Neutrino Mass Seesaw Version 3 : Recent Developments

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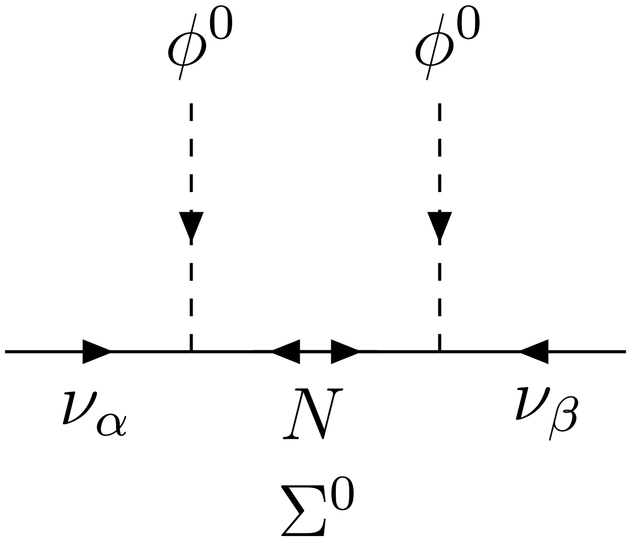
Contents

Neutrino Mass: Six Generic Mechanisms

Weinberg(1979): Unique dimension-five operator for Majorana neutrino mass in the standard model (SM):

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

Ma(1998): Three tree-level realizations:
(I) fermion singlet N, (II) scalar triplet (ξ^{++}, ξ^+, ξ^0),
(III) fermion triplet $(\Sigma^+, \Sigma^0, \Sigma^-)$
[Foot/Lew/He/Joshi(1989)];
and three generic one-loop realizations (IV), (V), (VI).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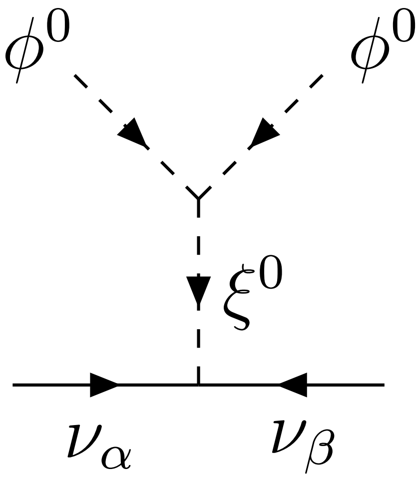
ϕ^0
ν_α
N
ν_β
Σ^0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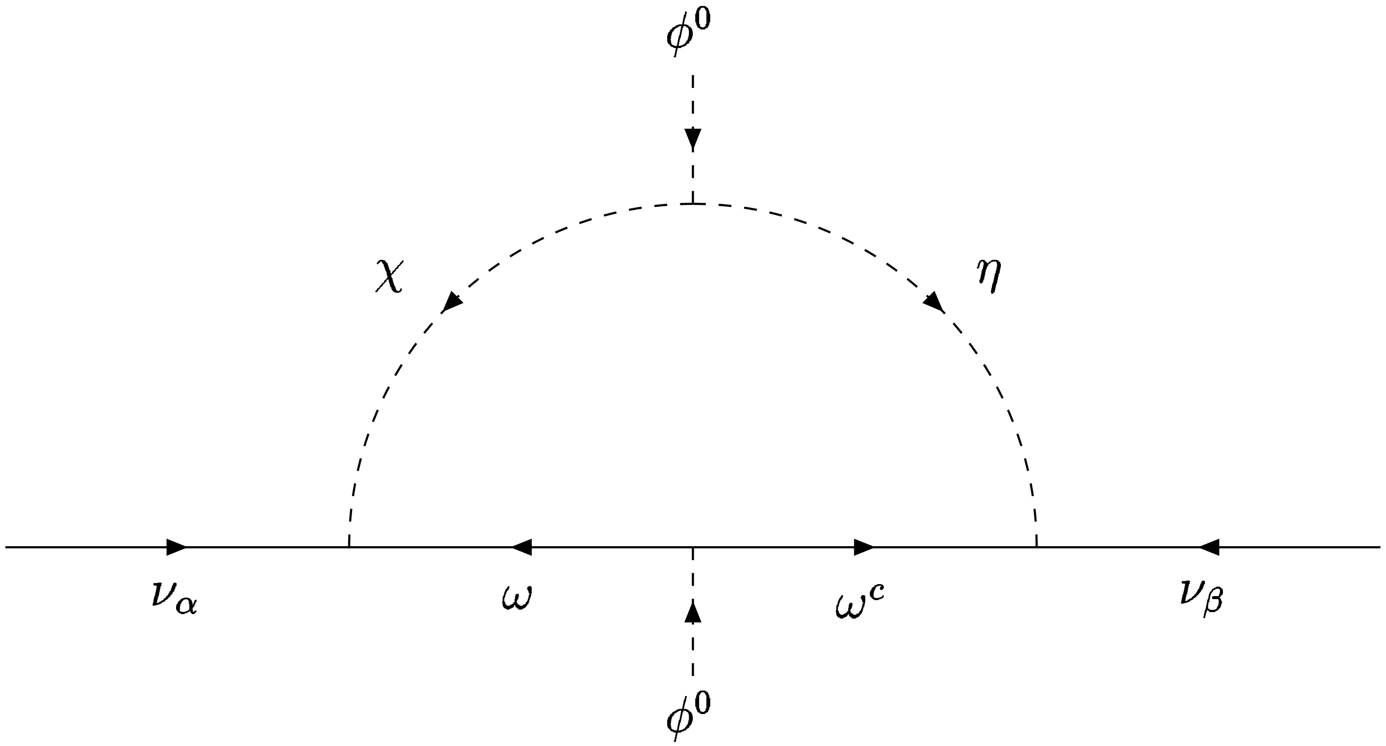
ϕ^0
ξ^0
ν_α
ν_β


