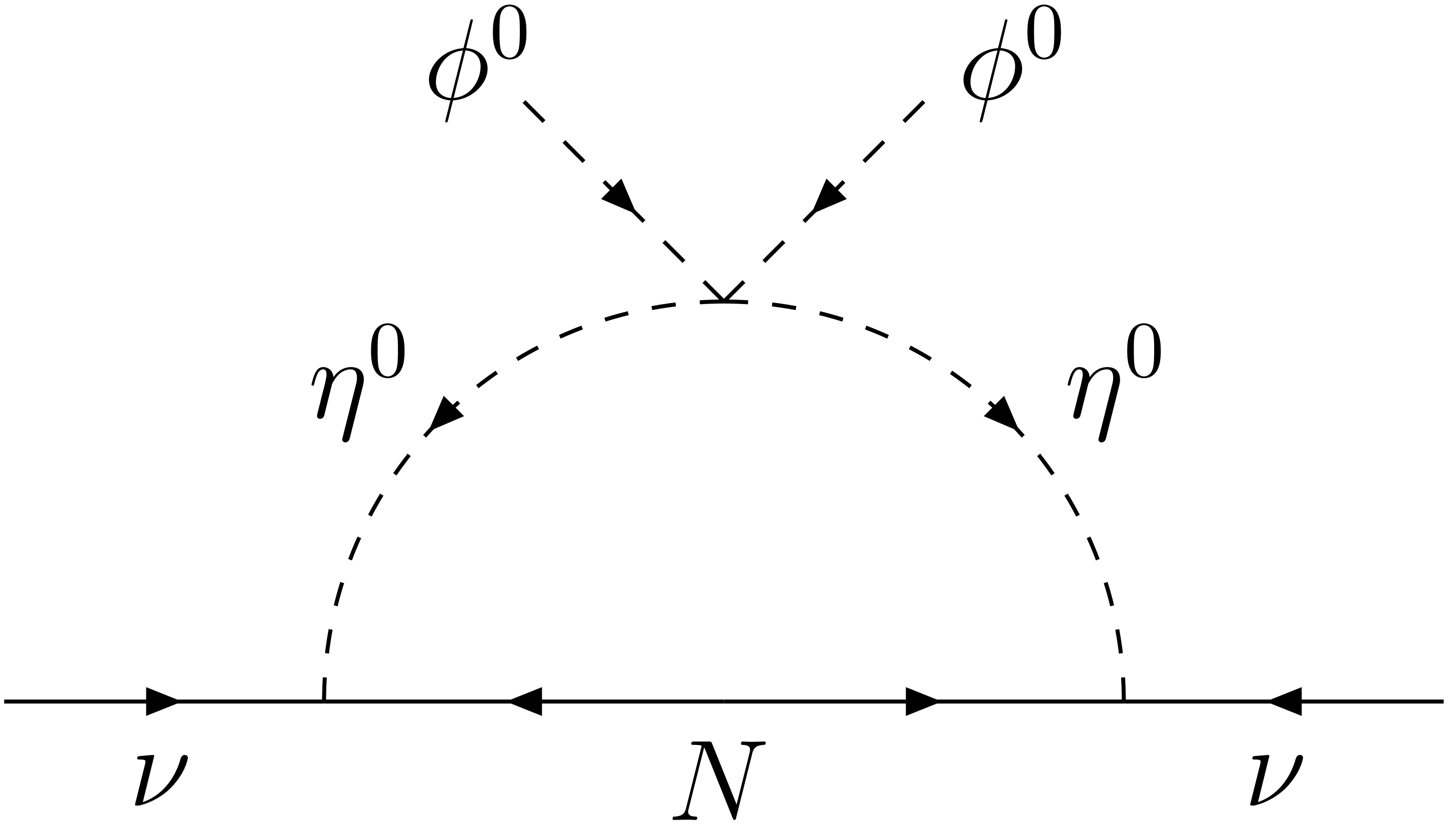
$\omega = (\nu, l), \omega^c = l^c$, $\chi = \chi^+, \eta = (\phi^+_{1,2}, \phi^0_{1,2}), \langle \phi^0_{1,2} \rangle \neq 0$.

Ma(2006): (V) [scotogenic = caused by darkness]

$\omega = \omega^c = N$ or Σ, $\chi = \eta = (\eta^+, \eta^0), \langle \eta^0 \rangle = 0$.

