Common Origin of Neutrino Mass and Dark Matter

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Contents

Introduction

Physics Beyond the Standard Model (SM) should include neutrino mass and dark matter (DM).

Are they related?

In this talk, I propose that neutrino mass is due to the existence of dark matter. I will discuss some recent models and their phenomenological consequences.

A candidate for dark matter should be neutral and stable, the latter implying at least an exactly conserved odd-even symmetry (Z_2).

In the MSSM, the lightest neutral particle having odd R parity is a candidate. It is usually assumed to be a fermion, i.e. the lightest neutralino. The lightest neutral boson, presumably a scalar neutrino, is excluded by direct search experiments because the elastic cross section for $\tilde{\nu}q \to \tilde{\nu}q$ via Z exchange is too big by 8 to 9 orders of magnitude.

Suppose we take the SM instead and add to it by hand a second scalar doublet (η^+, η^0) which is odd under Z_2 with all SM particles even. This is then a simple DM scenario.

(η^+, η^0) differs from the scalar MSSM $(\tilde{\nu}, \tilde{l})$ doublet, because η_R^0 and η_I^0 are split in mass by the Z_2 conserving term $(\lambda_5/2)(\Phi^\dagger \eta)^2 + H.c.$ which is absent in the MSSM.

Since $(\eta^0)^* \partial_\mu \eta^0 - \eta^0 \partial_\mu (\eta^0)^* = i(\eta_R^0 \partial_\mu \eta_I^0 - \eta_I^0 \partial_\mu \eta_R^0)$, the interaction $\eta_R^0 q \to \eta_I^0 q$ via Z exchange is forbidden by phase space if η_I^0 is heavier than η_R^0 by about 1 MeV.

The elastic interaction $\eta_R^0 q \to \eta_R^0 q$ via SM Higgs exchange exists at about 2 orders of magnitude below present bounds, but is within reach of future direct search experiments.

Neutrino Mass: Six Generic Mechanisms

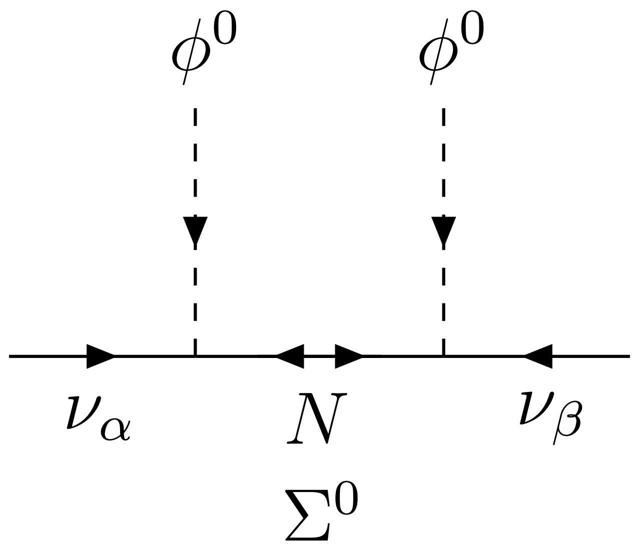
Weinberg(1979):

Unique dimension-five operator for Majorana neutrino mass in SM:

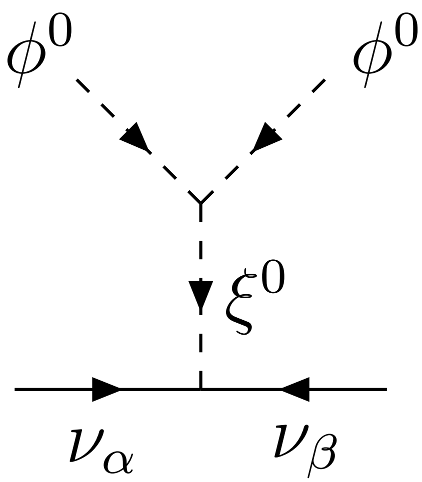
$$\frac{f_{\alpha\beta}}{2\Lambda}(\nu_\alpha\phi^0 - l_\alpha\phi^+)(\nu_\beta\phi^0 - l_\beta\phi^+).$$

Ma(1998):

Three tree-level realizations: (I) N, (II) (ξ^{++},ξ^+,ξ^0), (III) $(\Sigma^+,\Sigma^0,\Sigma^-)$; and three generic one-loop realizations: (IV), (V), (VI).



