Dark Vector-Gauge-Boson Model and the LHC

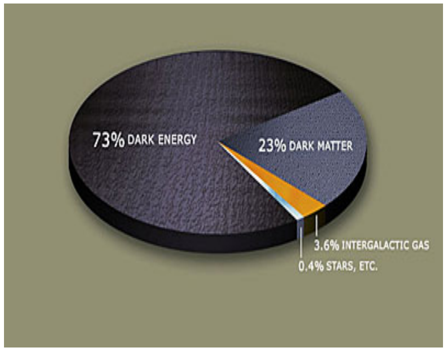
Subhaditya Bhattacharya

References

- Phys.Rev. D85 (2012) 055008 [arXiv:1107.2093] with *J. Lorenzo Diaz-Cruz, Ernest Ma and Daniel Wegman*

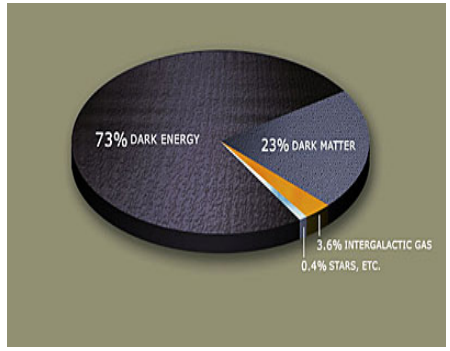
Vector Boson DM: Introduction

- Existence of Dark Matter (DM) is well motivated:



Vector Boson DM: Introduction

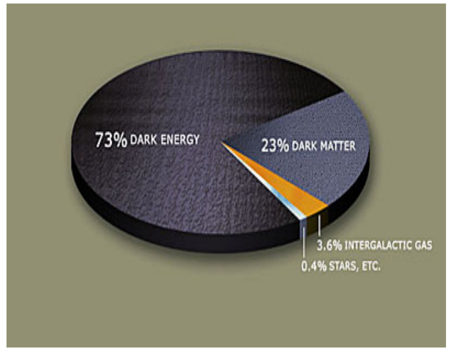
- Existence of Dark Matter (DM) is well motivated:



- Nature of DM is debated: scalars, fermions or vector bosons ?

Vector Boson DM: Introduction

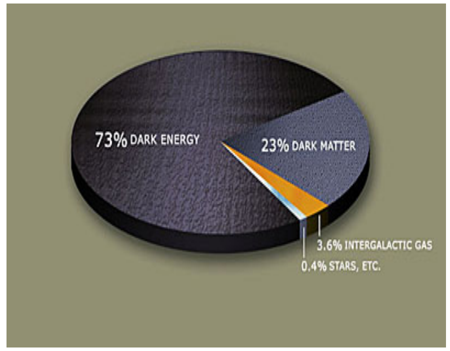
- Existence of Dark Matter (DM) is well motivated:



- Nature of DM is debated: scalars, fermions or vector bosons ?
- Vector Boson DM has already appeared in UED or little Higgs models.

Vector Boson DM: Introduction

- Existence of Dark Matter (DM) is well motivated:



- Nature of DM is debated: scalars, fermions or vector bosons ?
- Vector Boson DM has already appeared in UED or little Higgs models.
- Our model predicts Vector Boson DM, which is a bit less exotic one!

The Model: Outline

- A model based on $SU(3)_C \times SU(2)_L \times U(1)_Y \times SU(2)_N$
- $SU(2)_N$ vector gauge bosons (X_1, X_2, X_3) are neutral and one of them can be DM

The Model: Outline

- A model based on $SU(3)_C \times SU(2)_L \times U(1)_Y \times SU(2)_N$
- $SU(2)_N$ vector gauge bosons (X_1, X_2, X_3) are neutral and one of them can be DM
- An extra global U(1) symmetry S imposed, so that $(-1)^L$, where $L = S + T_{3N}$ conserved
- $R \equiv (-1)^{3B+L+2S}$ holds although non-supersymmetric

The Model: Outline

- A model based on $SU(3)_C \times SU(2)_L \times U(1)_Y \times SU(2)_N$
- $SU(2)_N$ vector gauge bosons (X_1, X_2, X_3) are neutral and one of them can be DM
- An extra global U(1) symmetry S imposed, so that $(-1)^L$, where $L = S + T_{3N}$ conserved
- $R \equiv (-1)^{3B+L+2S}$ holds although non-supersymmetric
- See if the DM is really a good one !
- LHC is on $\longrightarrow$ Any possible signatures ?

