$SU(2)_L \times SU(2)_R$ minimal DM with simplified Higgs sector

Takaaki Nomura (KIAS)

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1. Introduction

$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ gauge extension from SM

Pati, Salam (1974) Mohapatra, Senjaovic (1974)

- ❖ **Right-handed fermions belong to $SU(2)_R$ doublet**
- ❖ **New massive gauge bosons: W' and Z'**
- ❖ **Phenomenologically interesting**

There are several way to break the symmetry

- ❖ **By $SU(2)_L$ triplet + $SU(2)_R$ triplet + bidoublet Higgs VEV**
- ❖ **By $SU(2)_L$ doublet + $SU(2)_R$ doublet + bidoublet Higgs VEV**

✧ **Higgs sector can be simplified loosening exact left-right symmetry**

Introducing a DM to left-right model

- ❖ **Right-handed neutrino DM** Bezrukov, Hettmansperg, Lindner (2009) Nemevsek, Sanjanovic, Zhang (2012) Etc.
- ❖ **Higher multiplet (minimal DM)** Heeck, Patra (2015)

We consider a scenario:
$SU(2)_R$ doublet + bidoublet Higgs + minimal DM scenario

Outline of our analysis

Constructing a minimal DM model in left-right model

- We consider simplified Higgs sector: bidoublet + $SU(2)_R$ doublet
- $SU(2)_{R,L}$ multiplet fermion(scalar) as a DM candidate
- Looking for minimal DM candidate

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- **Looking for minimal DM candidate**

Investigate DM phenomenology

- **We estimate mass splitting inside DM multiplet**

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- Compute relic density of DM

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- Compute relic density of DM
- Discuss direct detection and collider physics

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- **$SU(2)_R$ multiplet fermion as a DM candidate**
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Investigate DM phenomenology

- **We estimate mass splitting inside DM multiplet**
- **Compute relic density of DM**
- **Discuss direct detection and collider physics**
- **We take W' mass as 2 TeV**
  - Motivated by diboson excess at LHC 8 TeV

Unfortunately no significant excess is found at LHC 13 TeV
But it is not completely excluded yet

2. A model

Particle contents: $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

Scalar: $H:(2,\bar{2},0), \quad H_R:(1,2,1)$ ***Simplified scalar sector**

Fermion: $q_L:(2,1,1/3), \quad q_R:(1,2,1/3), \quad \ell_L:(2,1,-1), \quad \ell_R:(1,2,-1)$

- ✓ We can add singlet fermion S(1,1,0) for inverse seesaw mechanism

Scalar VEV and symmetry breaking

$$\langle H \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} k_1 & 0 \\ 0 & k_2 \end{pmatrix}, \quad \langle H_R \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_R \end{pmatrix}$$

$$SU(2)_R \times SU(2)_L \times U(1)_{B-L} \xrightarrow{\langle H_R \rangle} SU(2)_L \times U(1)_Y \xrightarrow{\langle H \rangle} U(1)_{EM}$$

$$Q = T_L^3 + T_R^3 + \frac{1}{2} Q_{B-L}, \quad \left(Y = T_R^3 + \frac{1}{2} Q_{B-L} \right)$$

Mass eigenstate of gauge boson

$$\begin{pmatrix} W_L^\pm \\ W_R^\pm \end{pmatrix} = \begin{pmatrix} \cos\xi & \sin\xi \\ -\sin\xi & \cos\xi \end{pmatrix} \begin{pmatrix} W^\pm \\ W'^\pm \end{pmatrix},$$

$$\begin{pmatrix} W_{3L} \\ W_{3R} \\ X \end{pmatrix} = \begin{pmatrix} c_W c_X & c_W s_X & s_W \\ -s_W s_M c_X - c_M s_X & -s_W s_M s_X + c_M c_X & c_W s_M \\ -s_W c_M c_X + s_M s_X & -s_W c_M s_X - s_M c_X & c_W c_M \end{pmatrix} \begin{pmatrix} Z \\ Z' \\ A \end{pmatrix},$$

$$\left(s_M = \tan\theta_W \frac{g_L}{g_R}, \quad c_M = \frac{g_L}{g_R}\sqrt{\left(\frac{g_R}{g_L}\right)^2 - \tan^2\theta_W}, \quad s_X(c_X) \approx 0(1) \right)$$