ϕ^0
ϕ^0
ν_α
N
Σ^0
ν_β



ϕ^0
ϕ^0
ξ^0
ν_α
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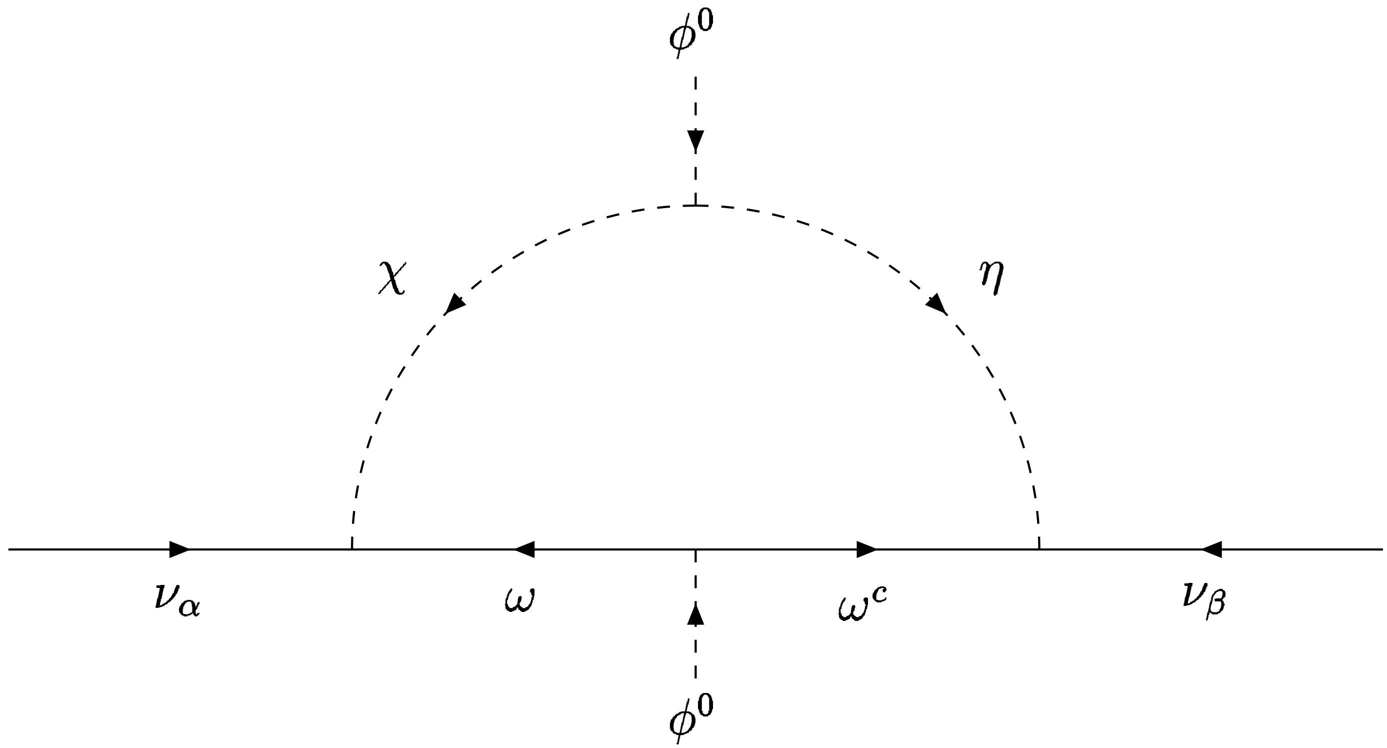

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ω^c
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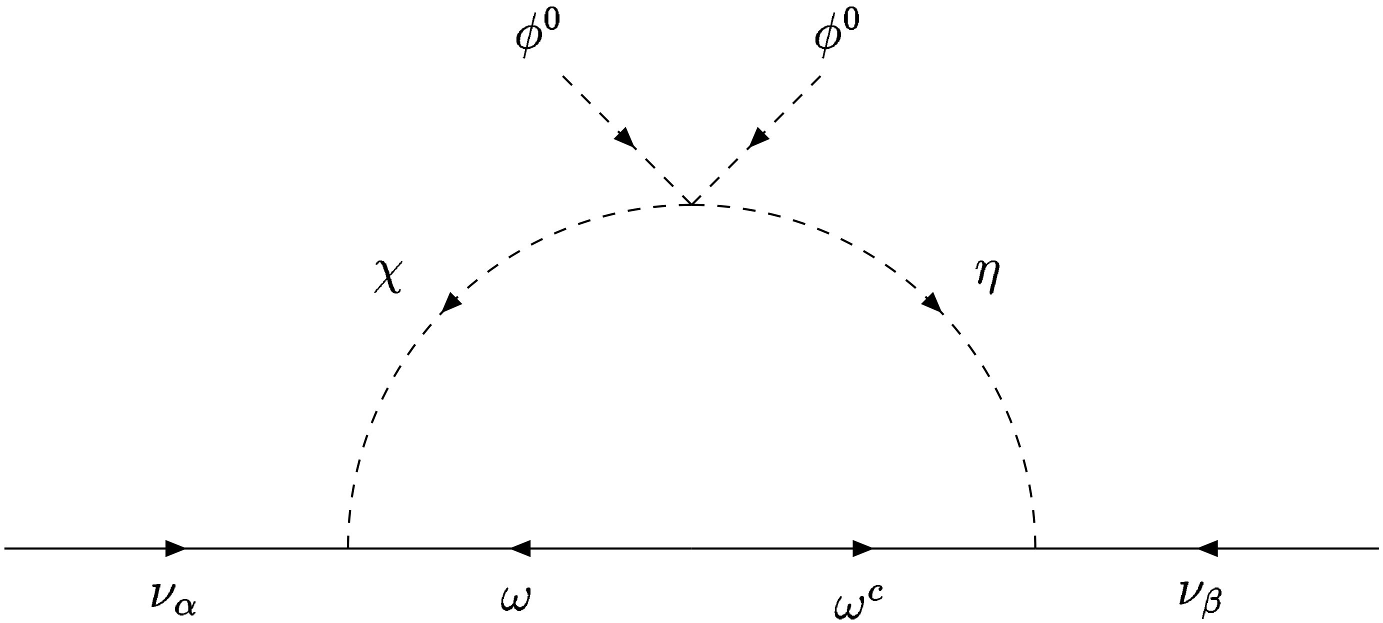
ϕ^0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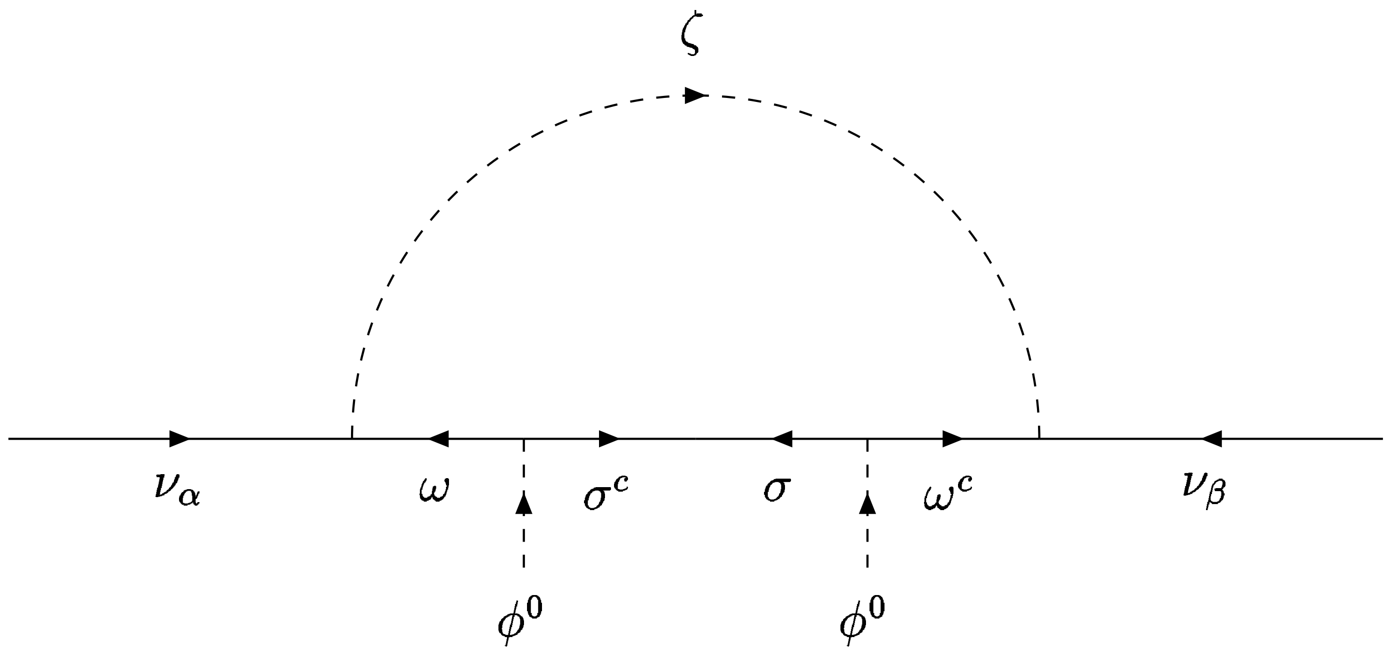