Particle content: $SU(3)_C \times SU(2)_L \times U(1)_Y \times SU(2)_N \times S$

- $$\begin{pmatrix} u \\ d \end{pmatrix} \sim (3, 2, 1/6, 1; 0), \quad u^c \sim (3^*, 1, -2/3, 1; 0),$$
  $$(h^c, d^c) \sim (3^*, 1, 1/3, 2; -1/2), \quad h \sim (3, 1, -1/3, 1; 1),$$
  $$\begin{pmatrix} N & \nu \\ E & e \end{pmatrix} \sim (1, 2, -1/2, 2; 1/2), \quad \begin{pmatrix} E^c \\ N^c \end{pmatrix} \sim (1, 2, 1/2, 1; 0),$$
  $$e^c \sim (1, 1, 1, 1; -1), \quad (\nu^c, n^c) \sim (1, 1, 0, 2; -1/2),$$

Particle content: $SU(3)_C \times SU(2)_L \times U(1)_Y \times SU(2)_N \times S$

- $$\begin{pmatrix} u \\ d \end{pmatrix} \sim (3, 2, 1/6, 1; 0), \quad u^c \sim (3^*, 1, -2/3, 1; 0),$$
$$(h^c, d^c) \sim (3^*, 1, 1/3, 2; -1/2), \quad h \sim (3, 1, -1/3, 1; 1),$$
$$\begin{pmatrix} N & \nu \\ E & e \end{pmatrix} \sim (1, 2, -1/2, 2; 1/2), \quad \begin{pmatrix} E^c \\ N^c \end{pmatrix} \sim (1, 2, 1/2, 1; 0),$$
$$e^c \sim (1, 1, 1, 1; -1), \quad (\nu^c, n^c) \sim (1, 1, 0, 2; -1/2),$$

- $Q = T_{3L} + Y$ is electric charge, $L = S + T_{3N}$ is generalized lepton number !

Particle content: $SU(3)_C \times SU(2)_L \times U(1)_Y \times SU(2)_N \times S$

- $$\begin{pmatrix} u \\ d \end{pmatrix} \sim (3, 2, 1/6, 1; 0), \quad u^c \sim (3^*, 1, -2/3, 1; 0),$$
  $$(h^c, d^c) \sim (3^*, 1, 1/3, 2; -1/2), \quad h \sim (3, 1, -1/3, 1; 1),$$
  $$\begin{pmatrix} N & \nu \\ E & e \end{pmatrix} \sim (1, 2, -1/2, 2; 1/2), \quad \begin{pmatrix} E^c \\ N^c \end{pmatrix} \sim (1, 2, 1/2, 1; 0),$$
  $$e^c \sim (1, 1, 1, 1; -1), \quad (\nu^c, n^c) \sim (1, 1, 0, 2; -1/2),$$
- $Q = T_{3L} + Y$ is electric charge, $L = S + T_{3N}$ is generalized lepton number !
- h, N, E, n^c are odd under R, SM ones are even.

Higgs sector: $SU(3)_C \times SU(2)_L \times U(1)_Y \times SU(2)_N \times S$

The Higgs sector consists of one bidoublet, two doublets, and one triplet:

$$\begin{pmatrix} \phi_1^0 & \phi_3^0 \\ \phi_1^- & \phi_3^- \end{pmatrix} \sim (1,2,-1/2,2;1/2), \quad \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix} \sim (1,2,1/2,1;0),$$

$$(\chi_1^0, \chi_2^0) \sim (1,1,0,2;-1/2), \begin{pmatrix} \Delta_2^0/\sqrt{2} & \Delta_3^0 \\ \Delta_1^0 & -\Delta_2^0/\sqrt{2} \end{pmatrix} \sim (1,1,0,3;1).$$

Higgs sector: $SU(3)_C \times SU(2)_L \times U(1)_Y \times SU(2)_N \times S$

The Higgs sector consists of one bidoublet, two doublets, and one triplet:

$$\begin{pmatrix} \phi_1^0 & \phi_3^0 \\ \phi_1^- & \phi_3^- \end{pmatrix} \sim (1,2,-1/2,2;1/2), \quad \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix} \sim (1,2,1/2,1;0),$$

$$(\chi_1^0, \chi_2^0) \sim (1,1,0,2;-1/2), \begin{pmatrix} \Delta_2^0/\sqrt{2} & \Delta_3^0 \\ \Delta_1^0 & -\Delta_2^0/\sqrt{2} \end{pmatrix} \sim (1,1,0,3;1).$$