ϕ^0
χ
η
ν_α
ω
ω^c
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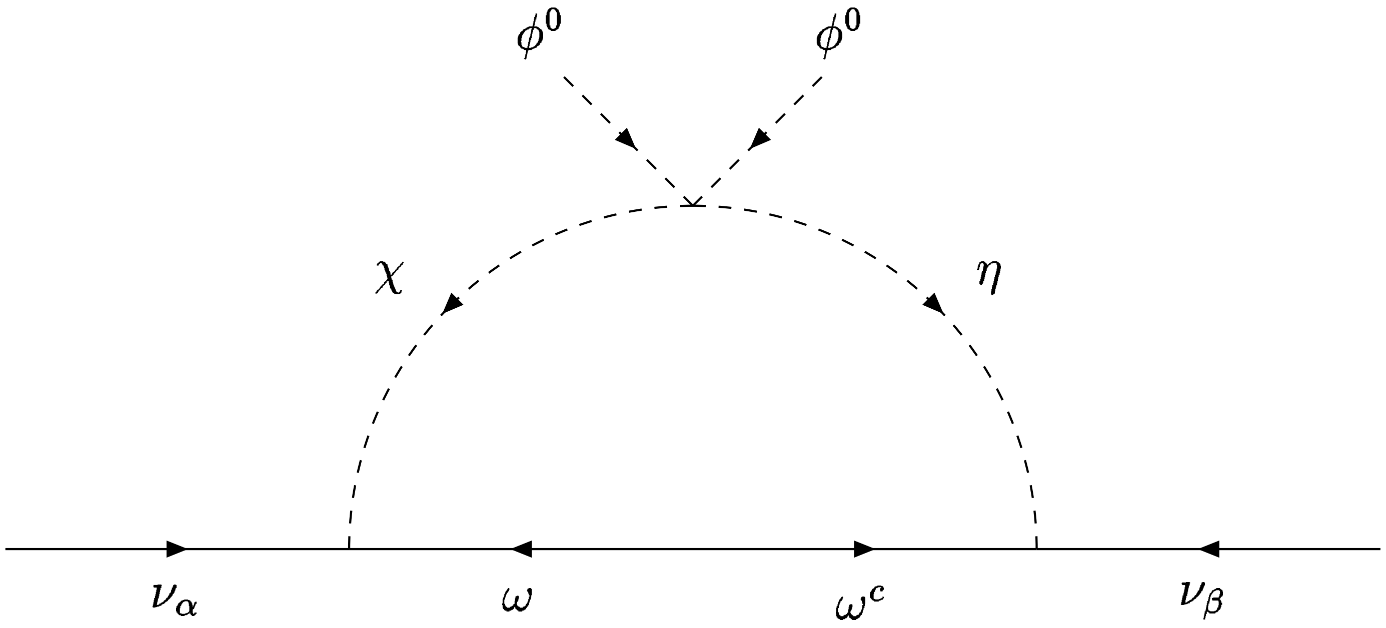
ϕ^0


