Dark Vector Boson from $E_6/SU(2)_N$ Extension of the Standard Model

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Contents

Dark Matter Varieties

There used to be just one candidate dark-matter theory, i.e. $R-$parity conserving supersymmetry (MSSM), but in recent years, many more have been proposed.

Dark matter must be neutral (so that it is dark) and stable (so that it is still here).

In the MSSM, the candidates are the lightest sneutrino (scalar boson) or the lightest neutralino (spin-one-half fermion).

The former is ruled out by direct-detection experiments, because it interacts with quarks through the Z boson, with a cross section many orders of magnitude larger than is allowed by observation. The latter is OK, because a neutralino mass eigenstate is Majorana which does not contribute to the elastic scattering through Z exchange.

Ma(2006): Neutrino mass may also be due to dark matter (scotogenic). Add to the Standard Model (SM) a second scalar doublet (η^+, η^0) and 3 neutral singlet Majorana fermions $N_{1,2,3}$ which are odd under an exactly conserved Z_2, with all SM particles even.

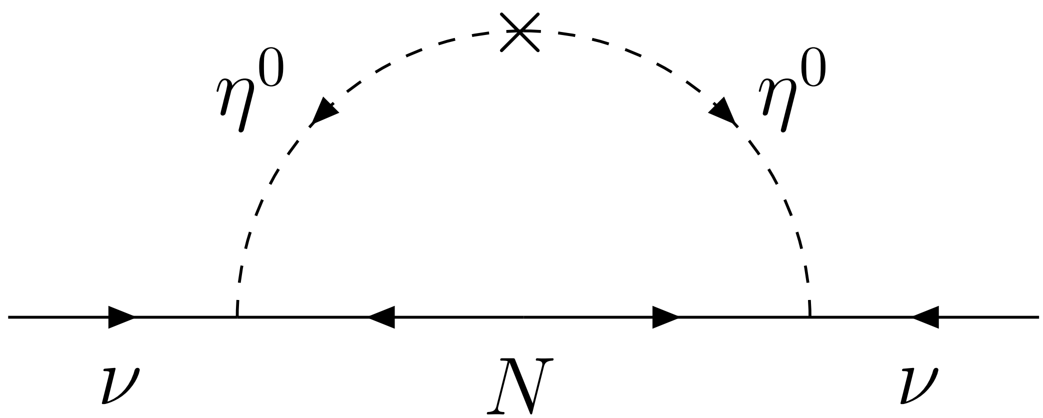


Figure 1: One-loop m_ν from Z_2 dark matter.

Hence $\nu N \phi^0$ is forbidden and $\nu N \eta^0$ is allowed, but $\langle \eta^0 \rangle = 0$. Thus N is not the Dirac mass partner of ν. Nevertheless, neutrino mass is generated in one loop, i.e. scotogenic, being caused by darkness. Here, η_R^0 is a dark-matter candidate, studied two months later by Barbieri/Hall/Rychkov(2006). They call η the inert Higgs doublet. I call it the dark scalar doublet.

Since η is a scalar doublet just like the supersymmetric (sneutrino, slepton) doublet, why is it not also ruled out? The reason is that the quartic interaction $(\eta^\dagger \Phi)^2$ is allowed by Z_2 but not by supersymmetry.

This term splits η_R^0 and η_I^0, which serves two purposes.

(1) It allows the one-loop scotogenic diagram to be nonzero and finite.

(2) Since Z couples to $\eta_R^0 \eta_I^0$ only, the direct-search experiments using elastic nuclear recoil are rendered ineffective for a mass gap of only 1 MeV.

Ma/Sarkar(2007): $E_6/U(1)_N$ realization of scotogenic neutrino mass in two loops.

Cao/Ma/Wudka/Yuan(2007): Multipartite dark matter may exist, then the least abundant has the largest cross section and may be discovered first at the LHC.

