Utility of a Special Second Scalar Doublet

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Introduction

The Minimal Standard Model (SM) has only one Higgs doublet $\Phi = (\phi^+, \phi^0)$. A second doublet is not necessary, but if it is added, there can be CP violation and flavor-changing interactions, etc.
Furthermore, in a supersymmetric extension, two Higgs superfields are necessary: (ϕ_1^0, ϕ_1^-) for $\mathcal{M}_d$ and $\mathcal{M}_e$ and (ϕ_2^+, ϕ_2^0) for $\mathcal{M}_u$. To accommodate the conservation of baryon and lepton numbers, R parity, i.e. $(-)^{3B+L+2j}$, is imposed, resulting in the Minimal Supersymmetric Standard Model (MSSM).

In the MSSM, the lightest neutral particle having odd R parity is absolutely stable and a candidate for dark matter (DM). 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. If all we want is DM, a very simple way is to add a second scalar doublet (η^+, η^0) which is odd under Z_2 with all SM particles even. This means that $\langle \eta^0 \rangle$ must also be zero, so this is a special second scalar doublet.

(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.

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 as DM 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 $\eta^+\eta^0_R W^-$, $\eta^+\eta^0_I W^-$, $\eta^+\eta^- Z$, $\eta^+\eta^-\gamma$, $\eta^0_R\eta^0_I Z$, and the scalar interactions $h(\eta^0_R)^2$, $h(\eta^0_I)^2$, $h\eta^+\eta^-$, $h^2(\eta^0_R)^2$, $h^2(\eta^0_I)^2$, $h^2\eta^+\eta^-$, $(\eta^\dagger\eta)^2$.

They are easily pair produced at the LHC through $q\bar{q}\to W^\pm, Z, \gamma$. The decays $\eta^+\to W^+\eta^0_R$ and $\eta^0_I\to Z\eta^0_R$ will carry distinct signatures. [Cao/Ma/Rajasekaran, Phys. Rev. D 76, 095011 (2007).]

The astrophysical signature $\eta^0_R\eta^0_R \to \gamma\gamma$ has also been studied by Gustaffson et al., Phys. Rev. Lett. 99, 041301 (2007).