ϕ^0
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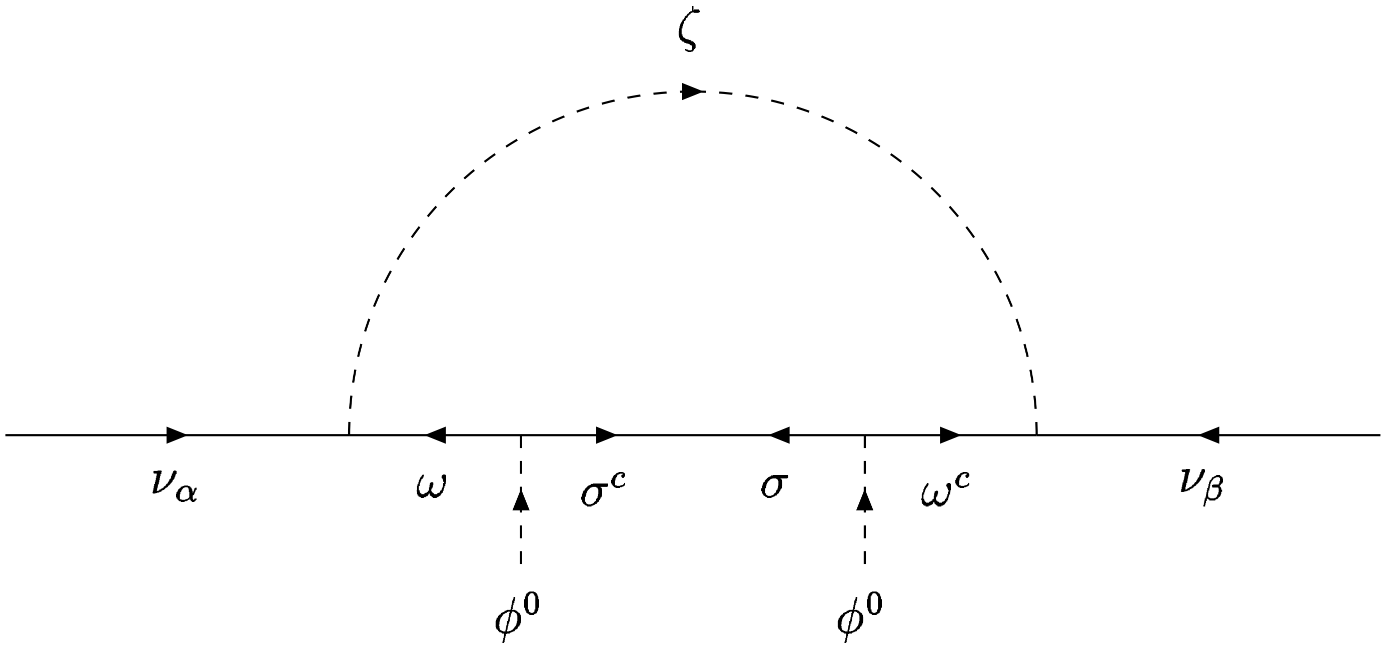

ζ
ν_α
ω
σ^c
σ
ω^c
ν_β
ϕ^0
ϕ^0

Gauge Coupling Unification

It is well-known that gauge-coupling unification occurs for the minimal supersymmetric standard model (MSSM) but not the SM. The difference can be traced to the addition of gauginos and higgsinos, transforming under $SU(3)_C \times SU(2)_L \times U(1)_Y$ as (8,1,0), (1,3,0), (1,2,$\pm$1/2), and a second Higgs scalar doublet. Note that the fermion triplet (1,3,0) is what makes the $SU(2)_L$ and $U(1)_Y$ couplings meet at high enough an energy scale to be acceptable for suppressing proton decay.