ζ
ν_α
ω
σ^c
σ
ω^c
ν_β
ϕ^0
ϕ^0

Dark Scalar Doublet

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. [Ma/Pakvasa/Tuan(1977): This doublet may even have a new conserved U(1) quantum number, i.e. η^0 is one particle.] This simple idea lay dormant for almost thirty years until [Ma, Phys. Rev. D 73, 077301 (2006)]. It was then studied seriously in Barbieri et al., Phys. Rev. D 74, 015007 (2006) and Lopez Honorez et al., JCAP 0702, 028 (2007).

Generically, the dark scalar doublet has the gauge interactions
$\eta^+\eta_R^0 W^-$, $\eta^+\eta_I^0 W^-$, $\eta^+\eta^- Z$, $\eta^+\eta^-\gamma$, $\eta_R^0\eta_I^0 Z$,
and the scalar interactions
$h(\eta_R^0)^2$, $h(\eta_I^0)^2$, $h\eta^+\eta^-$, $h^2(\eta_R^0)^2$, $h^2(\eta_I^0)^2$, $h^2\eta^+\eta^-$, $(\eta^\dagger\eta)^2$.
They are easily pair produced at the LHC through $q\bar{q} \to W^\pm, Z, \gamma$.
The decays $\eta^+ \to W^+\eta_R^0$ and $\eta_I^0 \to Z\eta_R^0$ will carry distinct signatures. [Cao/Ma/Rajasekaran, Phys. Rev. D 76, 095011 (2007).] Mass of $\eta_R^0 = 45$ to 75 GeV from dark matter relic abundance.