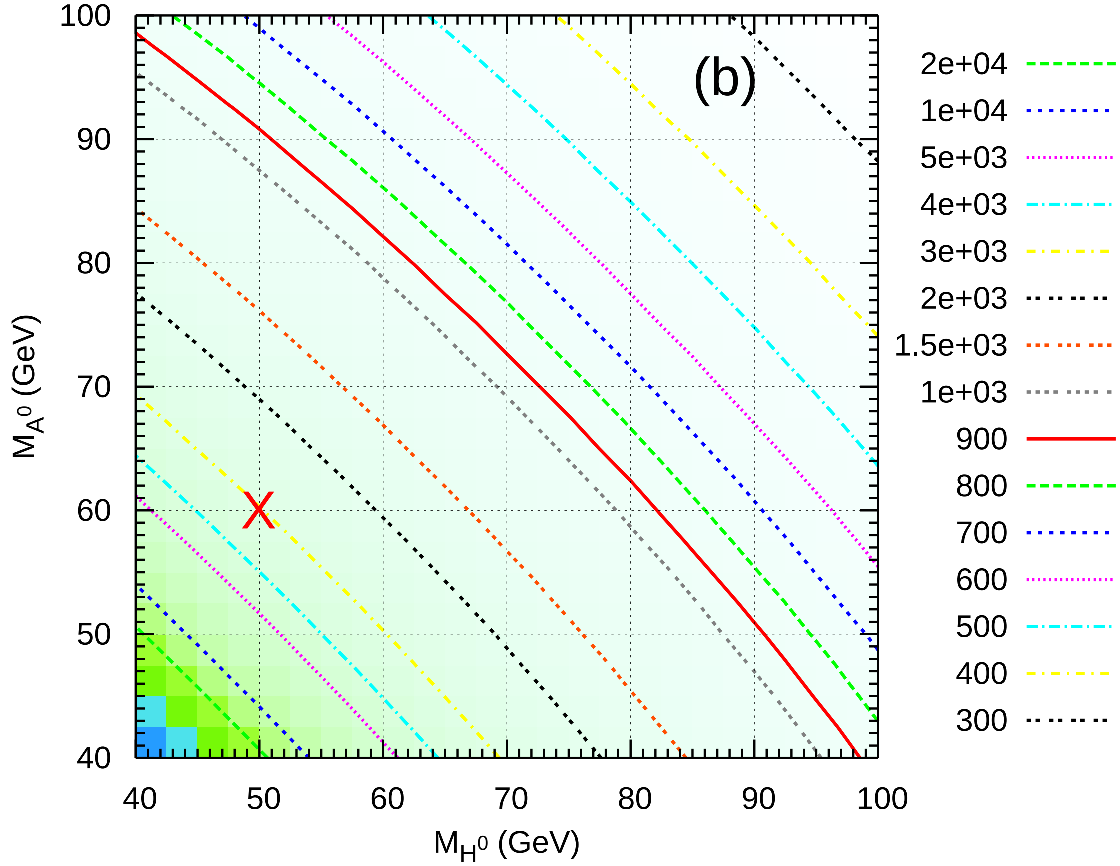


Figure 1: Contours of the $\eta_I^0 \eta_R^0$ $(=A^0 H^0)$ production cross section at the LHC in fb units.

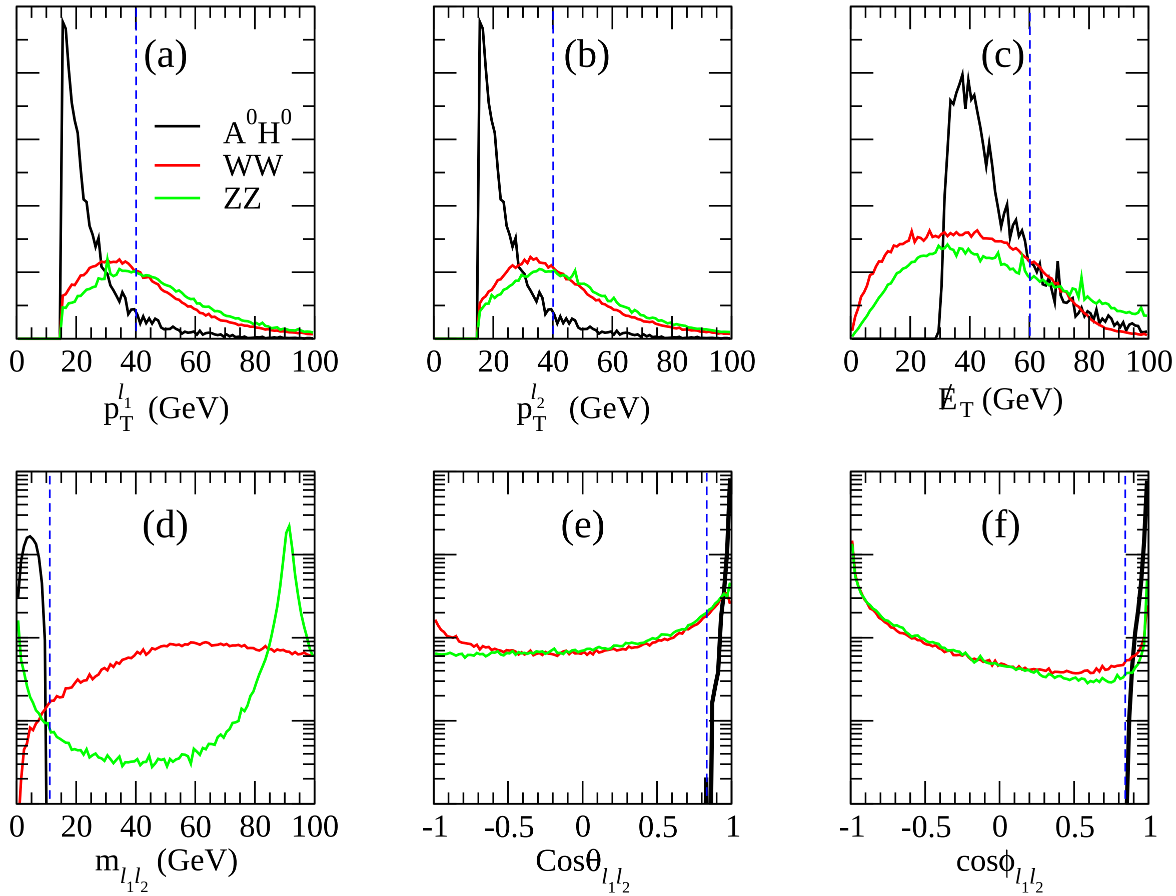


Figure 1: (Normalized) kinematic distributions of the $\eta_I^0 \eta_R^0$ production at the LHC for $(m_R, m_I, m_+) = (50, 60, 170)$ GeV. Red (green) curve is the WW (ZZ) background. Blue line is the optimal cut.