The one-loop renormalization-group equations for the evolution of gauge couplings between M_1 and M_2 are

$$\alpha_i(M_1)^{-1} - \alpha_i(M_2)^{-1} = (b_i/2\pi)\ln(M_2/M_1),$$

where $\alpha_i = g_i^2/4\pi$, and the numbers b_i are determined by the particle content of the model. In the SM, these are
$SU(3)_C \ : \ b_C = -11 + (4/3)N_f = -7$,
$SU(2)_L \ : \ b_L = -22/3 + (4/3)N_f + 1/6 = -19/6$,
$U(1)_Y \ : \ b_Y = (4/3)N_f + 1/10 = 41/10$, where $N_f = 3$ is the number of families and unification means
$\alpha_C(M_U) = \alpha_L(M_U) = (5/3)\alpha_Y(M_U) = \alpha_U$.

Using the input $\alpha_C(M_Z) = 0.122$, $\alpha_L(M_Z) = 0.0340$, $\alpha_Y(M_Z) = 0.0102$, it is easy to check that gauge couplings do not unify in the SM.

Model	$b_Y - b_L$	$b_L - b_C$	new fermions	new scalars
SM	7.27	3.83	none	none
MSSM	5.60	4.00	(1,3,0),(8,1,0) (1,2,$\pm$1/2)	(1,2,1/2)
m05	5.27	3.83	(1,3,0)	(1,3,0)$\times$2 (8,1,0)$\times$4
bs07	5.60	3.00	(1,3,0), (8,1,0)	(1,3,0) (8,1,0)

If all particles transforming under $SU(2)_L \times U(1)_Y$ are at the electroweak scale, then $\ln(M_U/M_Z) \simeq \sqrt{2}\pi^2[(3/5\tan^2\theta_W) - 1]/G_F M_W^2(b_Y - b_L)$.
Hence $M_U > 10^{16}$ GeV $\Rightarrow b_Y - b_L < 5.7$.
Ma(2005): all new particles $\sim$ TeV.
Bajc/Senjanovic(2007): color octets $\sim 10^8$ GeV.
Instead of just one $(\Sigma^+, \Sigma^0, \Sigma^-)$ fermion triplet, let there be three copies at an intermediate scale M_I, then gauge-coupling unification $\sim 10^{16}$ GeV $\Rightarrow M_I \sim 10^{10}$ GeV, which is also the right scale for leptogenesis through the decay of the lightest Σ [Fischler/Flauger(2008)].

LHC Phenomenology

If Σ exists at the TeV scale, it may be probed at the LHC. Its production is by pairs from quark fusion via the electroweak gauge bosons with a cross section of the order 1 fb for m_Σ of about 1 TeV, and rising to more than 10^2 fb if m_Σ is 300 GeV. The mass splitting between Σ^0 and $\Sigma^\pm$ is radiative and comes from electroweak gauge interactions. For large m_Σ, it is about 168 MeV, thus allowing $\Sigma^\pm \to \Sigma^0 \pi^\pm$ and $\Sigma^0 l^\pm \nu$. The dominant decays are however $\Sigma^\pm \to \nu W^\pm, l^\pm Z(h)$ and $\Sigma^0 \to l^\pm W^\mp, \nu Z(h)$ unless a symmetry forbids them.

del Aguila/Aguilar-Saavedra(2008):

final state	m_N(100 GeV)	m_ξ(300 GeV)	m_Σ(300 GeV)
6 leptons	–	–	×
5 leptons	–	–	28 fb^{-1}
$l^\pm l^\pm l^\pm l^\mp$	–	–	15 fb^{-1}
$l^+ l^+ l^- l^-$	–	19 fb^{-1}	7 fb^{-1}
$l^\pm l^\pm l^\pm$	–	–	30 fb^{-1}
$l^\pm l^\pm l^\mp$	< 180 fb^{-1}	3.6 fb^{-1}	2.5 fb^{-1}
$l^\pm l^\pm$	< 180 fb^{-1}	17.4 fb^{-1}	1.7 fb^{-1}
$l^+ l^-$	×	15 fb^{-1}	80 fb^{-1}
$l^\pm$	×	×	×

New U(1) Gauge Symmetry

Ma(2002) : Consider

$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_X$ with

$(u,d)_L \sim (3,2,1/6;n_1)$, $u_R \sim (3,1,2/3;n_2)$,

$d_R \sim (3,1,-1/3;n_3)$, $(\nu,e)_L \sim (1,2,-1/2;n_4)$,

$e_R \sim (1,1,-1;n_5)$, $\Sigma \sim (1,3,0;n_6)$.