Gage boson masses

$$m_{W'}^2 \simeq \frac{1}{4} g_R^2 v_R^2 \left(1 + \frac{K^2}{v_R^2}\right),$$

$$m_{Z'}^2 \simeq \frac{1}{4}(g_R^2 + g_{B-L}^2) v_R^2 \left(1 + \frac{K^2 c_M^2}{v_R^2}\right)$$

$$K^2 = k_1^2 + k_2^2$$

$$\Rightarrow \quad \frac{m_{Z'}}{m_{W'}} \simeq \frac{g_R/g_L}{\sqrt{(g_R/g_L)^2 - \tan^2\theta_W}}$$

If we consider $SU(2)_R$ triplet Higgs we have √2 factor

2. A model

Minimal dark matter

Cirelli, Farnengo, Strumia (2006)

- **Higher multiplet can be stable if no decaying dim < 6 operator**
- **We consider $SU(2)_L$ and $SU(2)_R$ multiplet fermions and scalars**
- **If hypercharge is non-zero it is excluded by direct detection**

Reps.	Interaction	Y_{DM}
$SU(2)_R$ multiplet scalar Φ_R		
(1,2,1)	$\Phi_R H_R^\dagger$	0
(1,3,0)	$\Phi_R \tilde{H}_R H_R$	0
(1,3,2)	$\Phi_R \tilde{H}_R \tilde{H}_R$	0
(1,4,1)	$\Phi_R \tilde{H}_R \tilde{H}_R H_R$	0
(1,4,3)	$\Phi_R \tilde{H}_R \tilde{H}_R \tilde{H}_R$	0
(1,5,0)	$\Phi_R \tilde{H}_R \tilde{H}_R H_R H_R$	0
(1,5,2)	$\Phi_R \tilde{H}_R \tilde{H}_R \tilde{H}_R H_R$	0
(1,5,4)	$\Phi_R \tilde{H}_R \tilde{H}_R \tilde{H}_R \tilde{H}_R$	0
$SU(2)_L$ multiplet scalar Φ_L		
(2,1,1)	$\Phi_L H_R^\dagger \tilde{H}$	1/2
(3,1,0)	$\Phi_L H \tilde{H}$	0
(3,1,2)	$\Phi_L \bar{\ell}_L^c \ell_L$	1
(4,1,1)	$\Phi_L H \tilde{H} H H_R$	1/2
(4,1,3)	$\Phi_L \bar{\ell}_L^c \ell_L H H_R$	3/2
(5,1,0)	$\Phi_L (H\tilde{H})(H\tilde{H})$	0
(5,1,2)	dim > 5	1
(5,1,4)	dim > 5	2

Reps.	Interaction	Y_{DM}
$SU(2)_R$ multiplet fermion Ψ_R		
(1,2,1)	$\bar{\Psi}_R \ell_R^c H^\dagger H$	0
(1,3,0)	$\bar{\Psi}_R \ell_R H_R$	0
(1,3,2)	$\bar{\Psi}_R \ell_R^c H_R$	0
(1,4,1)	$\bar{\Psi}_R \ell_R^c H_R \tilde{H}_R$	0
(1,4,3)	$\bar{\Psi}_R \ell_R^c H_R H_R$	0
(1,5,0)	dim > 5	0
(1,5,2)	dim > 5	0
(1,5,4)	dim > 5	0
$SU(2)_L$ multiplet fermion Ψ_L		
(2,1,1)	$\bar{\Psi}_L \ell_L^c H^\dagger H$	1/2
(3,1,0)	$\bar{\Psi}_L \ell_L H H_R$	0
(3,1,2)	$\bar{\Psi}_L \ell_L^c H H_R$	0
(4,1,1)	$\bar{\Psi}_L \ell_L^c H \tilde{H}$	1/2
(4,1,3)	dim > 5	3/2
(5,1,0)	dim > 5	0
(5,1,2)	dim > 5	1
(5,1,4)	dim > 5	2