$E_6/SU(3)^3$ **Extensions of the Standard Model**

Shortly after the first string revolution (1984-6), the superstring-inspired supersymmetric E_6 model was studied intensively. The fundamental <u>27</u> representation of E_6 is decomposed under its maximum subgroup $SU(3)_C \times SU(3)_L \times SU(3)_R$ as

$$\begin{pmatrix} d & u & h \\ d & u & h \\ d & u & h \end{pmatrix} + \begin{pmatrix} N & E^c & \nu \\ E & N^c & e \\ \nu^c & e^c & n^c \end{pmatrix} + \begin{pmatrix} d^c & d^c & d^c \\ u^c & u^c & u^c \\ h^c & h^c & h^c \end{pmatrix}.$$

The decomposition of $SU(3)L \to SU(2)_L \times U(1)_{Y_L}$ is completely fixed because of the SM. However, there are 3 choices for $SU(3)_R \to SU(2)' \times U(1)'$.

(1) The conventional choice of $SU(2)_R \times U(1)_{Y_R}$ means that (ν^c, e^c) and (u^c, d^c) are $SU(2)_R$ doublets.

(2) Ma(1987): Alternative Left-Right Model, i.e.

$$\begin{pmatrix} d & u & h \\ d & u & h \\ d & u & h \end{pmatrix} + \begin{pmatrix} \nu & E^c & N \\ e & N^c & E \\ n^c & e^c & \nu^c \end{pmatrix} + \begin{pmatrix} h^c & h^c & h^c \\ u^c & u^c & u^c \\ d^c & d^c & d^c \end{pmatrix}.$$

Here (n^c, e^c) and (u^c, h^c) are $SU(2)_R$ doublets.

Khalil/Lee/Ma(2009,2010): Simpler nonsupersymmetric versions exist with n^c as a dark-matter fermion (scotino).

(3) London/Rosner(1986): $SU(2)' = SU(2)_N$, i.e.

$$\begin{pmatrix} d & u & h \\ d & u & h \\ d & u & h \end{pmatrix} + \begin{pmatrix} N & \nu & E^c \\ E & e & N^c \\ \nu^c & n^c & e^c \end{pmatrix} + \begin{pmatrix} d^c & d^c & d^c \\ h^c & h^c & h^c \\ u^c & u^c & u^c \end{pmatrix}.$$

Here (ν^c, n^c) and (h^c, d^c) are $SU(2)_N$ doublets.

Diaz-Cruz/Ma(2010): The analog of the $W_R^\pm$ gauge boson in (2) is now neutral and could be a vector-boson dark-matter candidate.

Dark $SU(2)_N$ Model

Fermion content with $S = L - T_{3N}$:

$$u^c \sim 0, (h^c, d^c) \sim -\frac{1}{2}, h \sim 1, e^c \sim -1, (\nu^c, n^c) \sim -\frac{1}{2},$$

$$\begin{pmatrix} u \\ d \end{pmatrix} \sim 0, \quad \begin{pmatrix} N & \nu \\ E & e \end{pmatrix} \sim \frac{1}{2}, \quad \begin{pmatrix} E^c \\ N^c \end{pmatrix} \sim 0.$$

All fields are left-handed, with $SU(2)_L$ doublets vertical [$T_{3L} = \pm 1/2$ for upper (lower) components] and $SU(2)_N$ doublets horizontal [$T_{3N} = \pm 1/2$ for right (left) components].