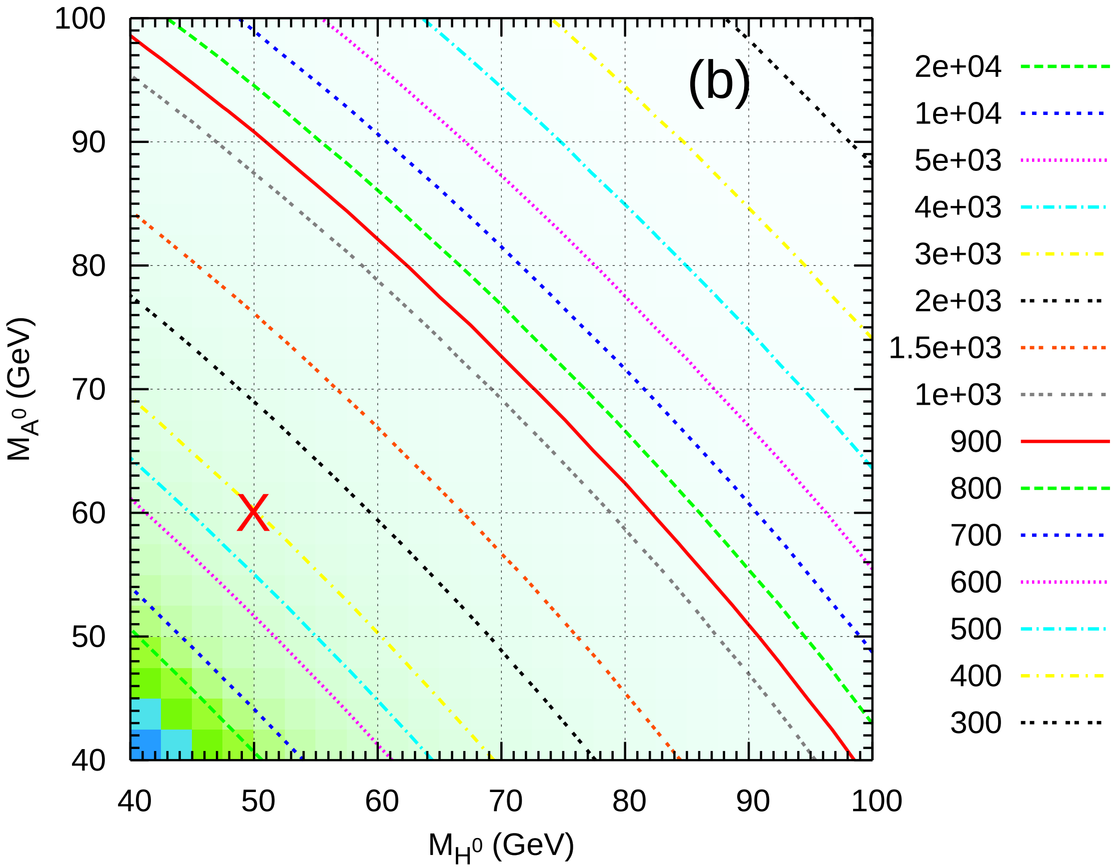


Figure 1: Contours of the $\eta_I^0\eta_R^0$ $(=A^0H^0)$ production cross section at the LHC in fb units.

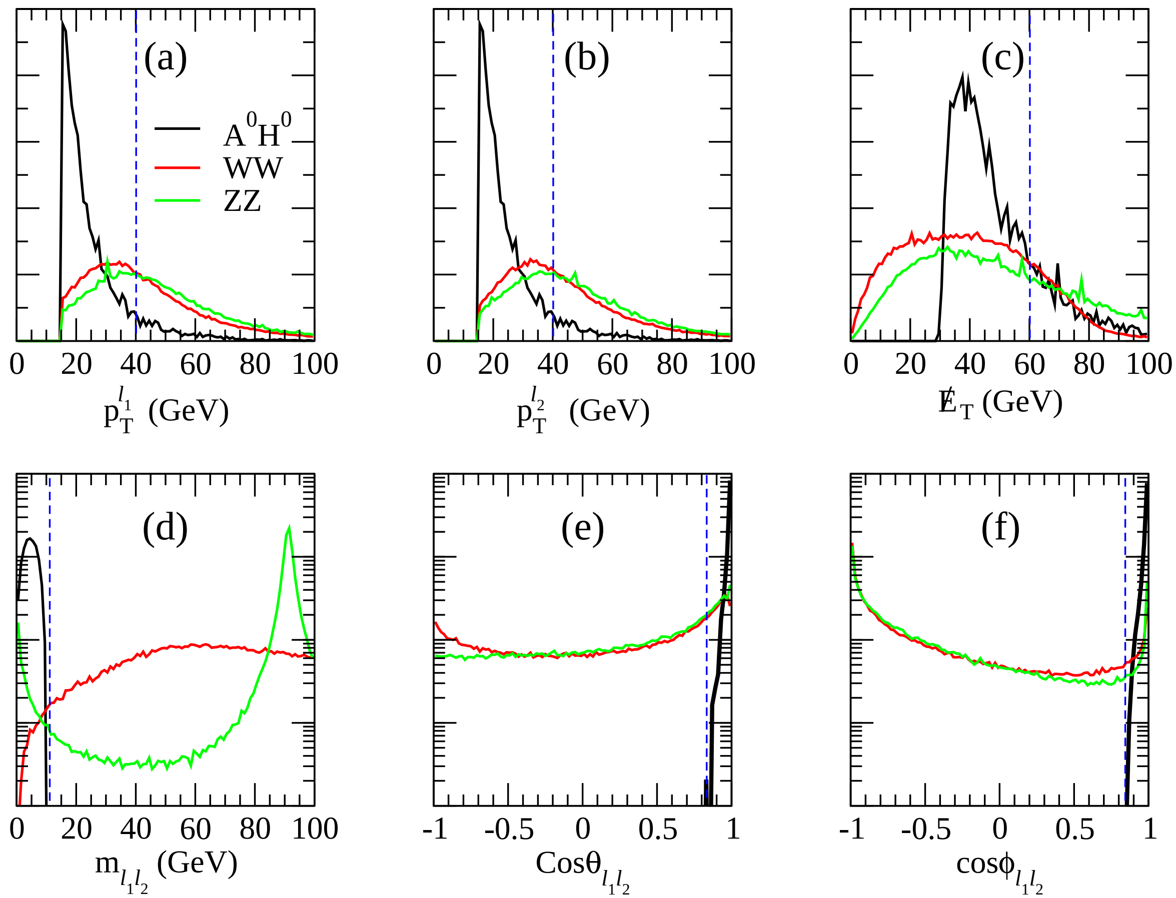


Figure 1: (Normalized) kinematic distributions of the $\eta_I^0\eta_R^0$ production at the LHC for $(m_R, m_I, m_+) = (50, 60, 170)$ GeV. Red (green) curve is the WW (ZZ) background. Blue line is the optimal cut.

Signal $= H^0 A^0 \to l^+ l^- +$ missing energy.

Background comes from WW and ZZ production.

Basic cuts: $p_T^l > 15$ GeV, $|\eta^l| < 3.0$.

Optimal cuts: $p_T^l < 40$ GeV, missing $E_T < 60$ GeV, $\cos\theta_{ll} > 0.9$, $\cos\phi_{ll} > 0.9$.