2. A model

Minimal dark matter

Cirelli, Farnengo, Strumia (2006)

➢ **Higher multiplet can be stable if no decaying dim < 5 operator**

- ❖ $SU(2)_R$ quintuplets are candidate (B-L = 0,2,4)
- ❖ $SU(2)_L$ quintuplet (B-L=0) is same as original minimal DM
- ❖ We focus on the $SU(2)_R$ quintuplet as DM candidate

(1,4,1)	$\Phi_R \tilde{H}_R \tilde{H}_R H_R$	0	(1,4,1)	$\bar{\Psi}_R \ell^c_R H_R \tilde{H}_R$	0
(1,4,3)	$\Phi_R \tilde{H}_R \tilde{H}_R \tilde{H}_R$	0	(1,4,3)	$\bar{\Psi}_R \ell^c_R H_R H_R$	0
(1,5,0)	$\Phi_R \tilde{H}_R \tilde{H}_R H_R H_R$	0	(1,5,0)	dim > 5	0
(1,5,2)	$\Phi_R \tilde{H}_R \tilde{H}_R \tilde{H}_R H_R$	0	(1,5,2)	dim > 5	0
(1,5,4)	$\Phi_R \tilde{H}_R \tilde{H}_R \tilde{H}_R \tilde{H}_R$	0	(1,5,4)	dim > 5	0
$SU(2)_L$ multiplet scalar Φ_L			$SU(2)_L$ multiplet fermion Ψ_L		
(2,1,1)	$\Phi_L H^\dagger_R \tilde{H}$	1/2	(2,1,1)	$\bar{\Psi}_L \ell^c_L H^\dagger H$	1/2
(3,1,0)	$\Phi_L H \tilde{H}$	0	(3,1,0)	$\bar{\Psi}_L \ell_L H H_R$	0
(3,1,2)	$\Phi_L \bar{\ell}^c_L \ell_L$	1	(3,1,2)	$\bar{\Psi}_L \ell^c_L H H_R$	0
(4,1,1)	$\Phi_L H \tilde{H} H H_R$	1/2	(4,1,1)	$\bar{\Psi}_L \ell^c_L H \tilde{H}$	1/2
(4,1,3)	$\Phi_L \bar{\ell}^c_L \ell_L H H_R$	3/2	(4,1,3)	dim > 5	3/2
(5,1,0)	$\Phi_L (H\tilde{H})(H\tilde{H})$	0	(5,1,0)	dim > 5	0
(5,1,2)	dim > 5	1	(5,1,2)	dim > 5	1
(5,1,4)	dim > 5	2	(5,1,4)	dim > 5	2

3. DM pheno

DM candidate : $SU(2)_R$ quintuplet fermions (B-L=0,2,4)

$$\Psi^0 = \begin{pmatrix} \chi^{++} & \chi^{+} & \chi^{0} & \chi^{--} & \chi^{-} \end{pmatrix}$$: B-L=0, Majorana fermion

$$\Psi^2 = \begin{pmatrix} \eta^{+++} & \eta^{++} & \eta_1^{+} & \eta^{0} & \eta_2^{-} \end{pmatrix}$$:B-L=2, Dirac fermion

$$\Psi^4 = \begin{pmatrix} \zeta^{++++} & \zeta^{+++} & \zeta^{++} & \zeta^{+} & \zeta^{0} \end{pmatrix}$$:B-L=4, Dirac fermion