Higgs sector:

$$\begin{pmatrix} \phi_1^0 & \phi_2^0 \\ \phi_1^- & \phi_2^- \end{pmatrix} \sim \frac{1}{2}, \quad \begin{pmatrix} \eta^+ \\ \eta^0 \end{pmatrix} \sim 0, \quad (\chi_1^0, \chi_2^0) \sim -\frac{1}{2}.$$

Allowed Yukawa couplings are $(d\phi_1^0 - u\phi_1^-)d^c - (d\phi_2^0 - u\phi_2^-)h^c$, $(u\eta^0 - d\eta^+)u^c$, $(h^c\chi_2^0 - d^c\chi_1^0)h$, $(N\phi_2^- - \nu\phi_1^- - E\phi_2^0 + e\phi_1^0)e^c$, $(E\eta^+ - N\eta^0)n^c - (e\eta^+ - \nu\eta^0)\nu^c$, $(EE^c - NN^c)\chi_2^0$ – $(eE^c - \nu N^c)\chi_1^0$, $(E^c\phi_1^- - N^c\phi_1^0)n^c - (E^c\phi_2^- - N^c\phi_2^0)\nu^c$.
Thus m_d, m_e come from $\langle\phi_1^0\rangle = v_1$; m_u, m_ν from $\langle\eta^0\rangle = v_3$; m_h, m_E, m_N from $\langle\chi_2^0\rangle = u_2$.

This structure conserves L and guarantees the absence of tree-level flavor-changing neutral currents. $SU(2)_N$ is completely broken by u_2 so that $m_X^2 = (1/2)g_N^2 u_2^2$ for each $X_{1,2,3}$ gauge boson. Whereas $X_3 = Z'$ has $L = 0$, $(X_1 \mp iX_2)/\sqrt{2}$ are the neutral analogs of $W_R^\pm$ with $L = \pm 1$ and can be dark matter. Consider now the addition of a Higgs triplet $(\xi_3^0, \xi_4^0, \xi_5^0) \sim 1$, with $\langle \xi_3^0 \rangle = u_3$ and $\langle \xi_5^0 \rangle = u_5$. Then L is broken by u_5 to $(-1)^L$ and neutrinos obtain seesaw Majorana masses. There is also a large Majorana mass term for n^c from u_3 so that there is no more massless particle in the (N, N^c, n^c) sector.

X_1 Vector Boson as Dark Matter

Gauge boson masses:

$$m_W^2 = \frac{1}{2} g_2^2 (v_1^2 + v_3^2), \quad m_{X_{1,2}}^2 = \frac{1}{2} g_N^2 [u_2^2 + 2(u_3 \mp u_5)^2],$$

$$m_{Z,Z'}^2 = \frac{1}{2} \begin{pmatrix} (g_1^2 + g_2^2)(v_1^2 + v_3^2) & -g_N \sqrt{g_1^2 + g_2^2} v_1^2 \\ -g_N \sqrt{g_1^2 + g_2^2} v_1^2 & g_N^2 [u_2^2 + v_1^2 + 4(u_3^2 + u_5^2)] \end{pmatrix}$$

Let X_1 be the lightest particle of odd $R = (-1)^{3B+L+2j}$, then it can be a viable dark-matter candidate.

Note that there is no $X_1 X_1 Z'$ interaction; only $X_1 X_2 Z'$ is allowed. However, $X_1 X_1$ annihilation to $d\bar{d}, \nu\bar{\nu}, e^- e^+, \phi_1 \phi_1^\dagger$ is possible through h, N, E, ϕ_2 exchange respectively. The nonrelativistic cross section $\times$ relative velocity is $(g_N^4 m_X^2 / 72\pi) \times$

$$\sum_h \frac{3}{(m_h^2 + m_X^2)^2} + \sum_E \frac{2}{(m_E^2 + m_X^2)^2}$$

$$+ \frac{2}{(m_{\phi_2}^2 + m_X^2)^2} + \frac{1}{m_X^2 (m_{\phi_2}^2 + m_X^2)} + \frac{3}{8 m_X^4}.$$

where the sum over h, E is for 3 generations.

The factor of 3 for h is the number of colors, the factor of 2 for E, ϕ_2 is to account for them being doublets. Let $\sigma v_{rel} > 0.86$ pb be the benchmark for the correct dark-matter relic abundance and assuming $g_N^2 = g_2^2 = e^2/\sin^2\theta_W \simeq 0.4$ with all exotic particle masses equal, the upper bound $m_X < 1.28$ TeV is obtained.