Mass window cut: $0 < m_{ll} < 10$ GeV.

events	basic cut	optimal	$m_{ll} < 10$ GeV
signal	117	37	37
background	1.3×10^5	113	62
S/B	9×10^{-4}	0.33	0.60
$S/\sqrt{B}$	0.32	3.48	4.70

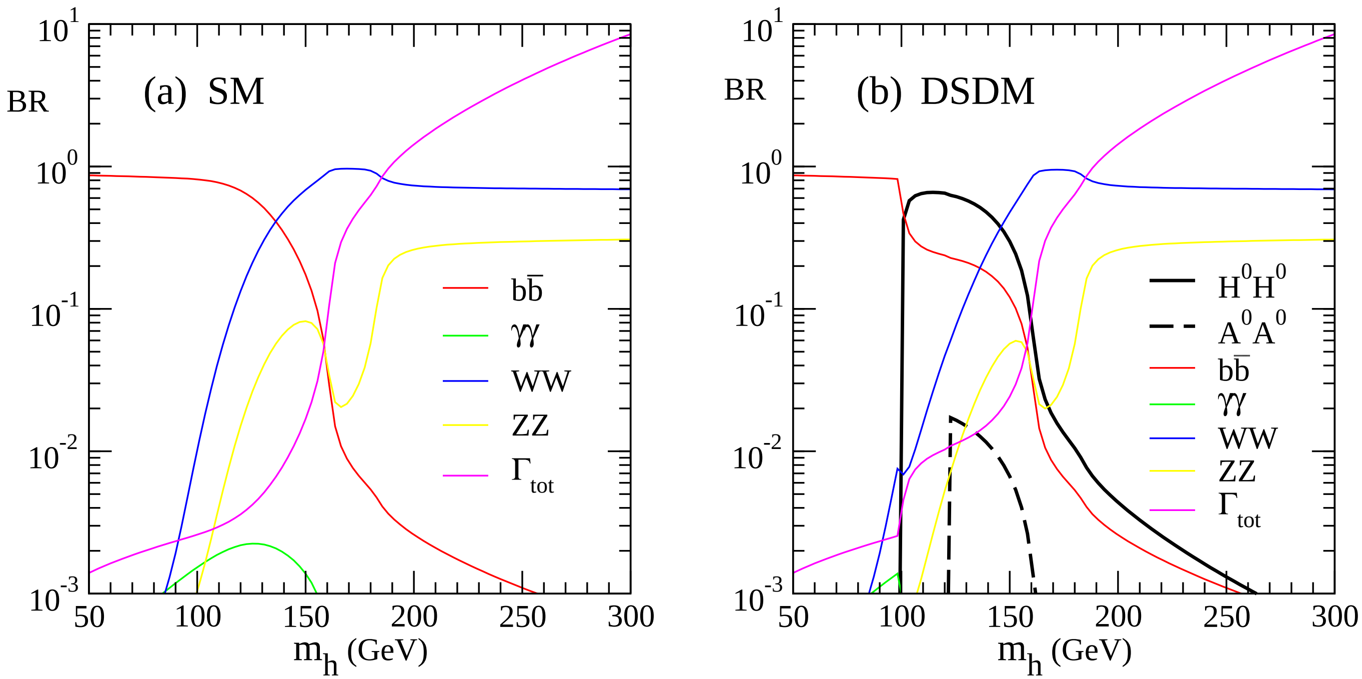


Figure 1: Higgs decay branching fractions in the (a) SM, and (b) DSDM for $(m_R, m_I, m_+) = (50, 60, 170)$ GeV.

Radiative Neutrino Mass and Dark Matter

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)
$\omega = \omega^c = N$, $\chi = \eta = (\eta^+, \eta^0), \langle \eta^0 \rangle = 0$.
Note: N interacts with ν, but they are not Dirac mass partners. This is due to an exactly conserved Z_2 symmetry, under which N and (η^+, η^0) are odd, and all SM particles are even.

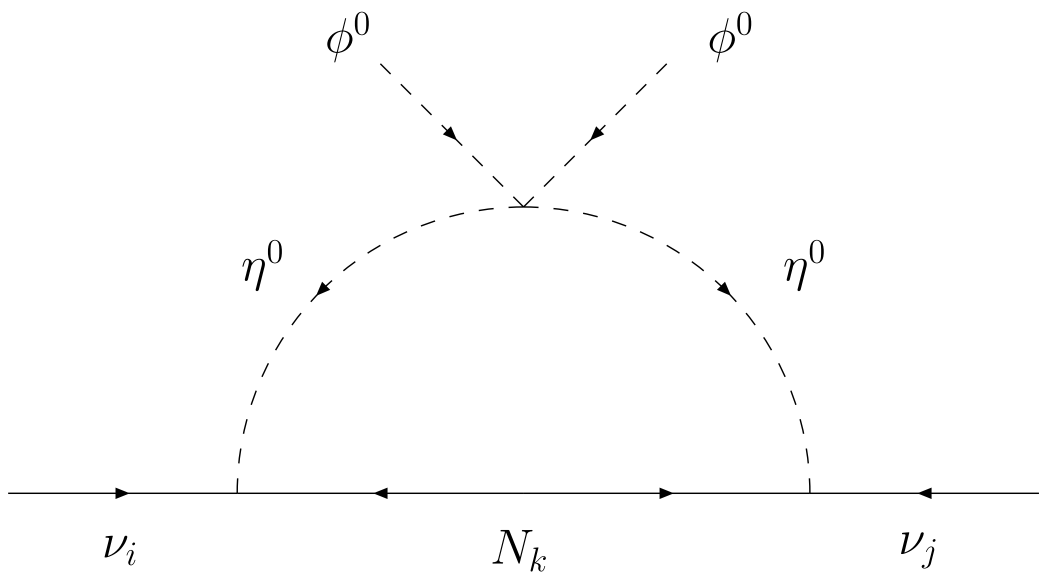


Figure 1: One-loop generation of neutrino mass with Z_2 dark matter.