Tree level mass : M

Gauge interaction;

$$L \supset -s_W s_M g_R Q \bar{\psi}^Q Z^\mu \gamma_\mu \psi^Q + c_M g_R \left(Q - \frac{Q_{B-L}}{2c_M^2} \right) \bar{\psi}^Q Z'^\mu \gamma_\mu \psi^Q$$
$$+ c_W s_M g_R Q \bar{\psi}^Q A^\mu \gamma_\mu \psi^Q + \frac{g_R}{\sqrt{2}} (c_{2m} \bar{\psi}^{Q+1} W'^{+\mu} \gamma_\mu \psi^Q + h.c.),$$

$$c_{2m} = \sqrt{(2+m+1)(2-m)} \text{ with } m = Q - Q_{B-L}/2.$$

Mass splitting of quintuplet

❖**Masses of the components in quintuplet is degenerate at tree level**

❖**Mass splitting appear from radiative correction**

Mass splitting formula

$$M_Q - M_0 \simeq \frac{g_R^2}{(4\pi)^2} M[Q(Q-Q_{B-L})f(r_{W'}) - c_M^2 Q\{Q - Q_{B-L}/c_M^2\} f(r_{Z'}) - s_W^2 s_M^2 Q^2 f(r_Z) - c_W^2 s_M^2 Q^2 f(r_\gamma)]$$

$$f(r_X) = 2\int_0^1 dx(1+x)\log[x^2 + (1-x)r_X^2], \quad r_X = \frac{m_X}{M}$$

✧ **Mass splitting pattern is different from L-R symmetric model with triplet Higgs fields**

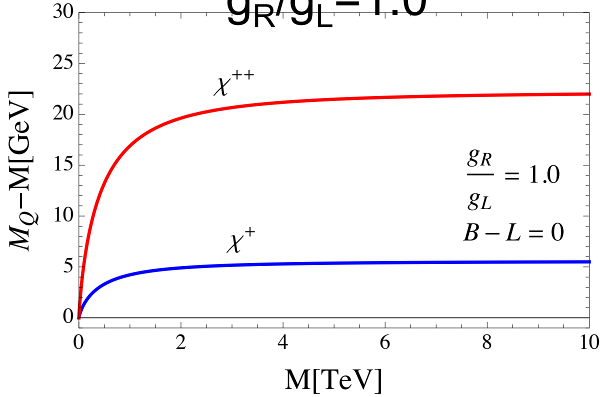
★ **due to different relation between W' and Z' mass**