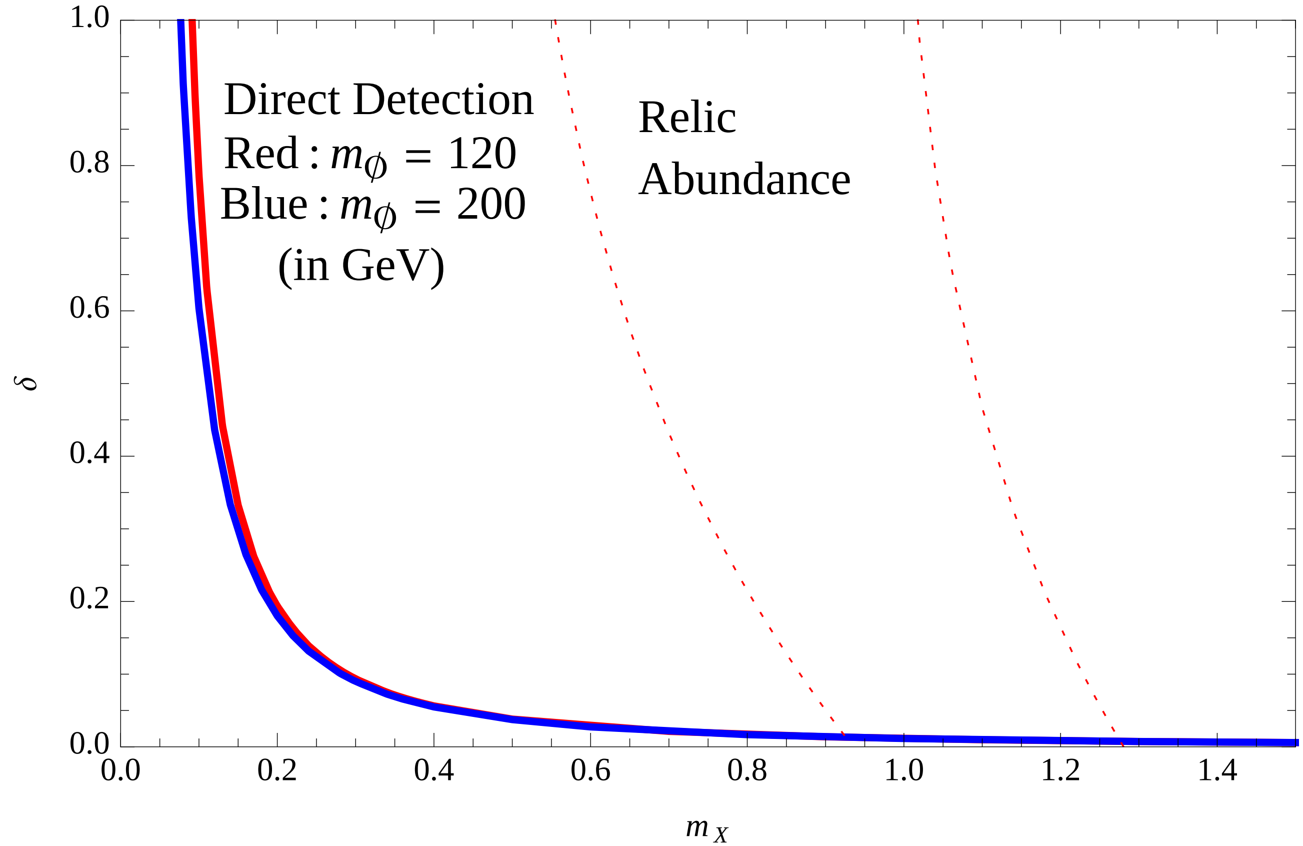
The fundamental interaction of X_1 with nuclei is only through the d quark, but there are induced effective interactions. [Hisano/Ishiwata/Nagata/Yamanaka(2010)]

The coherent spin-independent elastic cross section is

$$\sigma_0 = \frac{1}{\pi}\left(\frac{m_N}{m_X}\right)^2 \left|\frac{Zf_p + (A-Z)f_n}{A}\right|^2,$$

where f_p and f_n are form factors, and (Z, A) are the atomic and mass numbers of the target nucleus, say ^{73}Ge with $Z = 32$ and $A - Z = 41$.