N or Σ interacts with ν, but they are not Dirac mass partners, because of the exactly conserved Z_2 symmetry, under which N or Σ and (η^+, η^0) are odd, and all SM particles are even. Using $f(x) = -\ln x/(1-x)$,

$$(\mathcal{M}_\nu)_{\alpha\beta} = \sum_i \frac{h_{\alpha i} h_{\beta i} M_i}{16\pi^2} [f(M_i^2/m_R^2) - f(M_i^2/m_I^2)].$$


ϕ^0
ϕ^0
η^0
η^0
ν
N
ν

The linkage of neutrino mass to dark matter provides an important clue to the scale of new physics. It is a possible answer to the **Question**: Is the new physics responsible for neutrino mass also responsible for some other phenomenon in particle physics and astrophysics? Here the answer is yes, and it is dark matter. Since dark matter is mostly assumed to be a Weakly Interacting Massive Particle (WIMP), its mass scale is reasonably set at 1 TeV. This is the crucial missing piece of information which allows us to expect observable new physics related to both dark matter and neutrino mass at the LHC.

Neutrino Flavor Symmetry

The new physics responsible for neutrino mass may also explain its mixing pattern. This has prompted a large body of theory work based on non-Abelian discrete symmetries, the first successful use of which was A_4 [Ma/Rajasekaran(2001),Babu/Ma/Valle(2003),Ma(2004)].

The impact of this idea on the Yukawa couplings of the standard model is that renormalizability requires the Higgs sector to be extended, from one Higgs doublet to at least three.

Since the 2012 measurement of a nonzero θ_{13}, tribimaximal neutrino mixing (possibly based on A_4) is clearly not valid. It may however still be a good approximation. Many studies have been made since then on how this may be implemented. As for CP violation, there is a very intriguing pattern [Grimus/Lavoura(2004)]

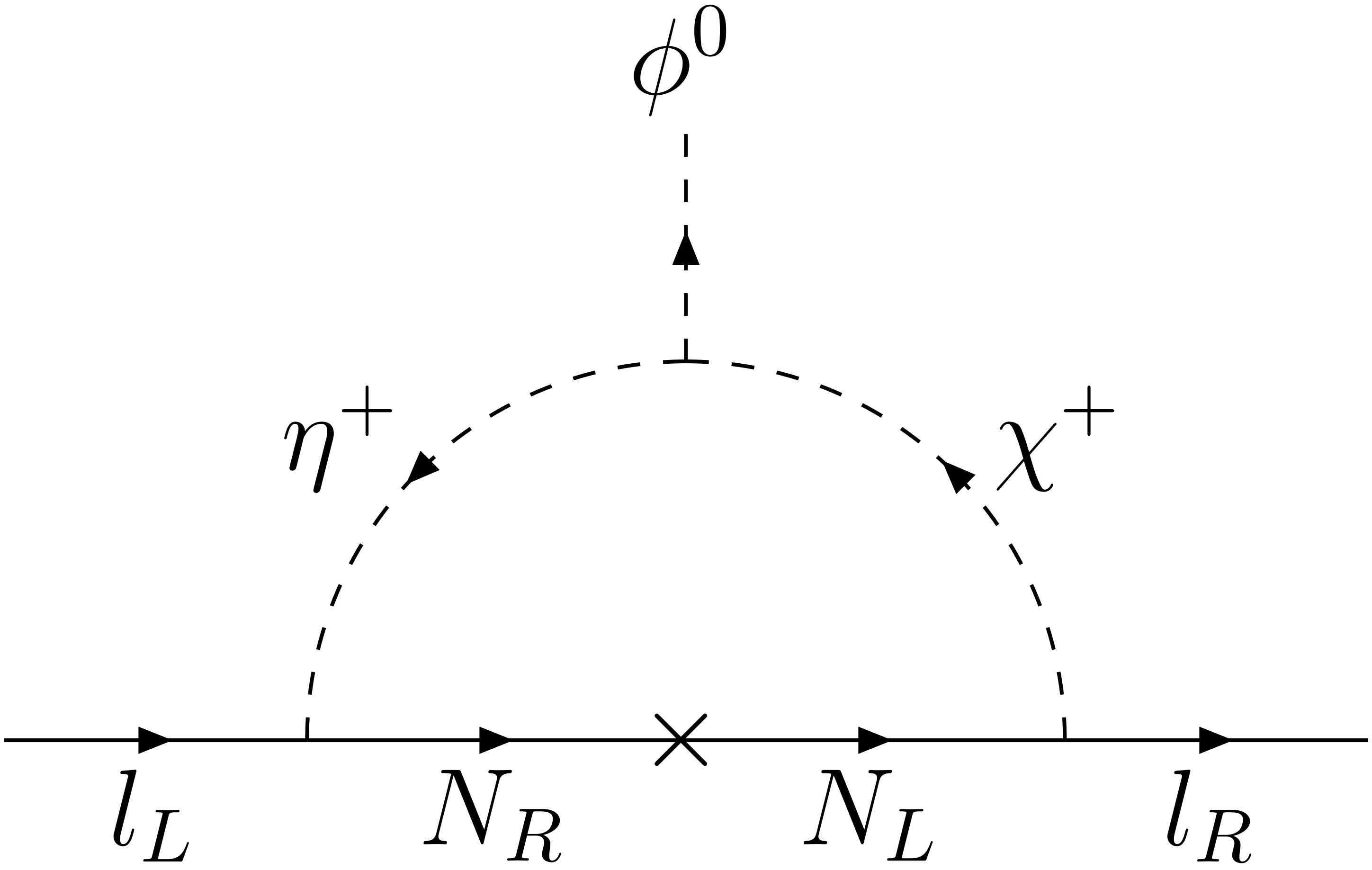
$$\mathcal{M}_\nu = \begin{pmatrix} A & C & C^* \\ C & D^* & B \\ C^* & B & D \end{pmatrix},$$