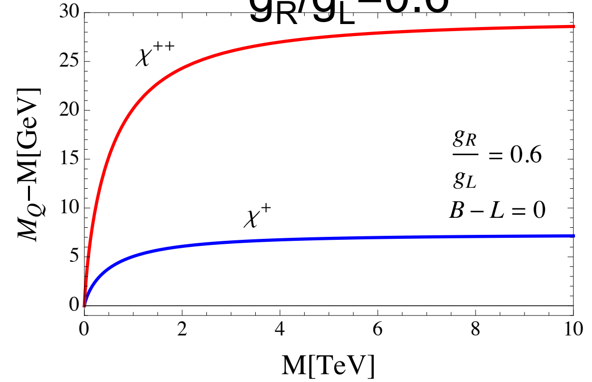
3. DM pheno

Mass splitting of quintuplet

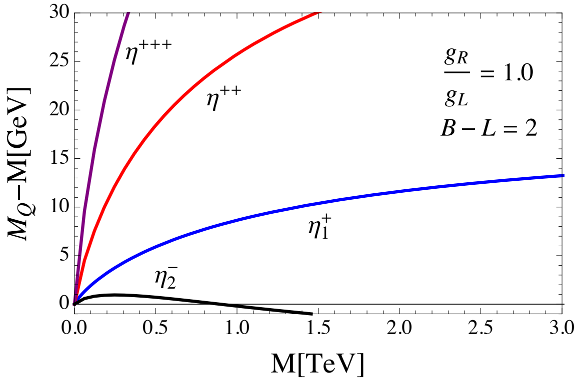
g_R/g_L=1.0 g_R/g_L=0.6

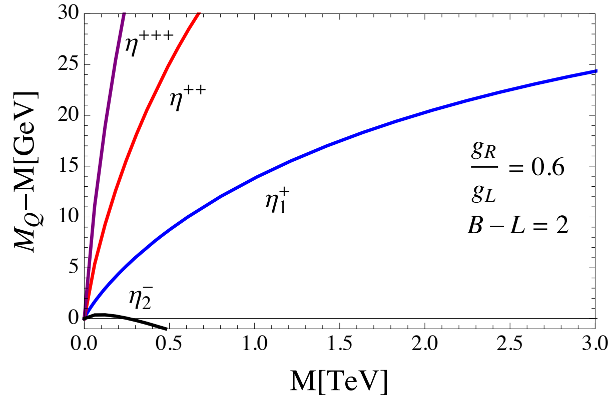
B-L=0



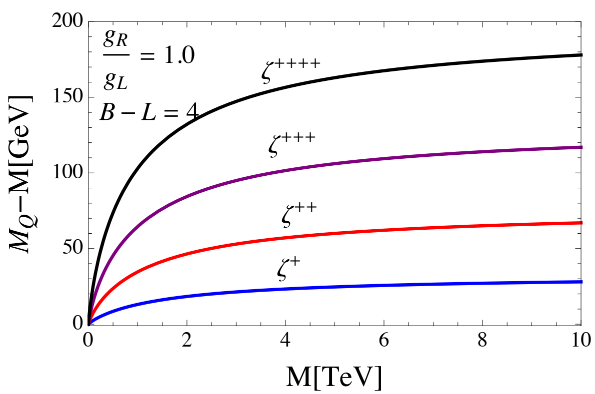


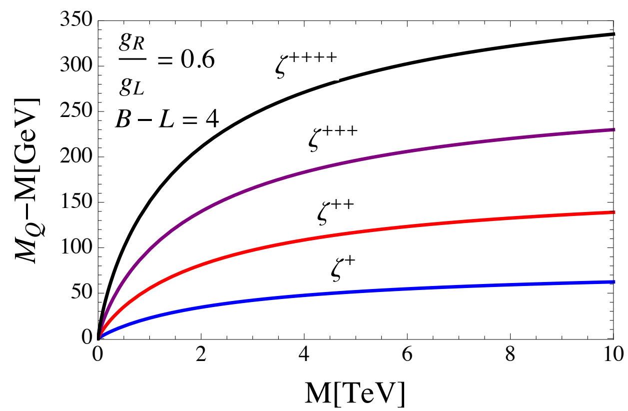
B-L=2





B-L=4





Relic density of DM

Relic density calculation

Relic density is obtained by solving Boltzmann equation :

$$\frac{dn_\chi}{dt} + 3Hn_\chi = - < \sigma v_{rel} > (n_\chi^2 - n_{\chi eq}^2)$$

Dominant DM annihilation processes

Annihilation process (f_{SM} is SM final state)

$$\psi^0 \psi^0 \to Z' \to f_{SM} f_{SM}$$ (For B-L ≠ 0)

Coannihilation process (f_{SM} is SM final state)