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

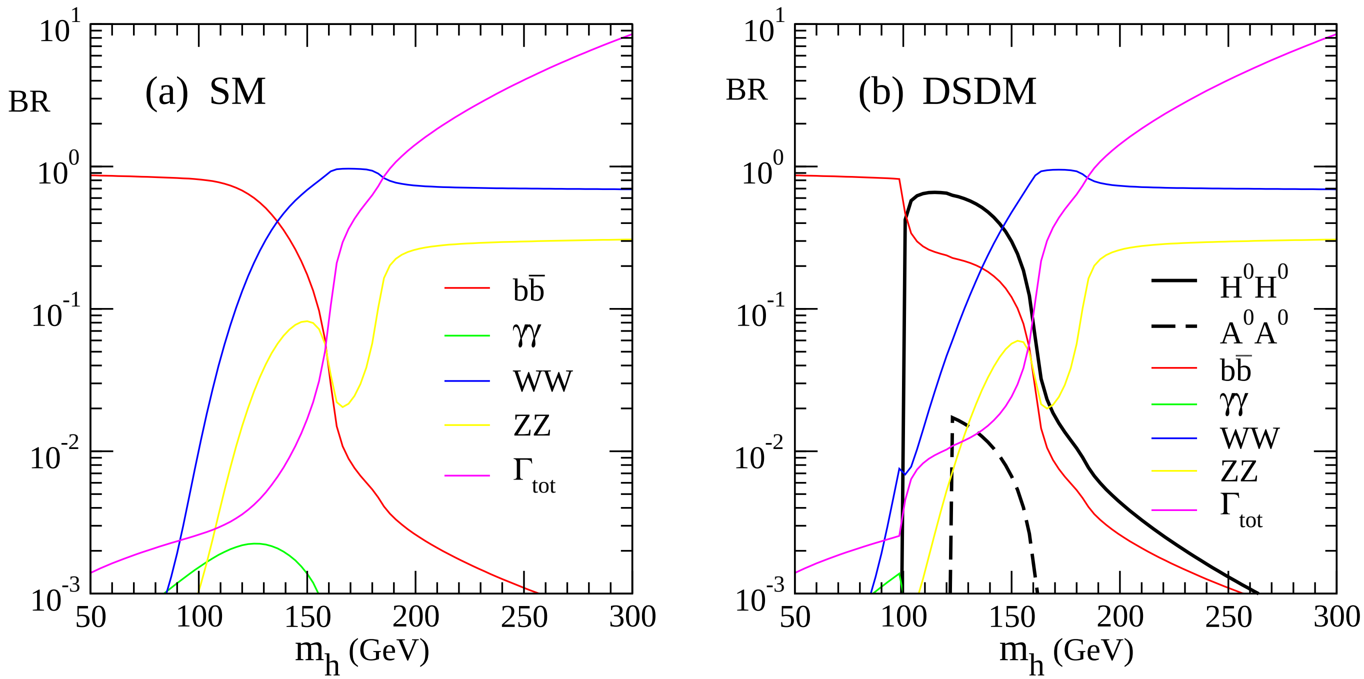


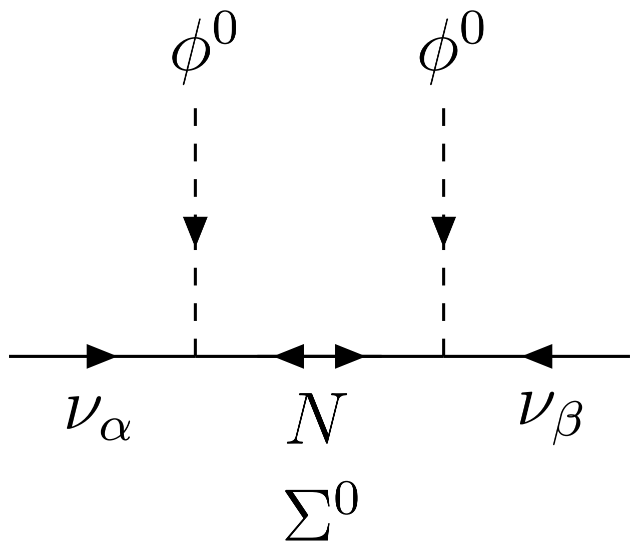
Figure 1: Higgs decay branching fractions in the (a) SM, and (b) DSDM for $(m_R, m_I, m_+) = (50, 60, 170)$ GeV.