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

where $f(x) = -\ln x/(1-x)$.

Let $m_R^2 - m_I^2 = 2\lambda_5 v^2 << m_0^2 = (m_R^2 + m_I^2)/2$, then

$$(\mathcal{M}_\nu)_{\alpha\beta} = \sum_i \frac{h_{\alpha i} h_{\beta i}}{M_i} I(M_i^2/m_0^2),$$

$$I(x) = \frac{\lambda_5 v^2}{8\pi^2} \left(\frac{x}{1-x} \right) \left[1 + \frac{x \ln x}{1-x} \right].$$

For $x_i >> 1$, i.e. N_i very heavy,

$$(\mathcal{M}_\nu)_{\alpha\beta} = \frac{\lambda_5 v^2}{8\pi^2} \sum_i \frac{h_{\alpha i} h_{\beta i}}{M_i} [\ln x_i - 1]$$

instead of the canonical seesaw $v^2 \sum_i h_{\alpha i} h_{\beta i} / M_i$.
In leptogenesis, the lightest M_i may then be much below the Davidson-Ibarra bound of about 10^9 GeV, thus avoiding a potential conflict of gravitino overproduction and thermal leptogenesis. In this scenario, η_R^0 or η_I^0 is 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 [Kubo/Ma/Suematsu(2006)]; however flavor changing radiative decays such as $\mu \to e\gamma$ are too big without some rather delicate fine tuning.

Babu/Ma(2007): Add real scalar singlet χ, then the new interaction

$$NN \to \chi \to hh$$

will allow the correct DM relic abundance without endangering $\mu \to e\gamma$. The singlet χ could also change the SM Higgs potential to allow for electroweak baryogenesis.

$\mathbf{Z_3}$ DM and Two-Loop Neutrino Mass

Simplest model of dark matter is to postulate a real scalar field D which is odd under Z_2.
[Silveira/Zee(1985); He/Li/Li/Tsai(2007); Barger/Langacker/McCaskey/Ramsey-Musolf/Shaughnessy(2007).]

This and all other previous proposals of DM are based on Z_2, but there is no fundamental principle requiring it.
Ma(2007): Consider instead Z_3 DM, i.e. complex singlet scalar χ, transforming as ω under Z_3 with $\omega^3 = 1$.

Add scalars: $\chi_{1,2,3} \sim \omega$,
and fermions: $(N,E)_{L,R}$, $S_{L,R} \sim \omega$,
then a two-loop neutrino mass is generated:

$$(\mathcal{M}_\nu)_{ij} = \frac{v^2}{512\pi^4} \sum_{k,l,m} h_{ik} h_{jl} \mu_{klm} \left[\frac{f_1^2 f_{3m}}{(M_{eff})^2} + \frac{f_2^2 f_{4m} m_N^2}{(M'_{eff})^4} \right].$$

Let χ_1 be the lightest, then it can be DM and may be discovered through $E \to l_i \chi_j$ and $\chi_2 \to \chi_1 l_i^+ l_j^-$, etc. Since S mixes with N, there is also the decay chain $N_2 \to N_1 Z$, then $N_1 \to \nu_i \chi_j$.

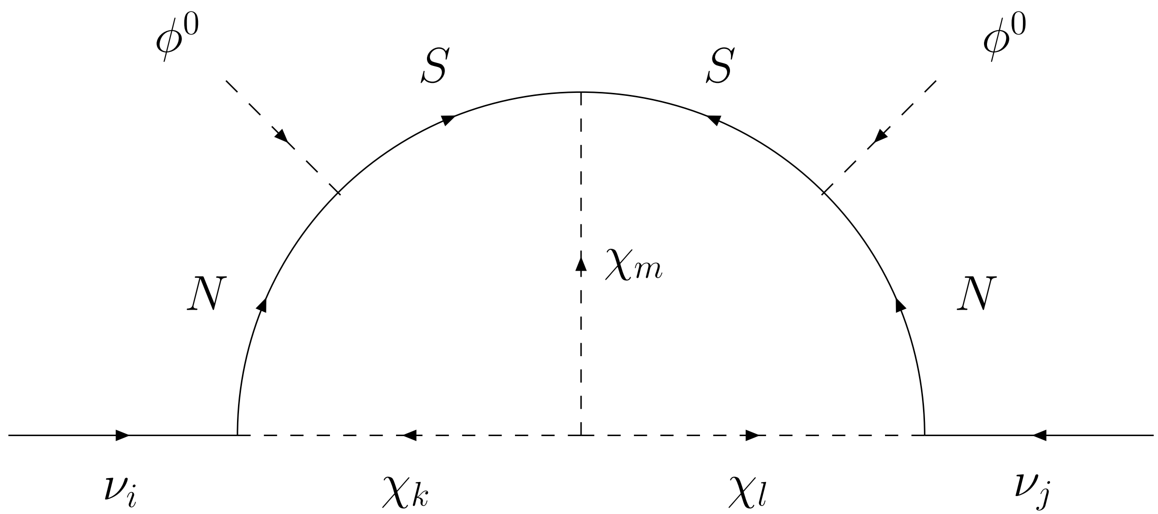


Figure 1: Two-loop generation of neutrino mass with Z_3 dark matter.