- $\langle \phi_1^0 \rangle = v_1$, $\langle \phi_2^0 \rangle = v_2$, $\langle \Delta_1^0 \rangle = u_1$, and $\langle \chi_2^0 \rangle = u_2$, $\langle \Delta_3^0 \rangle = u_3$

Higgs sector: $SU(3)_C \times SU(2)_L \times U(1)_Y \times SU(2)_N \times S$

The Higgs sector consists of one bidoublet, two doublets, and one triplet:

$$\begin{pmatrix} \phi_1^0 & \phi_3^0 \\ \phi_1^- & \phi_3^- \end{pmatrix} \sim (1, 2, -1/2, 2; 1/2), \quad \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix} \sim (1, 2, 1/2, 1; 0),$$

$$(\chi_1^0, \chi_2^0) \sim (1, 1, 0, 2; -1/2), \begin{pmatrix} \Delta_2^0/\sqrt{2} & \Delta_3^0 \\ \Delta_1^0 & -\Delta_2^0/\sqrt{2} \end{pmatrix} \sim (1, 1, 0, 3; 1).$$

- $\langle \phi_1^0 \rangle = v_1$, $\langle \phi_2^0 \rangle = v_2$, $\langle \Delta_1^0 \rangle = u_1$, and $\langle \chi_2^0 \rangle = u_2$, $\langle \Delta_3^0 \rangle = u_3$
- $\phi_3, {\chi_1}^0$ are odd under R

Gauge Bosons

- Spontaneous breaking of $SU(2)_N \times SU(2)_L \times U(1)_Y$ yields:

$$m_W^2 = \frac{1}{2} g_2^2 (v_1^2 + v_2^2), \quad m_{X_{1,2}}^2 = \frac{1}{2} g_N^2 [u_2^2 + v_1^2 + 2(u_1 \mp u_3)^2],$$

$$m_{Z,X_3}^2 = \frac{1}{2} \begin{pmatrix} (g_1^2 + g_2^2)(v_1^2 + v_2^2) & -g_N \sqrt{g_1^2 + g_2^2} v_1^2 \\ -g_N \sqrt{g_1^2 + g_2^2} v_1^2 & g_N^2 [u_2^2 + v_1^2 + 4(u_1^2 + u_3^2)] \end{pmatrix}.$$

Gauge Bosons

- Spontaneous breaking of $SU(2)_N \times SU(2)_L \times U(1)_Y$ yields:

$$m_W^2 = \frac{1}{2} g_2^2 (v_1^2 + v_2^2), \quad m_{X_{1,2}}^2 = \frac{1}{2} g_N^2 [u_2^2 + v_1^2 + 2(u_1 \mp u_3)^2],$$

$$m_{Z,X_3}^2 = \frac{1}{2} \begin{pmatrix} (g_1^2 + g_2^2)(v_1^2 + v_2^2) & -g_N \sqrt{g_1^2 + g_2^2} v_1^2 \\ -g_N \sqrt{g_1^2 + g_2^2} v_1^2 & g_N^2 [u_2^2 + v_1^2 + 4(u_1^2 + u_3^2)] \end{pmatrix}.$$

- SM gauge bosons and $X_3 (= Z')$ are even R, $X_{1,2}$ have odd R
- All those odd under R : $N, E, n^c, h, \phi_3, {\chi_1}^0, X_{1,2}$