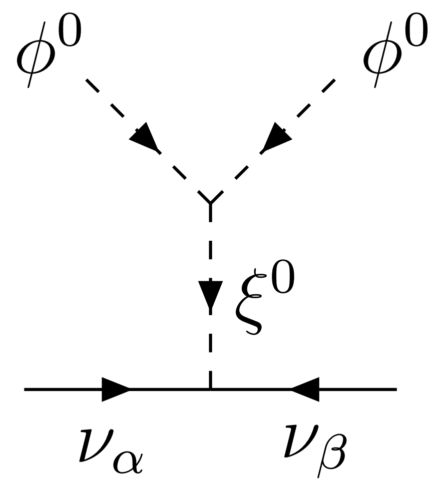
Neutrino Mass: Six Generic Mechanisms

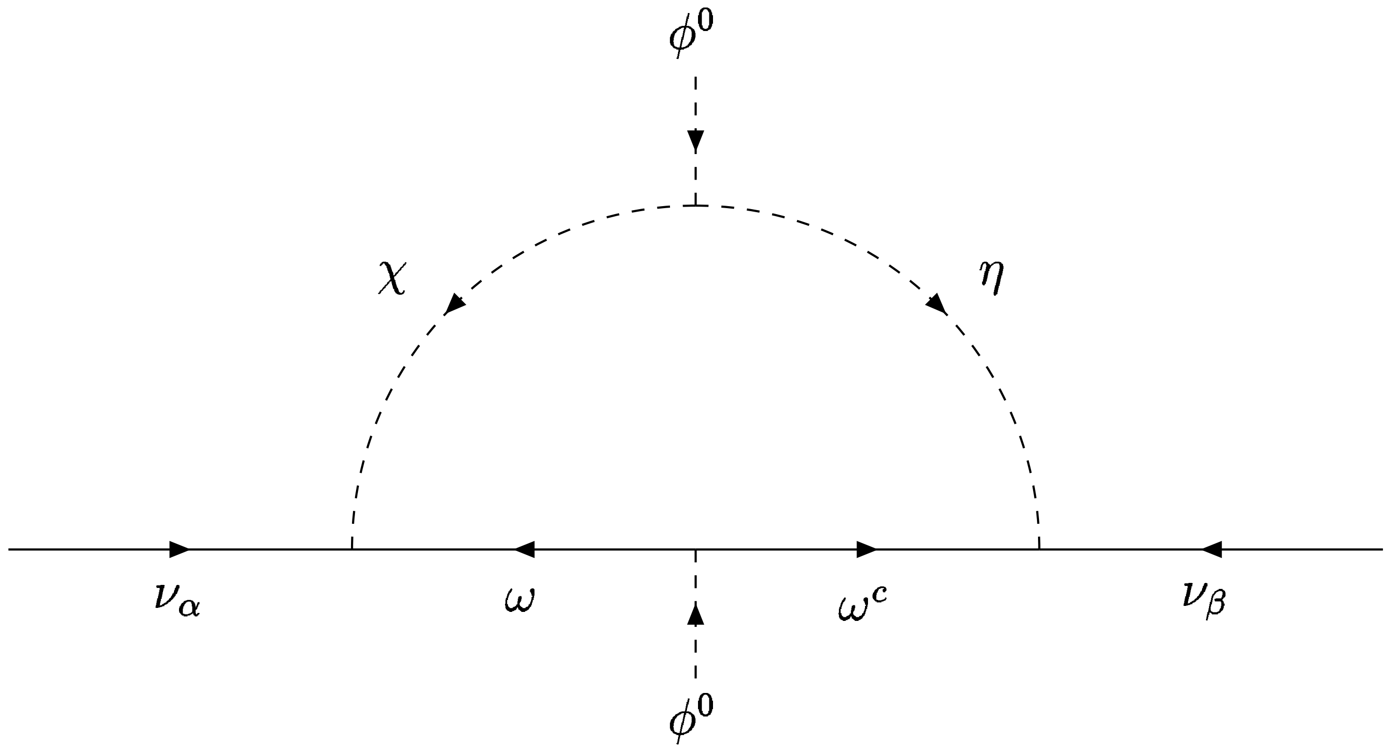
Weinberg(1979):
Unique dimension-five operator for Majorana neutrino mass in SM:

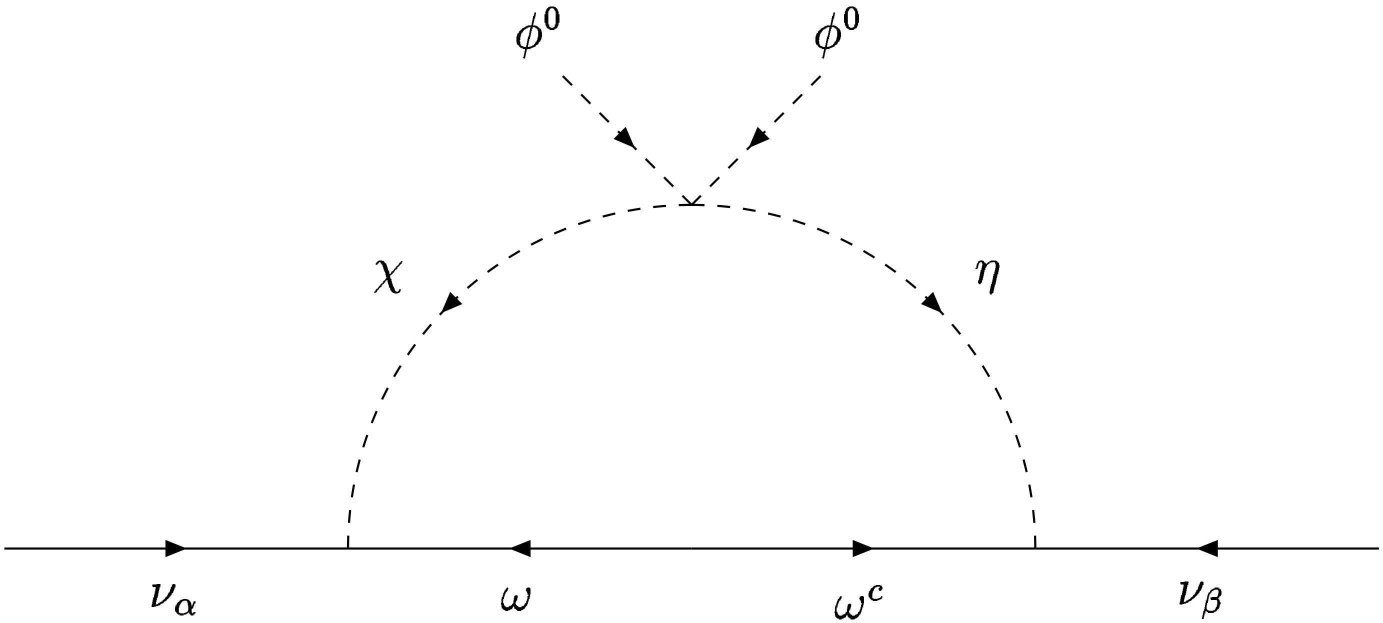
$$\frac{f_{\alpha\beta}}{2\Lambda}(\nu_\alpha \phi^0 - l_\alpha \phi^+)(\nu_\beta \phi^0 - l_\beta \phi^+).$$

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).