Supersymmetric $E_6/U(1)_N$ Model

Ma(1996): Under $E_6 \rightarrow SU(3)_C \times SU(3)_L \times SU(3)_R$,
$Q_N = 6Y_L + T_{3R} - 9Y_R$ defines $U(1)_N$:

superfield	$SU(5)$	Q_N
$(u,d), u^c, e^c$	10	1
$d^c, (\nu, e)$	5^*	2
$h,(E^c, N_E^c)$	5	-2
$h^c,(\nu_E, E)$	5^*	-3
S	1	5
N^c	1	0

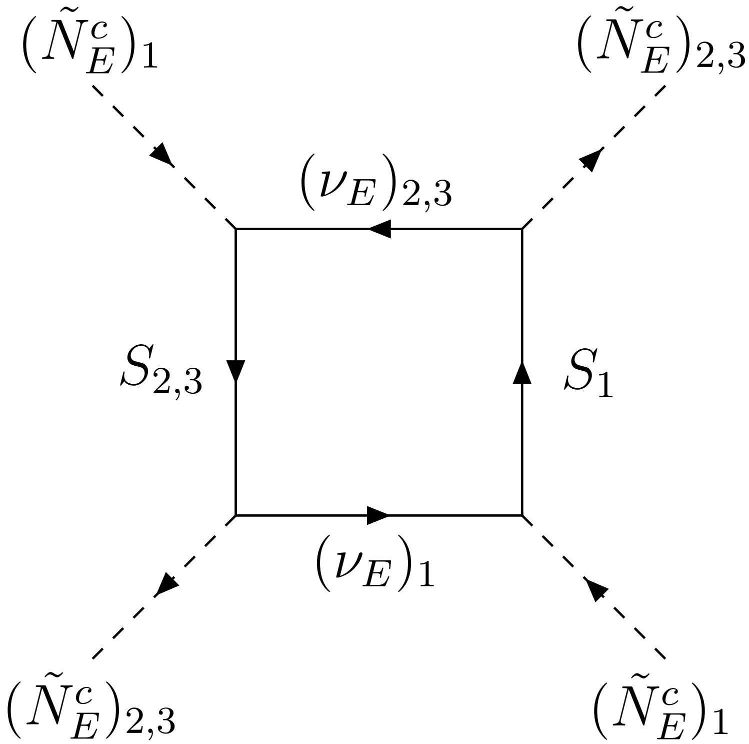
Ma/Sarkar(2007): Impose exact $Z_2 \times Z_2$ symmetry:

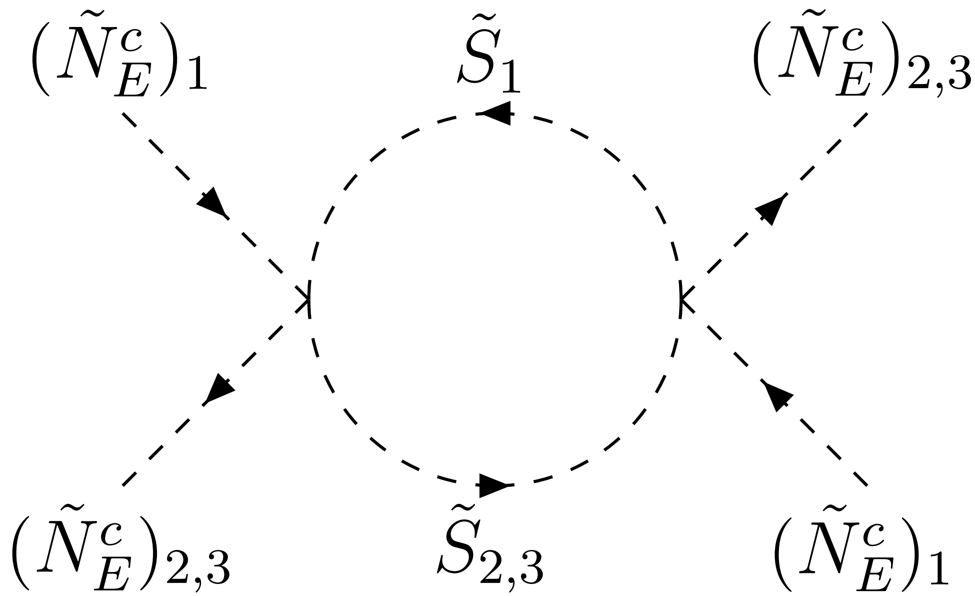
superfield	M	N
$(u,d), u^c, d^c$	$+$	$+$
$(\nu, e), e^c$	$-$	$+$
h, h^c	$-$	$+$
$[(\nu_E, E), (E^c, N_E^c), S]_1$	$+$	$+$
$[(\nu_E, E), (E^c, N_E^c), S]_{2,3}$	$+$	$-$
N^c	$-$	$-$

M parity implies the usual R parity with $B = 1/3$ and $L = 1$ for h.

The only terms involving N^c are the allowed Majorana mass terms $N^c N^c$ and the Yukawa terms $[\nu(N_E^c)_{2,3} - e(E^c)_{2,3}]N^c$, i.e. exactly as required for the seesaw mechanism.
However, N parity forbids m_ν at tree level, and the necessary λ_5 quartic scalar term for a one-loop mass, i.e. $[(\tilde{N}_E^c)^\dagger_{2,3}(\tilde{N}_E^c)_1]^2$, is not available in exact supersymmetry.

Fortunately, as the supersymmetry is broken by soft terms, an effective λ_5 term itself can be generated in one loop. Thus m_ν is a two-loop effect in this model.


$(\tilde{N}_E^c)_1$
$(\tilde{N}_E^c)_{2,3}$
$(\nu_E)_{2,3}$
$S_{2,3}$
S_1
$(\nu_E)_1$
$(\tilde{N}_E^c)_{2,3}$
$(\tilde{N}_E^c)_1$


$(\tilde{N}_E^c)_1$
$\tilde{S}_1$
$(\tilde{N}_E^c)_{2,3}$
$(\tilde{N}_E^c)_{2,3}$
$\tilde{S}_{2,3}$
$(\tilde{N}_E^c)_1$

At least two out of the following three particles are dark-matter candidates:

(1) the usual lightest neutralino of the MSSM with $(R,N) = (-,+)$,

(2) the lightest exotic neutral particle with $(+,-)$,

(3) and that with $(-,-)$.