Using the recent CDMS(2010) result that $\sigma_0 < 2.2 \times 10^{-7}$ pb $(m_X/1 \text{ TeV})^{0.86}$ in the range $0.3 < m_X < 1.0$ TeV, a lower bound on m_h (the one that couples to d) as a function of m_X is obtained.



Allowed region in $\delta = m_h/m_X - 1$ versus m_X (in TeV)
from relic abundance and from CDMS direct search.

LHC Phenomenology

Since $m_X \sim 1$ TeV or less, Z' is expected to be observable at the LHC, with $B(Z' \to \mu^- \mu^+) = 1/16$. It is in fact the linear combination $\sqrt{5/8} Z_\chi + \sqrt{3/8} Z_\psi$ from E_6 models. Distinguishing this Z' from others [Godfrey/Martin(2008)] is possible from
$\Gamma(Z' \to t\bar{t})/\Gamma(Z' \to \mu^- \mu^+) = 0$, and
$\Gamma(Z' \to b\bar{b})/\Gamma(Z' \to \mu^- \mu^+) = 3$.

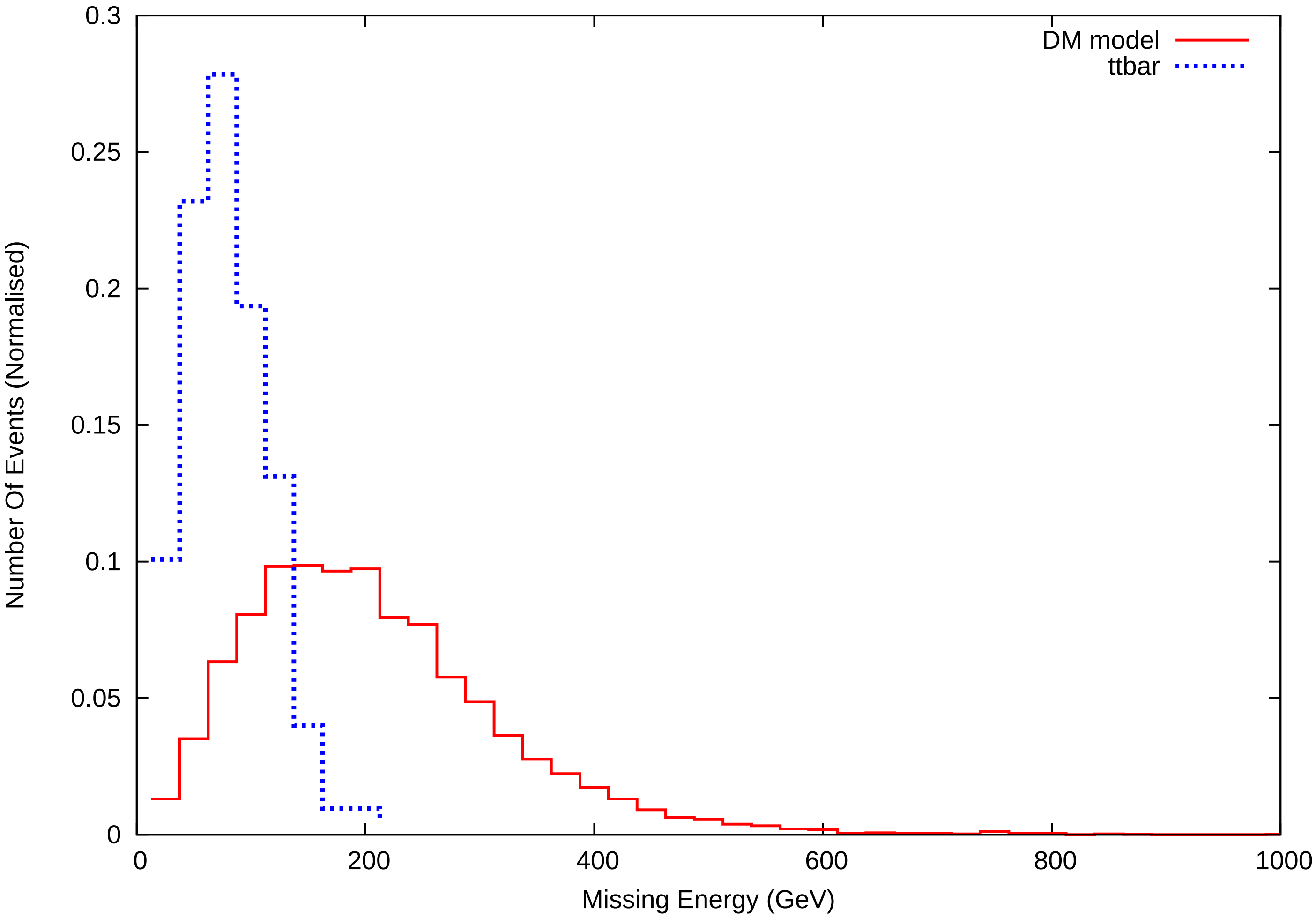
Since $Z - Z'$ mixing is limited to a few $\times 10^{-4}$, which is of order v_1^2/u_2^2, v_1 may be around 10 GeV. This means that the ϕ_1 Yukawa coupling to b quarks is large, making ϕ_1^0 observable at the LHC [Balazs/Diaz-Cruz/He/Tait/Yuan(1999)].