Gauge Bosons

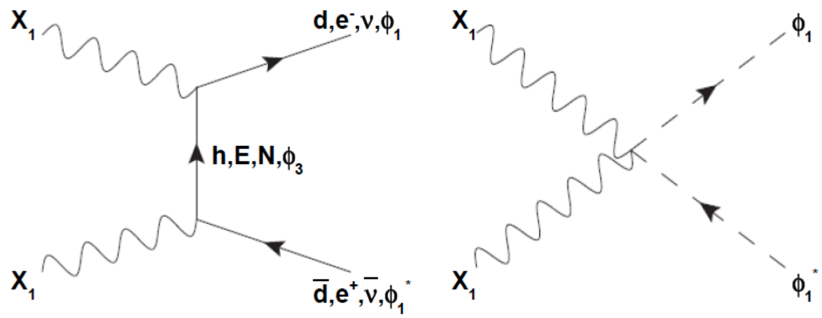
- Spontaneous breaking of $SU(2)_N \times SU(2)_L \times U(1)_Y$ yields:

$$m_W^2 = \frac{1}{2}g_2^2(v_1^2 + v_2^2), \quad m_{X_{1,2}}^2 = \frac{1}{2}g_N^2[u_2^2 + v_1^2 + 2(u_1 \mp u_3)^2],$$

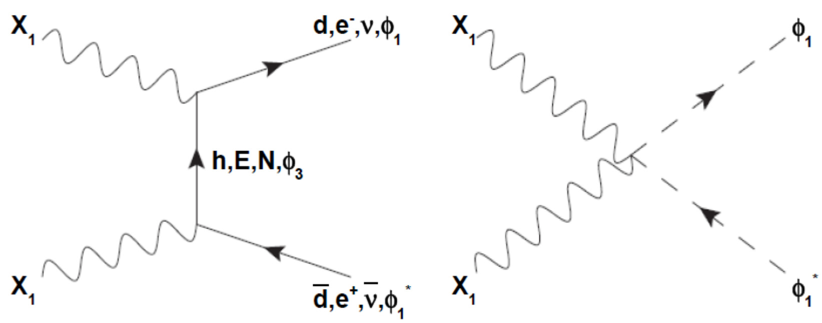
$$m_{Z,X_3}^2 = \frac{1}{2}\begin{pmatrix} (g_1^2 + g_2^2)(v_1^2 + v_2^2) & -g_N\sqrt{g_1^2 + g_2^2}v_1^2 \\ -g_N\sqrt{g_1^2 + g_2^2}v_1^2 & g_N^2[u_2^2 + v_1^2 + 4(u_1^2 + u_3^2)] \end{pmatrix}.$$

- SM gauge bosons and $X_3 (= Z')$ are even R, $X_{1,2}$ have odd R
- All those odd under R : $N, E, n^c, h, \phi_3, {\chi_1}^0, X_{1,2}$
- If X_1 is lighter than X_2, it is a DM !!

$X_1 X_1$ annihilation to SM model

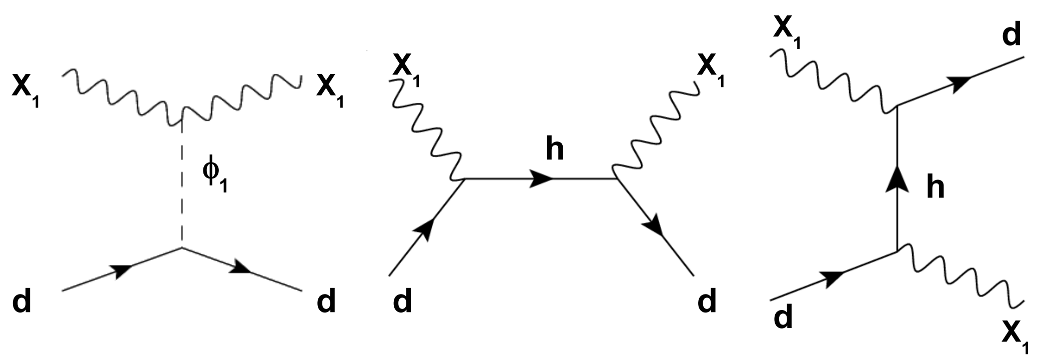


$X_1 X_1$ annihilation to SM model



$$\sigma v_{rel} = \frac{g_N^4 m_X^2}{72\pi}\left[\sum_h \frac{3}{(m_h^2+m_X^2)^2} + \sum_E \frac{2}{(m_E^2+m_X^2)^2} + \frac{2}{(m_{\phi_3}^2+m_X^2)^2} + \frac{1}{m_X^2(m_{\phi_3}^2+m_X^2)} + \frac{3}{8m_X^4}\right]$$

Direct dark matter search



- Spin-independent elastic cross section for X_1 scattering off a nucleus

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

Use ${}^{73}Ge$ with $Z = 32$ and $A - Z = 41$ in accordance with CDMS !