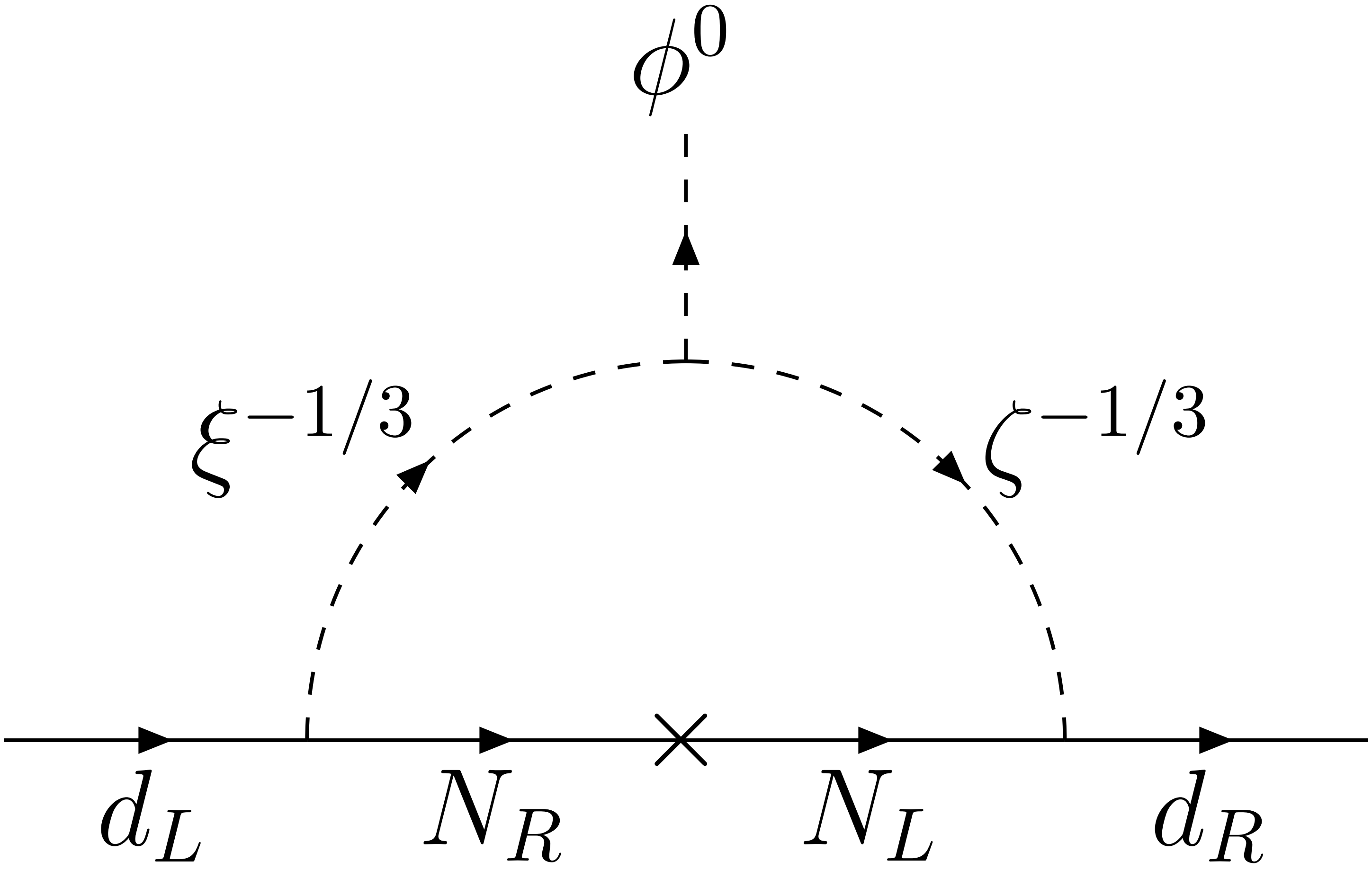
which guarantees $\theta_{23} = \pi/4$, $\theta_{13} \neq 0$, and $\exp(-i\delta_{CP}) = \pm i$, i.e. maximal CP violation.