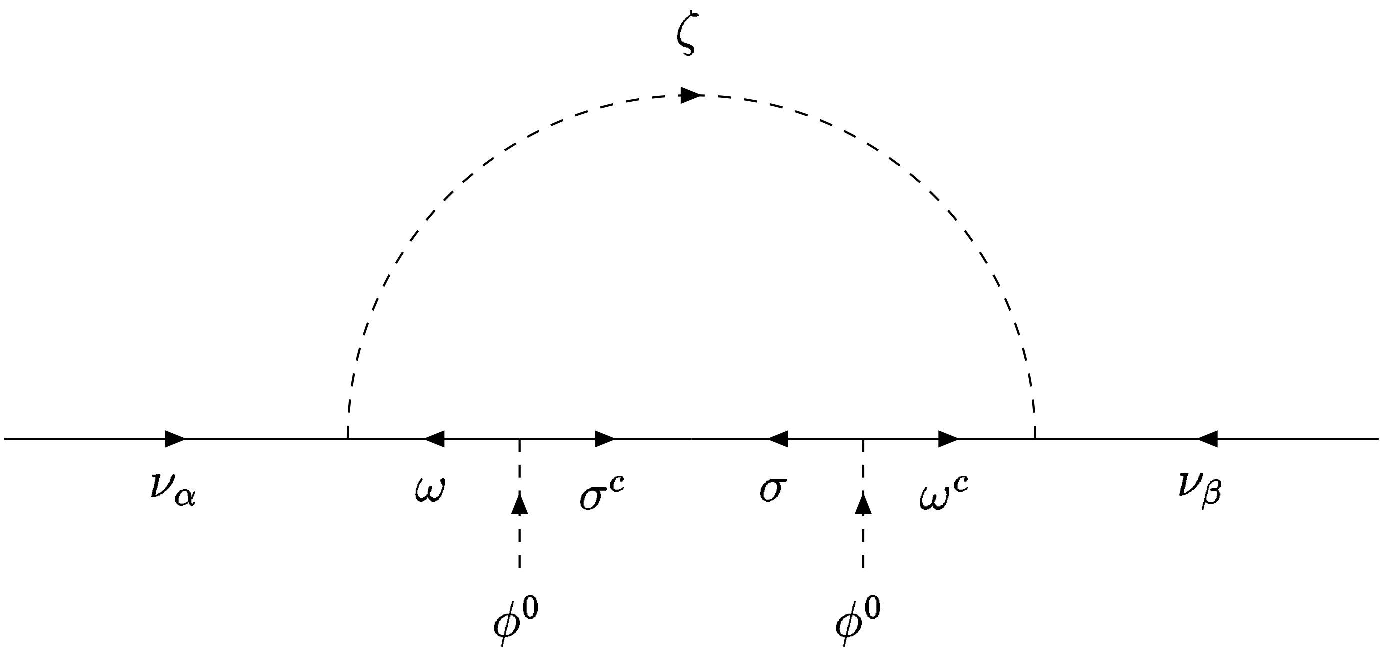

ϕ^0
ϕ^0
ν_α
N
Σ^0
ν_β


ϕ^0
ϕ^0
ξ^0
ν_α
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 Neutrino Mass with a Second Scalar Doublet

In the SM with $N_{1,2,3}$, the allowed terms $f_{ik}(\nu_i \phi^0 - l_i \phi^+) N_k + (1/2) M_k N_k N_k + H.c.$

$$\Rightarrow (\mathcal{M}_\nu)_{ij} = \frac{-f_{ik} f_{jk}}{M_k} \langle \phi^0 \rangle^2.$$

Ma(2001): Add (η^+, η^0) and assign it $L = -1$ with $L = 0$ for $N_{1,2,3}$, then L conservation requires Φ to be replaced by η in the seesaw formula. To obtain $\langle \eta^0 \rangle \neq 0$,

L must be violated. Add $\mu^2\Phi^\dagger\eta + H.c.$, then

$$\langle\eta^0\rangle \simeq \frac{-\mu^2\langle\phi^0\rangle}{m_\eta^2} << \langle\phi^0\rangle.$$

Radiative mechanisms: (IV) [Zee(1980)]
$\omega = (\nu, l), \omega^c = l^c$, $\chi = \chi^+, \eta = (\phi^+_{1,2}, \phi^0_{1,2}), \langle\phi^0_{1,2}\rangle \neq 0$.
(V) [Ma(2006)] $\omega = \omega^c = N$, $\chi = \eta = (\eta^+, \eta^0), \langle\eta^0\rangle = 0$.
Note: N interacts with ν, but they are not Dirac mass partners. This is enforced by an exactly conserved Z_2 symmetry, under which N and (η^+, η^0) are odd, and all SM particles are even.

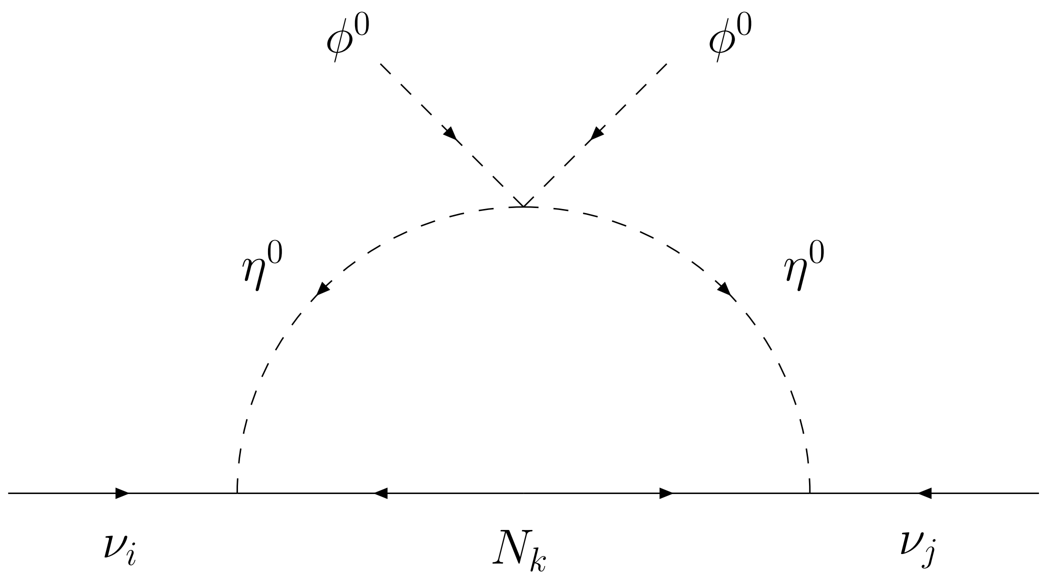


Figure 1: One-loop generation of neutrino mass with Z_2 dark matter.