Dark matter constraints on the model

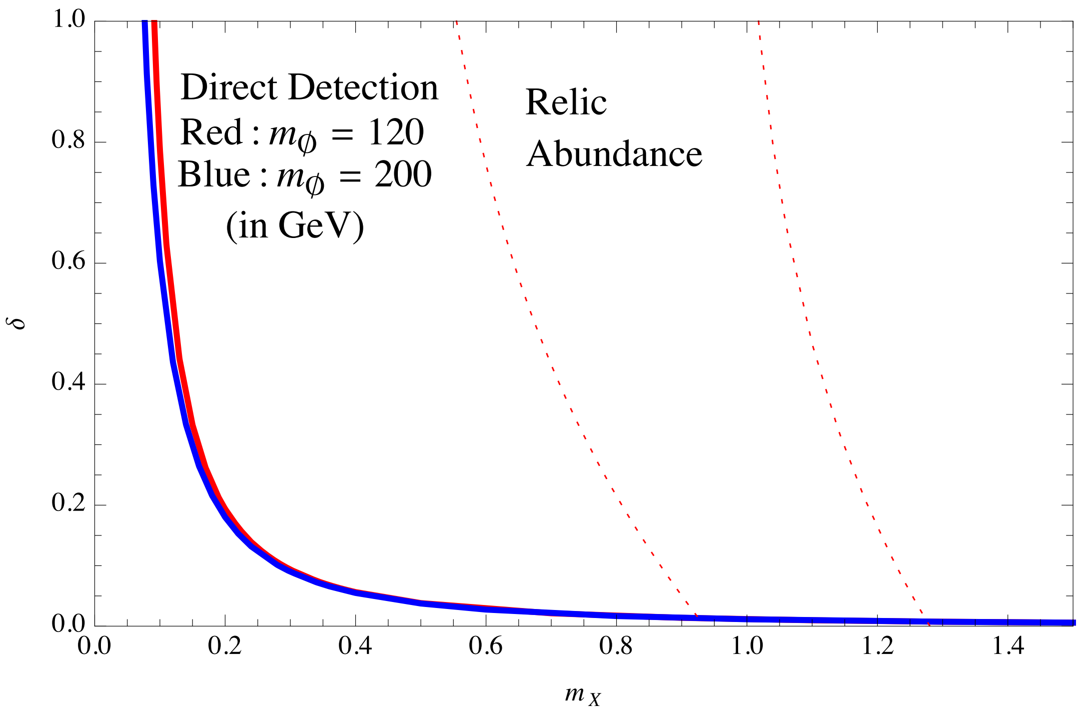


Figure 1: $\delta = m_h/m_X - 1$ versus m_X (in TeV) plot showing relic abundance and CDMS direct search bounds. $\sigma v_{rel} = 0.91 \pm 0.05$ pb

Collider search

- A possible mass heirarchy :

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

- Consider at LHC:

- $h \longrightarrow X_2 d$, then $X_2 \longrightarrow E^+ l^-, E^- l^+$, and $E^+ \rightarrow X_1 l^+$, $E^- \rightarrow X_1 l^-$

Collider search

- A possible mass heirarchy :

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

- Consider at LHC:

- $h \longrightarrow X_2 d$, then $X_2 \longrightarrow E^+ l^-, E^- l^+$, and $E^+ \rightarrow X_1 l^+$, $E^- \rightarrow X_1 l^-$

- Hence, $pp \rightarrow hX_1$ will end up with $\ell^+\ell^- + 1jet + \not{E}_T$

Signal: $\ell^+\ell^- + 1jet + \not{E}_T$

How to tackle background?

Signal: $\ell^+\ell^- + 1jet + \not{E}_T$

How to tackle background?