$$\psi^0 \psi^{\pm 1} \to W' \to f_{SM} f_{SM}$$

Search for the parameter region satisfying observed relic density

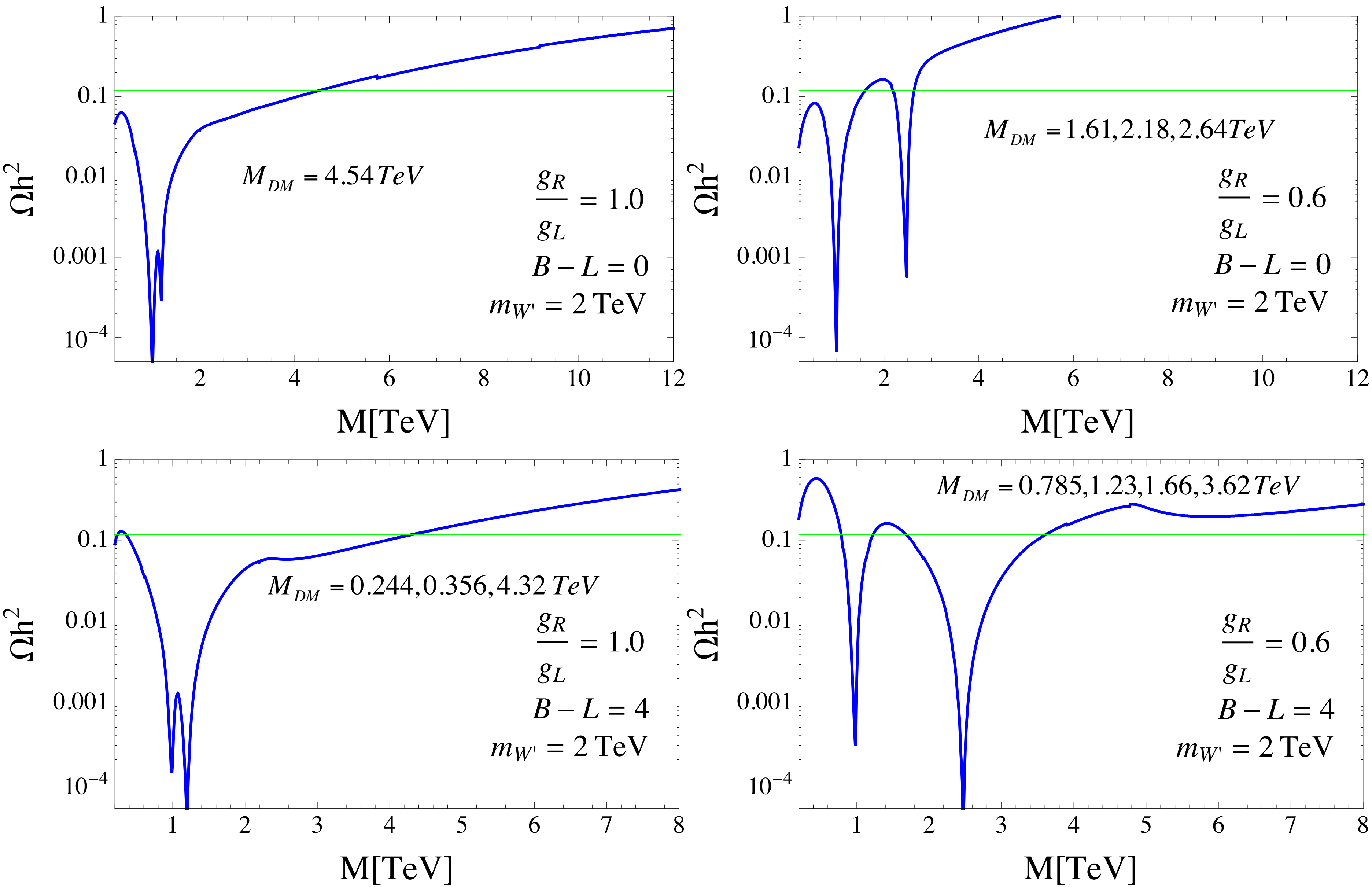
Planck data (90% C.L.) $0.1159 \le \Omega_D h^2 \le 0.1215$

P.A.R. Ade et al [Planck Collaboration] (2013)

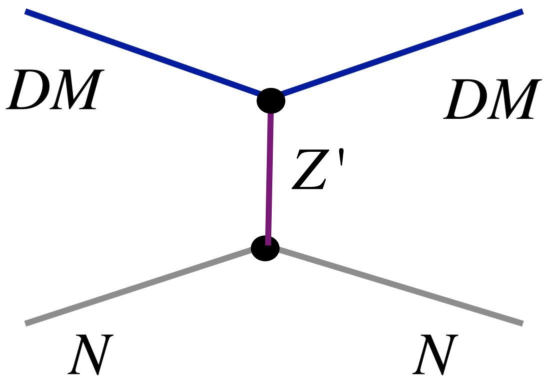
Ω_D is Calculated with MicrOMEGAs

(G. Belanger, F. Boudjema, A. Pukhov and A. Semenov)

Relic density of DM: Results



DM-Nucleon scattering: Direct detection of DM



If B-L ≠ 0

$$\sigma_{\xi^0 N} \approx \frac{4 g_R^2 g_{NNZ'}^2}{\pi c_M^2} \frac{1}{m_{Z'}^4} \frac{m_N^2 M^2}{(m_N + M)^2}$$

$$\begin{pmatrix} g_{ppZ'} = c_M g_R (1/2 - 1/(4c_M^2)) \\ g_{nnZ'} = -g_R/(4c_M) \end{pmatrix}$$

$$(\sigma_{\xi^0 p} + \sigma_{\xi^0 n})/2 \approx 6.8(1.1) \times 10^{-44}\ cm^2$$ **For g_R/g_L =1.0(0.6)**