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

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.

Supersymmetric SU(5) Completion

Ma(2006): The dark scalar doublet model was extended to include supersymmetry by the addition of a singlet superfield which is even under the imposed Z_2, together with the conventional R parity. At least two out of the following three particles are then dark-matter candidates: (1) the usual lightest neutralino of the MSSM with $(R, Z_2) = (-, +)$, (2) the lightest exotic neutral particle with $(+, -)$, and (3) that with $(-, -)$. The dark matter of the Universe may not be all the same, as most people have taken for granted!

Ma(2008): Add a pair of SU(5) $\underline{5}$ and $\underline{5}^*$ superfields and impose exact $Z_2' \times Z_2$ symmetry:

superfield	Z_2'	Z_2
$d^c, (\nu, e)$	$-$	$+$
$(u, d), u^c, e^c$	$-$	$+$
$(\phi_1^0, \phi_1^-), (\phi_2^+, \phi_2^0)$	$+$	$+$
N	$-$	$-$
$h^c, (\eta_1^0, \eta_1^-)$	$+$	$-$
$h, (\eta_2^+, \eta_2^0)$	$+$	$-$
χ	$+$	$-$

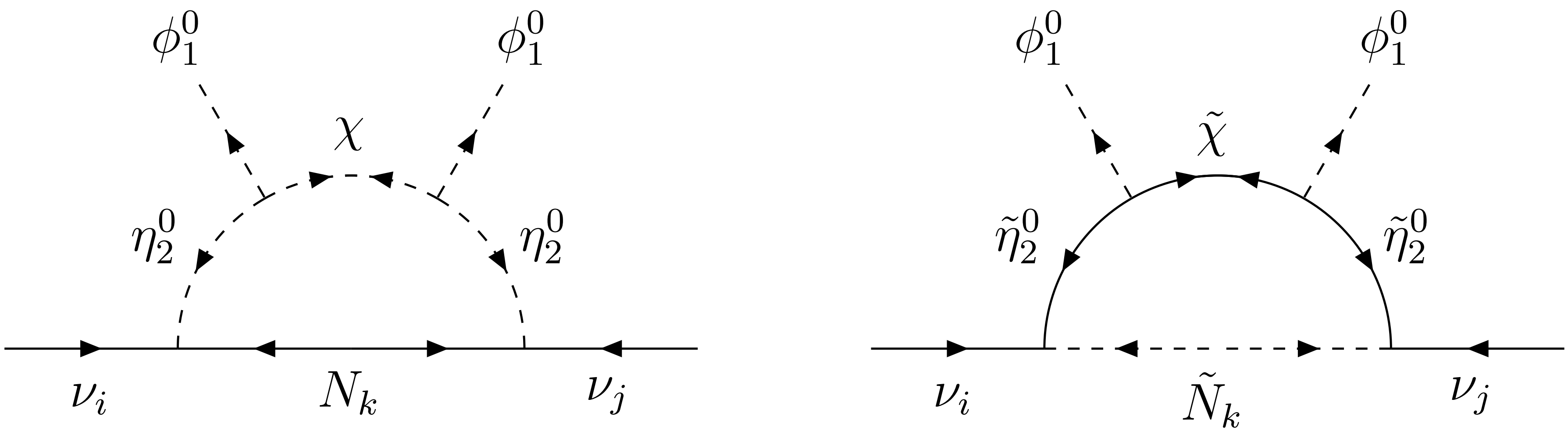


Figure 1: One-loop radiative contributions to neutrino mass.

The imposition of Z_2' parity implies the usual R parity with $B = 1/3$ and $(-)^L = -1$ for h.

Let $m_\eta, m_h <$ TeV, then the gauge-coupling unification of the MSSM remains undisturbed. Conventionally, the color triplets h, h^c are dangerous because they could mediate rapid proton decay. Here they are harmless because of the Z_2 symmetry, i.e. dark matter and baryon number conservation have the same origin. From the couplings hd^cN and $L\eta_2N$, the decay of h is into either $de^-\eta_2^+$ or $de^+\eta_2^-$. Thus $h\bar{h}$ production will result in same-sign dileptons plus quark jets plus missing energy.