The dark matter of the Universe may not be all the same, as most people have taken for granted! For a general discussion, see Cao/Ma/Wudka/Yuan, arXiv:0711.3881.

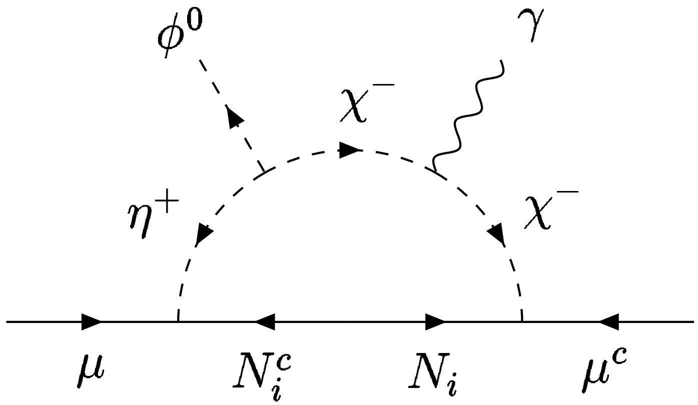
Conclusion

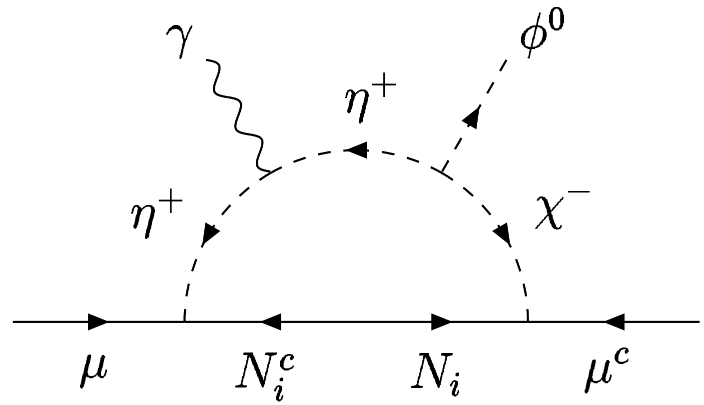
The evidence of dark matter signals a new class of particles at the TeV scale, which may manifest themselves indirectly through loop effects. They may be responsible for neutrino mass, and perhaps also muon anomalous magnetic moment, as well as leptogenesis. Observable bosonic dark matter at the electroweak scale are possible, as well as neutral singlet fermions at the TeV scale.

Muon $g-2$ and Neutrino Mass

Hambye/Kannike/Ma/Raidal(2006):

particles	$SU(2) \times U(1)$	$U(1)_L$	$(-1)^L$	Z_2
$L_\alpha = (\nu_\alpha, l_\alpha)$	$(2, -1/2)$	1	–	$+$
l^c_α	(1,1)	–1	–	$+$
$\Phi = (\phi^+, \phi^0)$	(2,1/2)	0	$+$	$+$
N_i	(1,0)	1	–	–
N^c_i	(1,0)	–1	–	–
$\eta = (\eta^+, \eta^0)$	(2,1/2)	0	$+$	–
χ^-	(1,–1)	0	$+$	–


ϕ^0
γ
χ^-
η^+
χ^-
μ
N_i^c
N_i
μ^c


γ
ϕ^0
η^+
η^+
χ^-
μ
N_i^c
N_i
μ^c

Mixing of χ^+ and η^+:

$$\Delta a_\mu = \frac{-\sin\theta\cos\theta}{16\pi^2}\sum_i h_{\mu i}h'_{\mu i}\frac{m_\mu}{M_i}[F(x_i) - F(y_i)],$$

where $x_i = m_X^2/M_i^2$, $y_i = m_Y^2/M_i^2$, and
$F(x) = [1 - x^2 + 2x\ln x]/(1-x)^3$.
Let $y_i << x_i \simeq 1$, $M_i \sim 1$ TeV,
$(-h_{\mu i}h'_{\mu i}\sin\theta\cos\theta/24\pi^2) \sim 10^{-5}$, then $\Delta a_\mu \sim 10^{-9}$,
whereas

$$(\Delta a_\mu)_{\rm exp't} = (22.4 \pm 10) \text{ to } (26.1 \pm 9.4) \times 10^{-10}.$$

Neutrino Mass: Allow soft breaking of $U(1)_L$, i.e.

$$\frac{1}{2} m_{ij} N_i^c N_j^c + \frac{1}{2} m'_{ij} N_i N_j + H.c.,$$

$$\text{then} \quad (\mathcal{M}_\nu)_{\alpha\beta} = \sum_{i,j} h_{\alpha i} h_{\alpha j} \tilde{m}_{ij}, \quad \text{where} \quad \tilde{m}_{ij} =$$

$$\frac{\lambda_5 v^2 m_{ij}}{8\pi^2 (M_i^2 - M_j^2)} \left[\frac{M_i^2}{m_0^2 - M_i^2} + \frac{M_i^4 \ln(M_i^2/m_0^2)}{(m_0^2 - M_i^2)^2} - (i \leftrightarrow j) \right].$$

Let $M_{i,j} \sim 1$ TeV, $m_{ij} \sim 0.1$ GeV, $h_{\alpha i} \sim 10^{-2}$, $\lambda_5 \sim 0.1$, $m_0 \sim v \sim 10^2$ GeV, then the entries of $\mathcal{M}_\nu \sim 0.1$ eV.