Absence of the axial-vector anomaly requires

$[SU(3)]^2 U(1)_X$: $2n_1 - n_2 - n_3 = 0$.

$[U(1)_Y]^2 U(1)_X$: $n_1 - 8n_2 - 2n_3 + 3n_4 - 6n_5 = 0$.

$U(1)_Y [U(1)_X]^2$: $n_1^2 - 2n_2^2 + n_3^2 - n_4^2 + n_5^2 =$

$(3n_1 + n_4)(7n_1 - 4n_2 - 3n_4)/4 = 0$.

$n_4 = -3n_1 \Rightarrow U(1)_Y$, so $n_2 = (7n_1 - 3n_4)/4$ will be assumed from now on. In that case, $n_3 = (n_1 + 3n_4)/4$ and $n_5 = (-9n_1 + 5n_4)/4$.

$[SU(2)]^2 U(1)_X : 3n_1 + n_4 - 4n_6 = 0.$

Mixed gravitational-gauge anomaly $U(1)_X$:

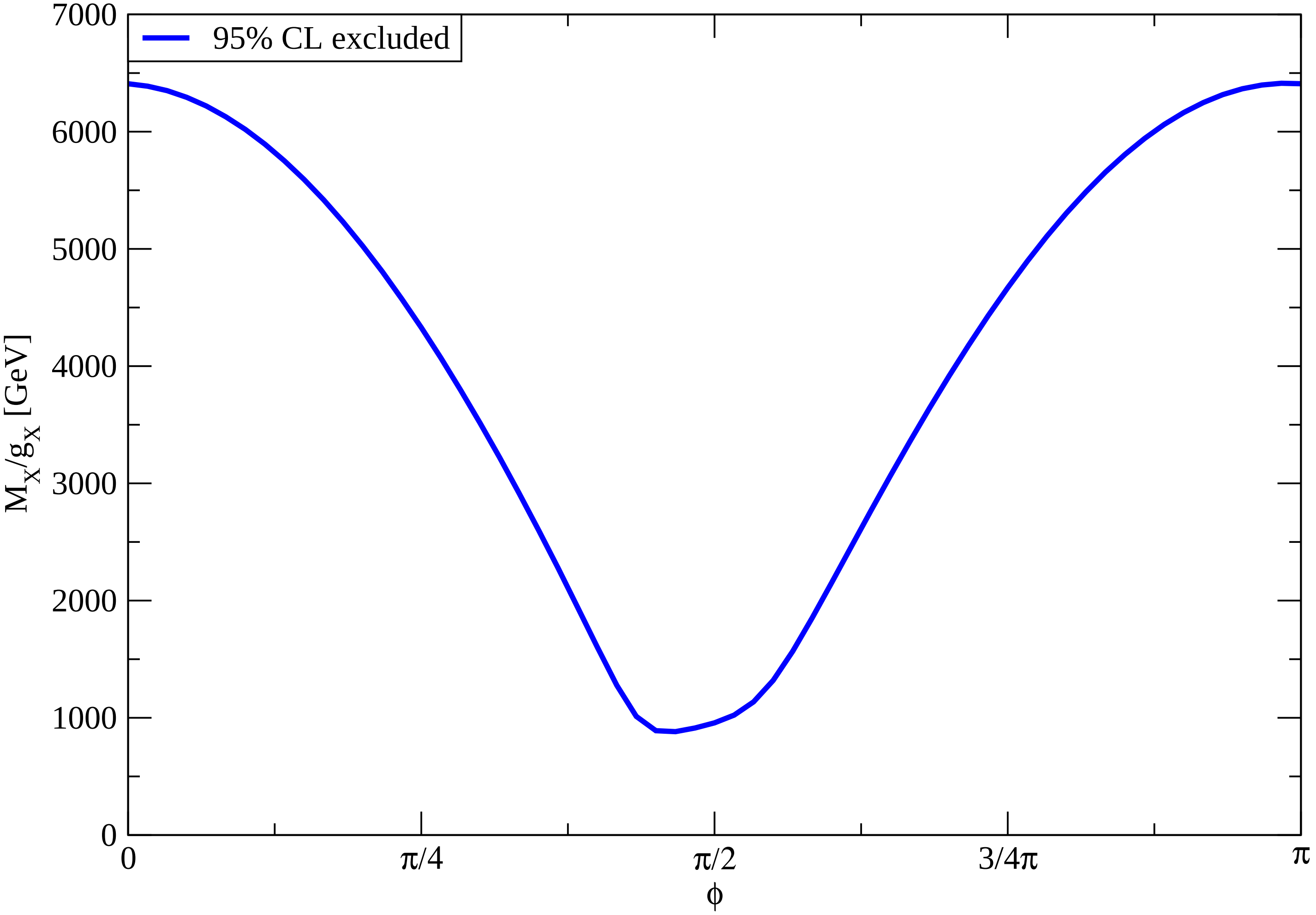
$6n_1 - 3n_2 - 3n_3 + 2n_4 - n_5 - 3n_6 = 3(3n_1 + n_4 - 4n_6)/4 = 0.$