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,(ν_E, E)	5^*	-3
S	1	5
N^c	1	0

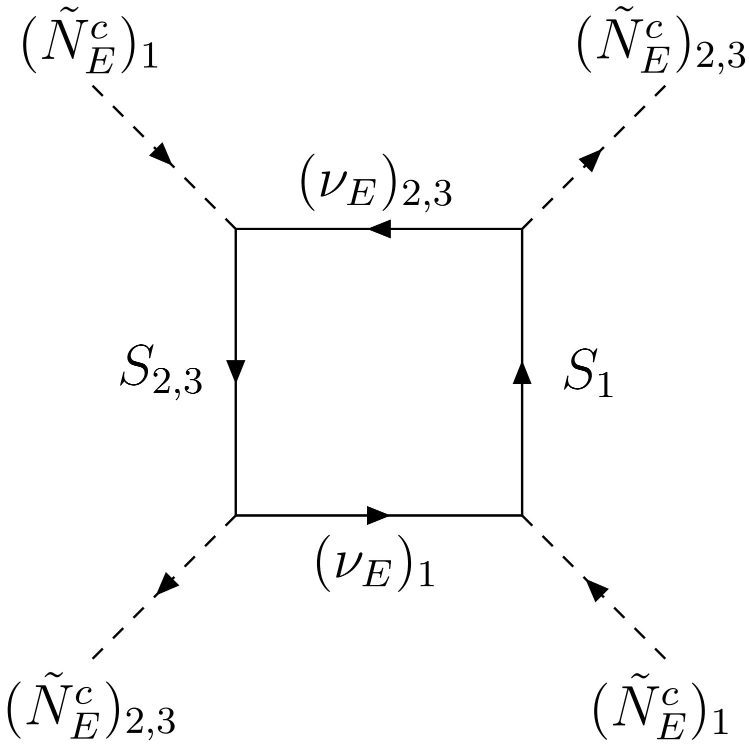
Ma/Sarkar(2007): Impose exact $Z_2 \times Z_2$ symmetry:

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	$-$	$-$

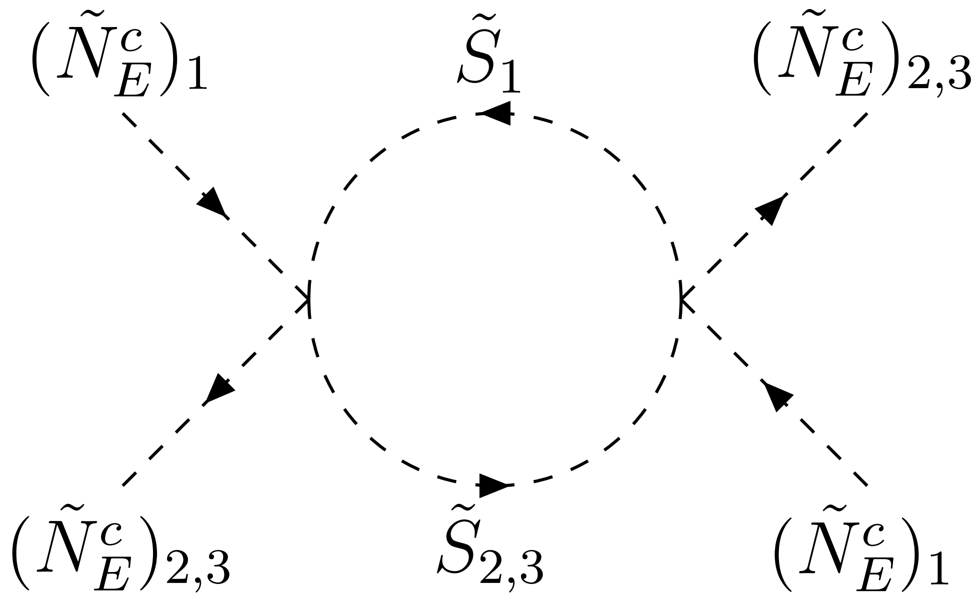
M parity implies the usual R parity with $B = 1/3$ and $L = 1$ for h.

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.



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


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

Conclusion

- A special second scalar doublet with zero vacuum expectation value is useful for the implementation of dark matter, as well as radiative neutrino mass.
- In the context of supersymmetry, it opens up the possibility of multipartite dark matter.
- If it is part of a grand unified theory, then there will be other accompanying particles which may become observable at the LHC.