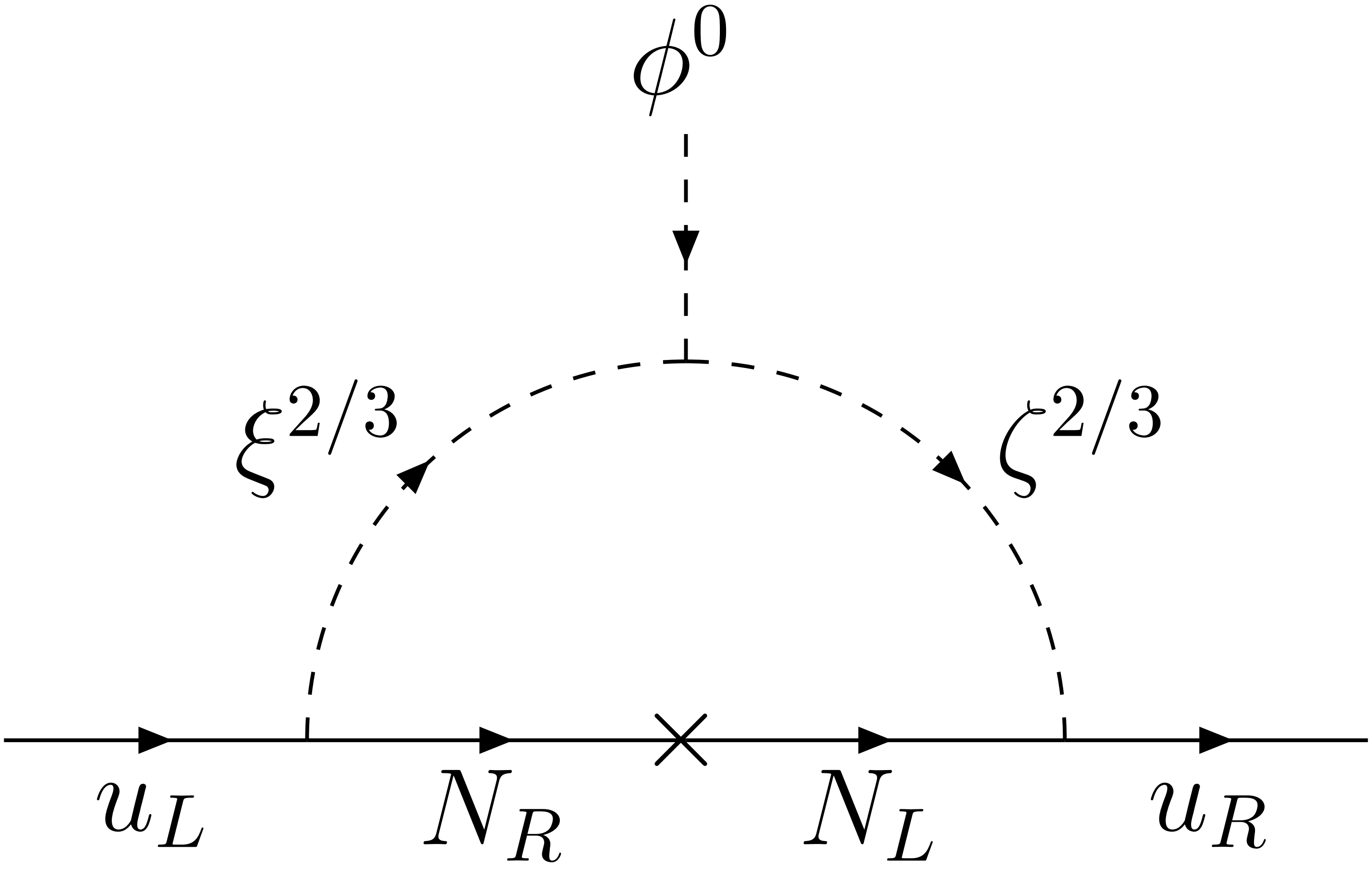
After the 2012 discovery of the 126 GeV particle at the LHC, which looks very much like the one Higgs of the standard model, and nothing else, the idea of three Higgs doublets carrying flavor is in apparent peril.