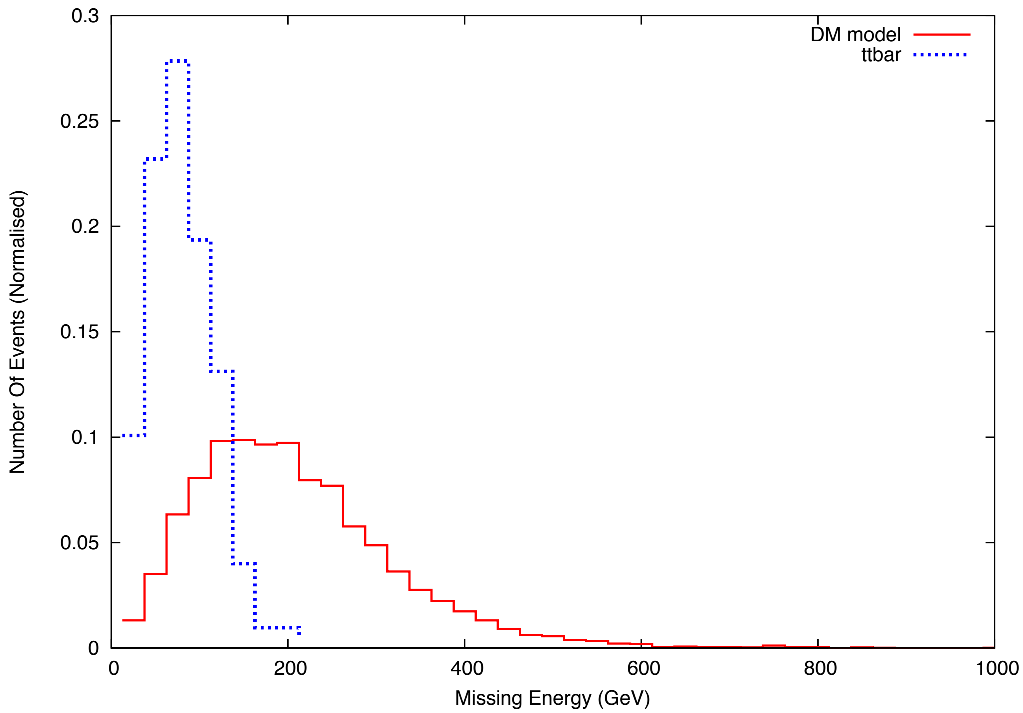


Figure 2: Normalized signal and background distributions as functions of MET

Event rates: $\ell^+\ell^- + 1jet + \not{E}_T$

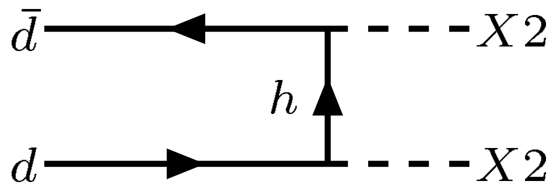
- $m_{X_1} =$ 700 GeV, $m_{E,N} =$ 735 GeV, $m_{X_2} =$ 770 GeV, and $m_h =$ 980 GeV

Event rates for $\ell^+\ell^- + 1jet + \not{E}_T$ with $p_{T_\ell} > 20$, $p_{T_j} > 50$					
$\not{E}_T > 100$		$\not{E}_T > 200$		$\not{E}_T > 300$	
Signal	Background	Signal	Background	Signal	Background
3.07	237	1.6	0	0.59	0

Table 1: Event rates (fb) for $\ell^+\ell^- + 1jet + \not{E}_T$ channel at LHC with $E_{cm} = 14$ TeV