$[U(1)_X]^3 : 6n_1^3 - 3n_2^3 - 3n_3^3 + 2n_4^3 - n_5^3 - 3n_6^3 = 3(3n_1 + n_4)^3/64 - 3n_6^3 = 0.$

Hence $n_6 = (3n_1 + n_4)/4$ satisfies all 3 conditions. If a fermion multiplet $(1, 2p+1, 0; n_6)$ is used, the only solutions are $p = 0$ $[U(1)_{B-L}]$ and $p = 1$ $[U(1)_X]$.

The scalar sector of this $U(1)_X$ model consists of two Higgs doublets (ϕ_1^+, ϕ_1^0) with charge $(9n_1 - n_4)/4$ which couples to charged leptons, and (ϕ_2^+, ϕ_2^0) with charge $(3n_1 - 3n_4)/4$ which couples to up and $down$ quarks as well as to Σ. To break the $U(1)_X$ gauge symmetry spontaneously, a singlet χ with charge $-2n_6$ is added, which also allows the Σ's to acquire Majorana masses at the $U(1)_X$ breaking scale.

Adhikari/Erler/Ma(2008): The new gauge boson X may be accessible at the LHC. Its decay branching ratios could determine the parameter $r = n_4/n_1 = \tan\phi$.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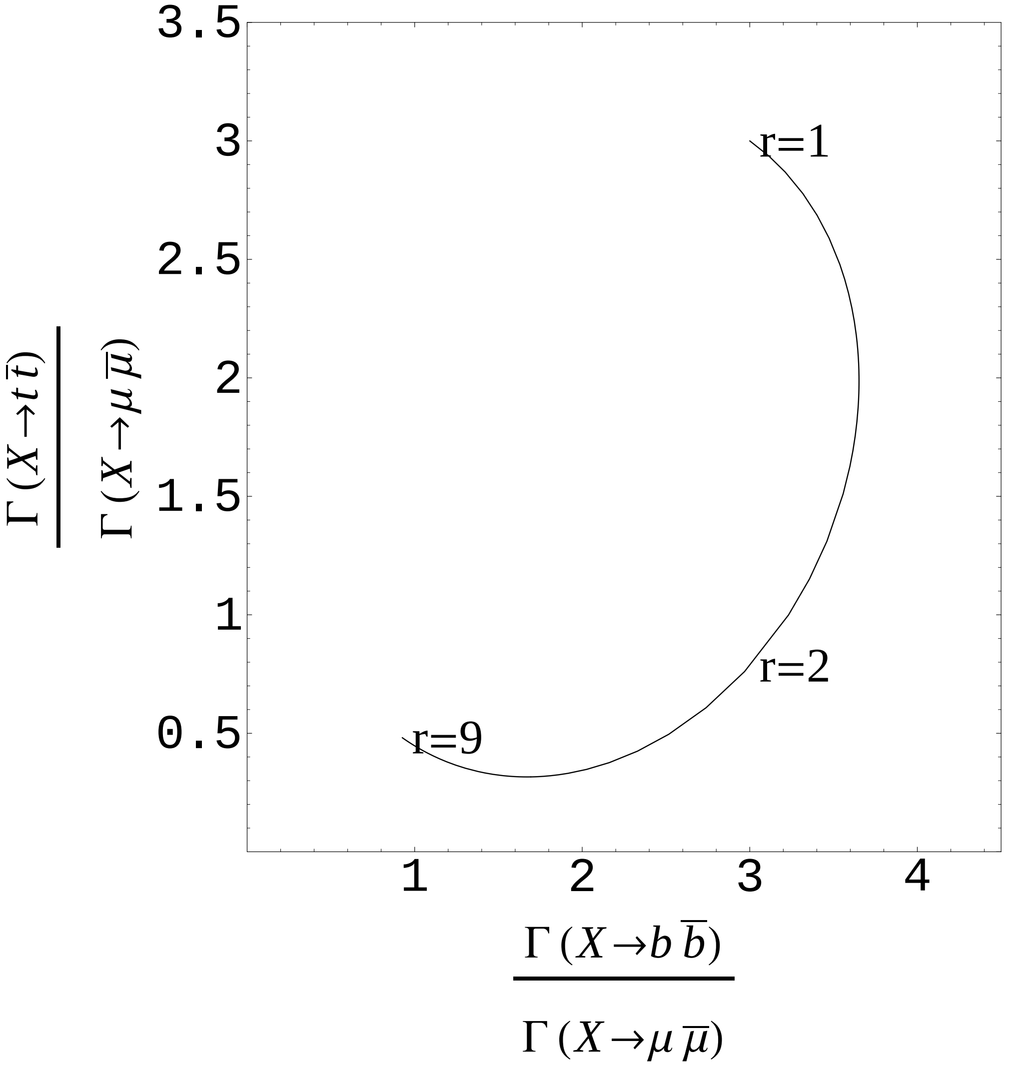
6000
5000
4000
3000
2000
1000
0
M_X/g_X [GeV]
0
π/4
π/2
3/4π
π
ϕ


3.5
3
2.5
2
1.5
1
0.5
1
2
3
4
r=1
r=2
r=9
$\frac{\Gamma(X\to t\bar{t})}{\Gamma(X\to\mu\bar{\mu})}$
$\frac{\Gamma(X\to b\bar{b})}{\Gamma(X\to\mu\bar{\mu})}$

Scotogenic Radiative Neutrino Mass

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_R^0 or η_I^0 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)

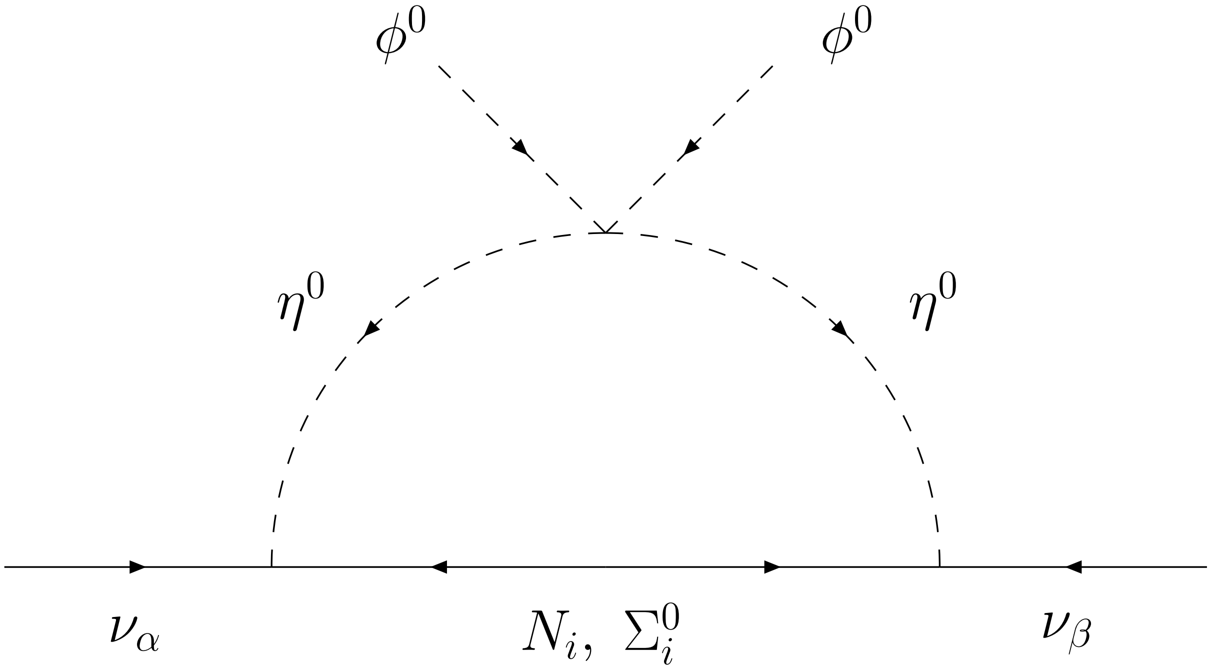
$\omega = (\nu, l), \omega^c = l^c$, $\chi = \chi^+, \eta = (\phi^+_{1,2}, \phi^0_{1,2}), \langle \phi^0_{1,2} \rangle \neq 0$.