Question: What does the one Higgs really tell us?

The answer may be that flavor and dark matter are also connected and they do so through the one Higgs: [Ma, PRL 112, 091801 (2014)]. This new notion extends the scotogenic neutrino mass to all (or most) quark and lepton masses, with flavored dark matter.


ϕ^0
η^+
χ^+
l_L
N_R
N_L
l_R


ϕ^0
$\xi^{-1/3}$
$\zeta^{-1/3}$
d_L
N_R
N_L
d_R


ϕ^0
$\xi^{2/3}$
$\zeta^{2/3}$
u_L
N_R
N_L
u_R

The dark-matter singlet neutral fermions $N_{1,2,3}$ carry flavor and their mixing pattern gets transmitted to the quarks, leptons, and neutrinos. Since flavor is organized through them, the production of scalar quarks, then $\tilde{q} \to q_{1,2} N_{1,2}$ with $N_2 \to \eta/\chi + \mu^\pm$ and $\eta/\chi \to N_1 e^\mp$ will result in 2 jets $+ \mu^\pm + e^\mp +$ missing energy at the LHC.

The fermion couplings of the 126 GeV particle also differs from the SM prediction of m_f/v [Fraser/Ma(2014)]. Consider the specific case of scotogenic lepton mass. The doublet (η^+, η^0) and singlet χ^+ mix through the term $\mu(\eta^+\phi^0 - \eta^0\phi^+)\chi^-$, where $\langle\phi^0\rangle = v/\sqrt{2}$.

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

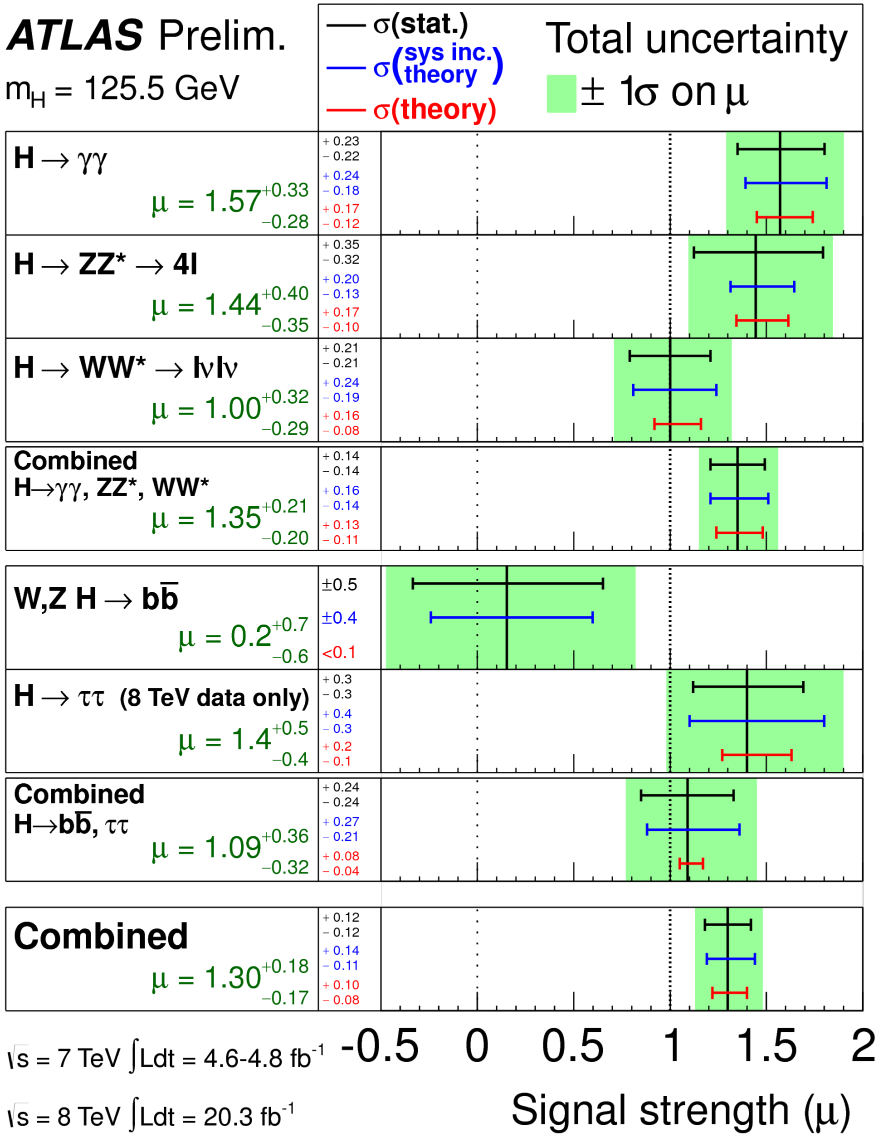
The Yukawa coupling of h to $\bar{l}l$ is now not exactly equal to m_l/v. It has three contributions, through $\eta^+\eta^-$, $\chi^+\chi^-$, and $\eta^\pm\chi^\mp$. Let $r_{\eta,\chi} = \lambda_{\eta,\chi} v^2/m_N^2$, then