Signal: $\ell^+\ell^-\ell^+\ell^- + \not{E}_T$

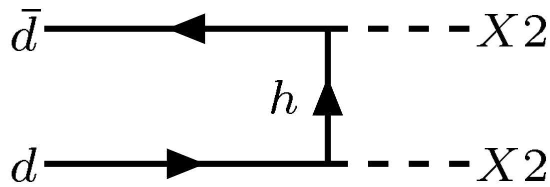
Consider: $pp \to X_2 X_2$



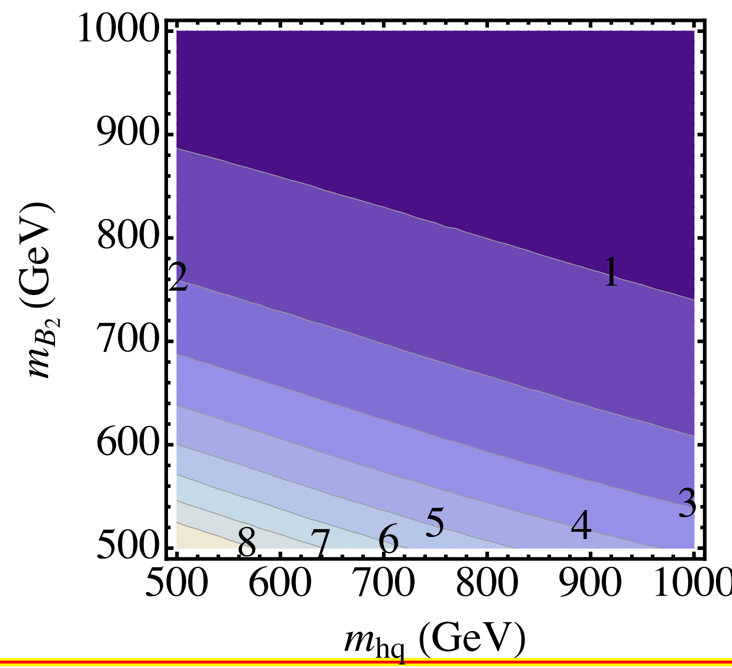
and $X_2 \longrightarrow \ell^+\ell^- X_1$. Hence, $pp \longrightarrow \ell^+\ell^-\ell^+\ell^- + \not{E}_T$ (Negligible background through ZZZ or $4W$)

Signal: $\ell^+\ell^-\ell^+\ell^- + \not{E}_T$

Consider: $pp \to X_2 X_2$



and $X_2 \longrightarrow \ell^+\ell^- X_1$. Hence, $pp \longrightarrow \ell^+\ell^-\ell^+\ell^- + \not{E}_T$ (Negligible background through ZZZ or $4W$)



Concluding remarks

- Relatively simpler model with vector boson dark matter !
- Identification of X_1 as dark-matter constrains the $SU(2)_N$ breaking scale to be about 1 TeV
- At LHC with $E_{cm} = 14$ TeV, we expect to see $\ell^+\ell^- + 1jet + \not{E}_T$, even with luminosity 10 fb^{-1}, or a $\ell^+\ell^-\ell^+\ell^- + \not{E}_T$, which are unique to models of this sort.

Thank You

Yukawa Interactions

$$(d\phi_1^0 - u\phi_1^-)d^c - (d\phi_3^0 - u\phi_3^-)h^c, \quad (u\phi_2^0 - d\phi_2^+)u^c, \quad (h^c\chi_2^0 - d^c\chi_1^0)h,$$
$$(N\phi_3^- - \nu\phi_1^- - E\phi_3^0 + e\phi_1^0)e^c, \quad (E\phi_2^+ - N\phi_2^0)n^c - (e\phi_2^+ - \nu\phi_2^0)\nu^c,$$
$$(EE^c - NN^c)\chi_2^0 - (eE^c - \nu N^c)\chi_1^0, \quad n^c n^c \Delta_1^0 + (n^c\nu^c + \nu^c n^c)\Delta_2^0/\sqrt{2} - \nu^c\nu^c\Delta_3^0.$$

Yukawa Interactions

$$(d\phi_1^0 - u\phi_1^-)d^c - (d\phi_3^0 - u\phi_3^-)h^c, \quad (u\phi_2^0 - d\phi_2^+)u^c, \quad (h^c\chi_2^0 - d^c\chi_1^0)h,$$
$$(N\phi_3^- - \nu\phi_1^- - E\phi_3^0 + e\phi_1^0)e^c, \quad (E\phi_2^+ - N\phi_2^0)n^c - (e\phi_2^+ - \nu\phi_2^0)\nu^c,$$
$$(EE^c - NN^c)\chi_2^0 - (eE^c - \nu N^c)\chi_1^0, \quad n^c n^c \Delta_1^0 + (n^c\nu^c + \nu^c n^c)\Delta_2^0/\sqrt{2} - \nu^c\nu^c\Delta_3^0.$$

- $\langle\phi_1^0\rangle = v_1$, $\langle\phi_2^0\rangle = v_2$, $\langle\Delta_1^0\rangle = u_1$, and $\langle\chi_2^0\rangle = u_2$, are scalar fields with $L = 0$, while $\langle\Delta_3^0\rangle = u_3$, which breaks L to $(-1)^L$. Thus m_d, m_e come from v_1, and $m_u, m_{\nu\nu^c}(= -m_{Nn^c})$ come from v_2, whereas $m_h, m_E(= -m_{NN^c})$ come from u_2, and n^c, ν^c obtain Majorana masses from u_1 and u_3. The scalar fields $\phi_3^{0,-}$ and Δ_2^0 have $L = 1$, whereas χ_1^0 has $L = -1$ and Δ_3^0 has $L = 2$.