- ❖M=0.244, 0.356, 4.32 (0.785) TeV for g_R/g_L =1.0(0.6) are excluded
- ❖M > 1 TeV for g_R/g_L = 0.6 points are allowed
- ❖For B-L=0, DM scattering with N is through 1-loop with W'

  → very small cross section

Charged components production at the LHC

Production processes

$$pp \to V \to \bar{\psi}^{Q}\psi^{Q}, \quad (V = Z', Z, \gamma)$$

$$pp \to W' \to \bar{\psi}^{Q}\psi^{Q\pm1}$$

Decay mode of charged component

$$\psi^{Q} \to \psi^{Q\pm1}(W'^{\pm} \to \bar{q}q')$$

$$\Gamma(\psi^{Q} \to \psi^{Q-1}\bar{q}'q) \simeq N_c c_{2m}^2 \frac{g_R^4}{120\pi^3}\frac{\Delta M^5}{m_{W'}^4}$$

- ❖ Signal event is jets + missing E_T
- ❖ Cross section is estimated with CalcHEP
- ❖ Total cross section is O(0.1~1)fb for M~1 TeV

Summary of phenomenological aspects

$B-L$	g_R/g_R	m_{DM}[TeV]	ΔM[GeV]	$\sigma_{\psi_Q \psi_{Q'}}$[fb]	$\sigma_{\rm DM-N}$[cm^2]	$\sigma_{\rm Lux}$[cm^2]
0	1	4.54	5.34	$\ll 10^{-2}$	$\ll 10^{-45}$	$\sim 57. \times 10^{-45}$
0	0.6	1.61	5.79	0.11(0.18)	$\ll 10^{-45}$	$\sim 18. \times 10^{-45}$
		2.18	6.18	0.034(0.069)	$\ll 10^{-45}$	$\sim 26. \times 10^{-45}$
		2.64	6.39	$\ll 10^{-2}$	$\ll 10^{-45}$	$\sim 30. \times 10^{-45}$
4	1	~~0.244~~	~~5.07~~	~~2010(2380)~~	~~$1.9(12.) \times 10^{-44}$~~	~~$\sim 3.1 \times 10^{-45}$~~
		~~0.356~~	~~6.71~~	~~1420(1740)~~	~~$1.9(12.) \times 10^{-44}$~~	~~$\sim 4.3 \times 10^{-45}$~~
		~~4.32~~	~~23.7~~	~~$\ll 10^{-2}$~~	~~$1.9(12.) \times 10^{-44}$~~	~~$\sim 52. \times 10^{-45}$~~
4	0.6	~~0.785~~	~~19.1~~	~~371.(460)~~	~~$6.8(15.) \times 10^{-45}$~~	~~$\sim 8.9 \times 10^{-45}$~~
		1.23	25.9	1.44(2.05)	$6.8(15.) \times 10^{-45}$	$\sim 14. \times 10^{-45}$
		1.66	31.1	0.173(0.298)	$6.8(15.) \times 10^{-45}$	$\sim 19. \times 10^{-45}$
		3.62	45.7	$\ll 10^{-2}$	$6.8(15.) \times 10^{-45}$	$\sim 45. \times 10^{-45}$

- **Allowed DM mass is M > 1 TeV**
- **DM-N scattering cross section is different for proton and neutron**
- **Charged component would be produced at the LHC if M~1 TeV**

Summary & Discussions

$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ model with DM

- ✧Simplified Higgs sector is adopted
- ✧Minimal DM : $SU(2)_R$ quintuplet fermion
- ✧g_R/g_L=1 and 0.6 are considered

DM phenomenology

- ✧Relic density of DM
- ✧Direct detection of DM
- ✧Charged component production at the LHC

Thanks!