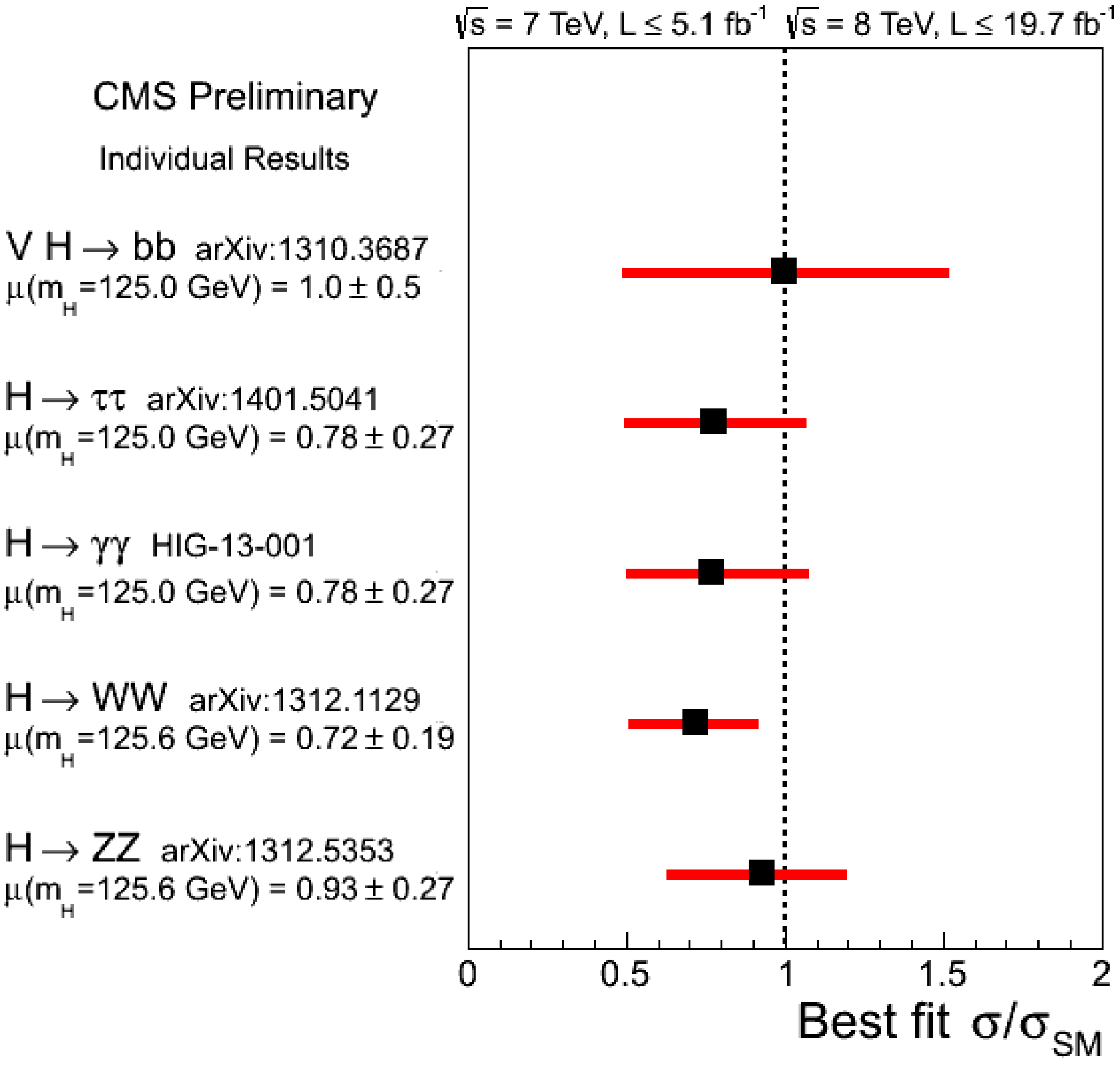
$$f_l v/m_l = 1 + a_+ F_+ + a_- F_-,$$

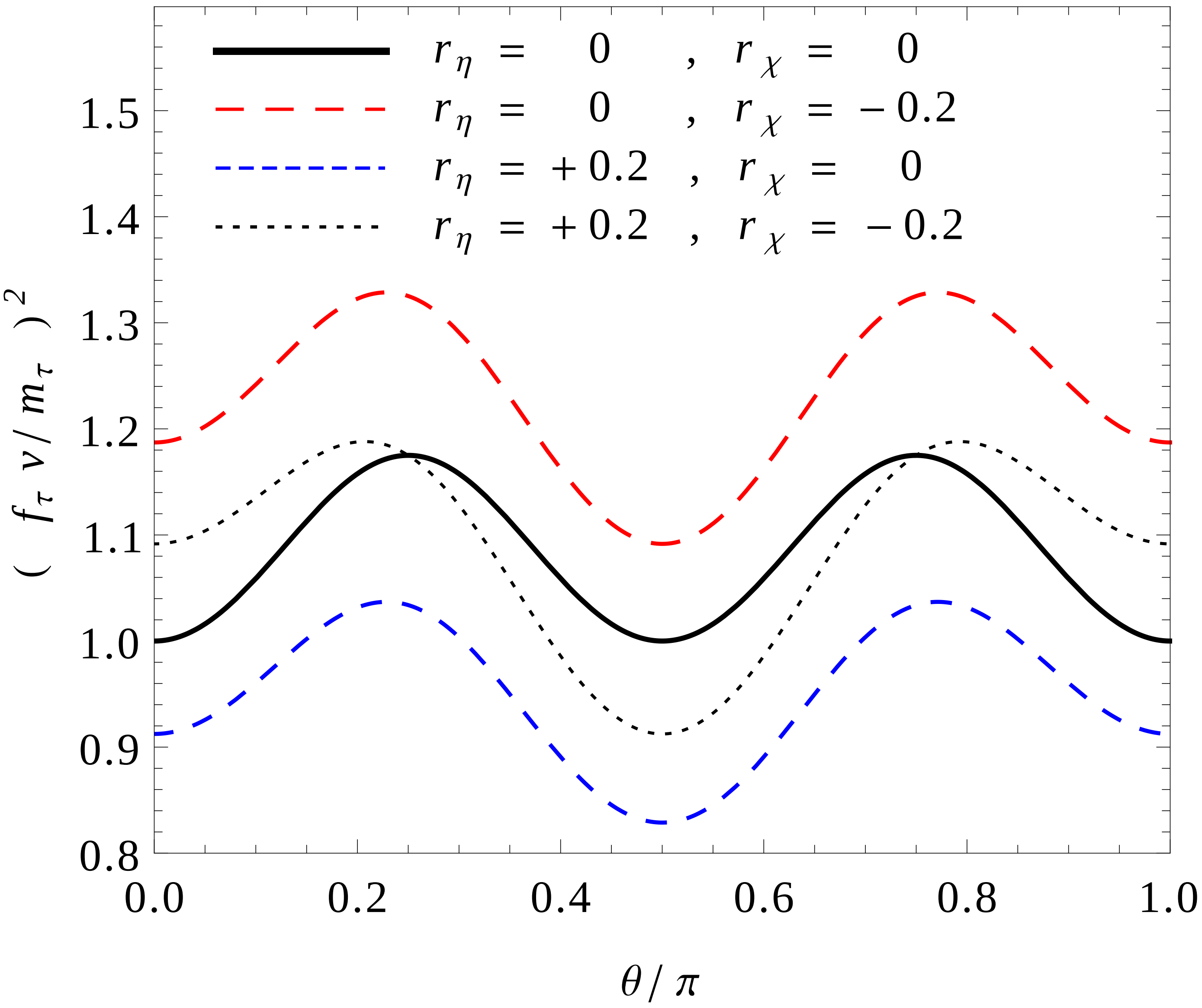
where $a_+ = (\sin 2\theta)^2/2 + \cos 2\theta(r_\eta - r_\chi)/(x_1 - x_2)$,
$a_- = (r_\eta + r_\chi)/(x_1 - x_2)$, and
$F_+ = [F(x_1, x_1) + F(x_2, x_2)]/2F(x_1, x_2) - 1$,
$F_- = [F(x_1, x_1) - F(x_2, x_2)]/2F(x_1, x_2)$, with