Back up: Scalar Potential

$$
\begin{aligned}
V &= \mu_1^2 Tr(\phi_{13}^\dagger \phi_{13}) + \mu_2^2 \phi_2^\dagger \phi_2 + \mu_\chi^2 \chi\chi^\dagger + \mu_\Delta^2 Tr(\Delta^\dagger \Delta) \\
&+ (\mu_{22}\tilde{\chi}\phi_{13}^\dagger \tilde{\phi}_2 + \mu_{12}\chi\Delta\tilde{\chi}^\dagger + \mu_{23}\tilde{\chi}\Delta\chi^\dagger + H.c.) + \frac{1}{2}\lambda_1 [Tr(\phi_{13}^\dagger \phi_{13})]^2 + \frac{1}{2}\lambda_2 (\phi_2^\dagger \phi_2)^2 \\
&+ \frac{1}{2}\lambda_3 Tr(\phi_{13}^\dagger \phi_{13}\phi_{13}^\dagger \phi_{13}) + \frac{1}{2}\lambda_4 (\chi\chi^\dagger)^2 + \frac{1}{2}\lambda_5 [Tr(\Delta^\dagger \Delta)]^2 + \frac{1}{4}\lambda_6 Tr(\Delta^\dagger \Delta - \Delta\Delta^\dagger)^2 \\
&+ f_1 \chi\phi_{13}^\dagger \phi_{13}\chi^\dagger + f_2 \chi\tilde{\phi}_{13}^\dagger \tilde{\phi}_{13}\chi^\dagger + f_3 \phi_2^\dagger \phi_{13}\phi_{13}^\dagger \phi_2 + f_4 \phi_2^\dagger \tilde{\phi}_{13}\tilde{\phi}_{13}^\dagger \phi_2 + f_5 (\phi_2^\dagger \phi_2)(\chi\chi^\dagger) \\
&+ f_6 (\chi\chi^\dagger) Tr(\Delta^\dagger \Delta) + f_7 \chi(\Delta^\dagger \Delta - \Delta\Delta^\dagger)\chi^\dagger + f_8 (\phi_2^\dagger \phi_2) Tr(\Delta^\dagger \Delta) \\
&+ f_9 Tr(\phi_{13}^\dagger \phi_{13}) Tr(\Delta^\dagger \Delta) + f_{10} Tr(\phi_{13}(\Delta^\dagger \Delta - \Delta\Delta^\dagger)\phi_{13}^\dagger),
\end{aligned}
$$

where

$$
\tilde{\phi}_2 = \begin{pmatrix} \bar{\phi}_2^0 \\ -\phi_2^- \end{pmatrix}, \quad \tilde{\phi}_{13} = \begin{pmatrix} \phi_3^+ & -\phi_1^+ \\ -\bar{\phi}_3^0 & \bar{\phi}_1^0 \end{pmatrix}, \quad \tilde{\chi} = (\bar{\chi}_2^0, -\bar{\chi}_1^0),
$$

and the μ_{23} term breaks L softly to $(-1)^L$.

Back up: Neutrino masses through Seesaw

We have five neutral fermions per family. Two have odd L parity, i.e. ν and ν^c. Their 2×2 mass matrix is of the usual seesaw form, i.e.

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D \\ m_D & M_3 \end{pmatrix},$$

where m_D comes from v_2 and M_3 from u_3. The other three have even L parity, i.e. N, N^c, and n^c.

Back up: Neutrino masses through Seesaw

We have five neutral fermions per family. Two have odd L parity, i.e. ν and ν^c. Their 2×2 mass matrix is of the usual seesaw form, i.e.

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D \\ m_D & M_3 \end{pmatrix},$$

where m_D comes from v_2 and M_3 from u_3. The other three have even L parity, i.e. N, N^c, and n^c. 3×3 mass matrix is given by

$$\mathcal{M}_N = \begin{pmatrix} 0 & -m_E & -m_D \\ -m_E & 0 & 0 \\ -m_D & 0 & M_1 \end{pmatrix},$$

where m_E comes from u_2 and M_1 from u_1. Since $(-1)^L$ is exactly conserved, ν, ν^c do not mix with N, N^c, n^c.