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_α
$N_i,\ \Sigma_i^0$
ν_β

Fermion Triplet Dark Matter

If η_R^0 or η_I^0 is dark matter, then its mass is 45 to 75 GeV. If N is dark matter, then all masses are of order 350 GeV or less, and its Yukawa couplings have to be large [Kubo/Ma/Suematsu(2006)], in which case flavor-changing radiative decays such as $\mu \to e\gamma$ are too big without some rather delicate fine tuning. Ma/Suematsu(2008): Use radiative seesaw version 3, then Σ^0 is a better dark-matter candidate because, unlike N, it has gauge interactions.

Since $\Sigma^{\pm}$ is naturally just 168 MeV heavier than Σ^{0}, coannihilation is an important mechanism for obtaining the correct dark-matter relic abundance. Using

$$\sigma(\Sigma^0\Sigma^0)|v| \simeq 2\pi\alpha_L^2/m_\Sigma^2, \quad \sigma(\Sigma^\pm\Sigma^\pm)|v| \simeq \pi\alpha_L^2/m_\Sigma^2,$$

$$\sigma(\Sigma^+\Sigma^-)|v| \simeq 37\pi\alpha_L^2/m_\Sigma^2, \quad \sigma(\Sigma^0\Sigma^\pm)|v| \simeq 29\pi\alpha_L^2/m_\Sigma^2,$$

m_Σ is estimated to be in the range 2.28 to 2.42 TeV to reproduce the observed data $\Omega h^2 = 0.11 \pm 0.006$ for its relic abundance. The Yukawa couplings of Σ may now be appropriately small, not to upset the experimental constraints from flavor-changing radiative decays.

Σ as lepton and N as baryon:

Assuming neutrino mass seesaw version 3, Σ should then be considered a lepton triplet. In that case, the fermion singlet N may in fact be reassigned as a baryon. The crucial missing link is a scalar diquark $\tilde{h} \sim (3, 1, -1/3)$ with baryon number $B = -2/3$, so that $ud\tilde{h}$, $u^c d^c \tilde{h}^*$, and $d^c N \tilde{h}$ are allowed. Thus N has $B = 1$, but since it is a gauge singlet, it is also allowed a large Majorana mass. Hence additive B breaks to multiplicative $(-)^{3B}$ and the decays of the lightest N would produce a baryon asymmetry of the Universe, in analogy to leptogenesis.

Conclusion

Using the fermion triplet $(\Sigma^+, \Sigma^0, \Sigma^-)$ as the seesaw anchor for neutrino masses (version 3), many new and interesting possibilities of physics beyond the SM exist.

(1) It may be the missing link for gauge-coupling unification in the SM without going to the MSSM.
(2) It is easier to detect at the LHC than N.
(3) It may be associated with a new U(1) gauge boson.
(4) It may be the source of radiative neutrino masses.
(5) It may be dark matter with a mass around 2.35 TeV.