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

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


ATLAS Prelim.
m_H = 125.5 GeV
σ(stat.)
σ(sys inc. theory)
σ(theory)
Total uncertainty
± 1σ on μ
H → γγ
μ = 1.57 +0.33 −0.28
+0.23 −0.22
+0.24 −0.18
+0.17 −0.12
H → ZZ* → 4l
μ = 1.44 +0.40 −0.35
+0.35 −0.32
+0.20 −0.13
+0.17 −0.10
H → WW* → lνlν
μ = 1.00 +0.32 −0.29
+0.21 −0.21
+0.24 −0.19
+0.16 −0.08
Combined H→γγ, ZZ*, WW*
μ = 1.35 +0.21 −0.20
+0.14 −0.14
+0.16 −0.14
+0.13 −0.11
W,Z H → bb̄
μ = 0.2 +0.7 −0.6
±0.5
±0.4
<0.1
H → ττ (8 TeV data only)
μ = 1.4 +0.5 −0.4
+0.3 −0.3
+0.4 −0.3
+0.2 −0.1
Combined H→bb̄, ττ
μ = 1.09 +0.36 −0.32
+0.24 −0.24
+0.27 −0.21
+0.08 −0.04
Combined
μ = 1.30 +0.18 −0.17
+0.12 −0.12
+0.14 −0.11
+0.10 −0.08
√s = 7 TeV ∫Ldt = 4.6-4.8 fb⁻¹
√s = 8 TeV ∫Ldt = 20.3 fb⁻¹
-0.5
0
0.5
1
1.5
2
Signal strength (μ)


√s = 7 TeV, L ≤ 5.1 fb⁻¹ √s = 8 TeV, L ≤ 19.7 fb⁻¹
CMS Preliminary
Individual Results
V H → bb arXiv:1310.3687
μ(m_H=125.0 GeV) = 1.0 ± 0.5
H → ττ arXiv:1401.5041
μ(m_H=125.0 GeV) = 0.78 ± 0.27
H → γγ HIG-13-001
μ(m_H=125.0 GeV) = 0.78 ± 0.27
H → WW arXiv:1312.1129
μ(m_H=125.6 GeV) = 0.72 ± 0.19
H → ZZ arXiv:1312.5353
μ(m_H=125.6 GeV) = 0.93 ± 0.27
0
0.5
1
1.5
2
Best fit σ/σ_SM


$r_\eta = 0 \ , \ r_\chi = 0$
$r_\eta = 0 \ , \ r_\chi = -0.2$
$r_\eta = +0.2 \ , \ r_\chi = 0$
$r_\eta = +0.2 \ , \ r_\chi = -0.2$
$(f_\tau v/m_\tau)^2$
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.0
0.2
0.4
0.6
0.8
1.0
θ/π

Conclusion

Neutrino theory attempts to answer several fundamental questions, but there are many possible answers, some more motivated than others. Foremost is the scale of new physics responsible for neutrino mass and mixing.

A possible hint is that they may also be connected to dark matter at the mass scale of 1 TeV. If so, its impact is verifiable in the near future at the LHC.