A favorable scenario for observing the structure of this model is possible with the following spectrum:

$$m_h > m_{X_2} > m_{E,N} > m_{X_1}.$$

[Bhattacharya/Diaz-Cruz/Ma/Wegman(2011)].
Consider the production d + gluon to $h + X_1$. Now h will decay into $X_1 d$ and $X_2 d$, then X_2 will decay into $E^+ l^-$, $E^- l^+$, $\bar{N}\nu$, $N\bar{\nu}$, and $E^+ \to X_1 l^+$, $E^- \to X_1 l^-$, $\bar{N} \to X_1 \bar{\nu}$, $N \to X_1 \nu$.

This means that about 1/4 of the time, $pp \to hX_1$ will end up with one quark jet + missing energy + $l_i^+ l_j^-$. We choose $m_{X_1} = 700$ GeV, $m_{E,N} = 735$ GeV, $m_{X_2} = 770$ GeV, $m_h = 980$ GeV, and the basic cuts $p_T > 20$ GeV and $|\eta| < 2.5$ for each lepton and $p_T > 50$ GeV for the quark jet. The background is then suppressed by choosing a large missing energy cut. At the LHC with $E_{cm} = 14$ TeV, we find a signal cross section of 1.6 fb with essentially no background if a cut on missing $E_t > 200$ GeV is made.



DM model
ttbar
Number Of Events (Normalised)
Missing Energy (GeV)
0.3
0.25
0.2
0.15
0.1
0.05
0
0
200
400
600
800
1000

Conclusion

Instead of a spin-zero scalar or a spin-one-half fermion or combinations of the two, dark matter may be a spin-one vector boson. The first such example from a unifiable theory based on E_6 has been proposed. This $SU(2)_N$ extension of the Standard Model allows one of the 3 gauge bosons, say X_1, to be the lightest particle with odd R parity. From the requirement of relic abundance, $m_X \sim 1$ TeV or less is predicted. It is verifiable at the LHC.