Constraining minimal $U(1)_{B-L}$ model from dark matter observations

Tanushree Basak

Physical Research Laboratory, India

10th PATRAS Workshop on Axions, WIMPs and WISPs
CERN Geneva, Switzerland

July 3, 2014

Motivation : Shortcomings of Standard Model

SM works beautifully, explaining all experimental phenomena to date with great precision → No compelling hints for deviations.

Motivation : Shortcomings of Standard Model

SM works beautifully, explaining all experimental phenomena to date with great precision → No compelling hints for deviations.

But many questions remain unanswered:

Motivation : Shortcomings of Standard Model

SM works beautifully, explaining all experimental phenomena to date with great precision → No compelling hints for deviations.

But many questions remain unanswered:

- Higgs mass is not protected by any symmetry ⇒ Hierarchy Problem.
- SM has 19 unknown parameters whose value are to be set experimentally.
- No cold dark matter candidate.
- Neutrinos are massless in SM.
- Does not explain fermion mass hierarchy.
- It can not explain baryogenesis and leptogenesis.
- It does not give the gauge coupling unification at some high scale.

Shortcomings of SM $\Longrightarrow$ Provides motivation for BSM Physics

In Standard Model : NO DM candidate !

Shortcomings of SM $\Longrightarrow$ Provides motivation for BSM Physics

In Standard Model : NO DM candidate !

Solution : Extensions of SM to accommodate a DM candidate

Shortcomings of SM $\Longrightarrow$ Provides motivation for BSM Physics

In Standard Model : NO DM candidate !

Solution : Extensions of SM to accommodate a DM candidate

Some of the possible extensions of SM :

- Supersymmetric extension (Neutralino, Gravitino ....)
- Gauge singlet scalar extension
- Fermion singlet and scalar singlet
- Gauge extension of SM

Gauged Minimal $U(1)_{B-L}$ Model

Framework of the Model

Particle content of minimal $U(1)_{B-L}$ extension (anomaly free) of SM :

Particle	Q	u_R	d_R	L	e_R	Φ	S	$N_{R^{1,2}}$	N_{R^3}
$SU(2)_L$	2	1	1	2	1	2	1	1	1
$U(1)_Y$	1/6	2/3	-1/3	-1	-1	1	0	0	0
$U(1)_{B-L}$	1/3	1/3	1/3	-1	-1	0	2	-1	-1
$\mathbb{Z}_2$	+	+	+	+	+	+	+	+	-

N. Okada *et al.* '10; Kanemura *et al.* '11; T. Basak *et al.* '14

Additional Z_2-symmetry imposed : Z_2 charge $+1$(or even) for all the particles except N_R^3

Ensures stability for $N_R^3 \Longrightarrow$ becomes a viable WIMP - DM candidate

Scalar potential

$$V(\Phi, S) = m^2\Phi^\dagger\Phi + \mu^2 \mid S \mid^2 + \lambda_1(\Phi^\dagger\Phi)^2 + \lambda_2 \mid S \mid^4 + \lambda_3\Phi^\dagger\Phi \mid S \mid^2$$

- After spontaneous symmetry breaking (SSB) the two scalar fields can be written as,

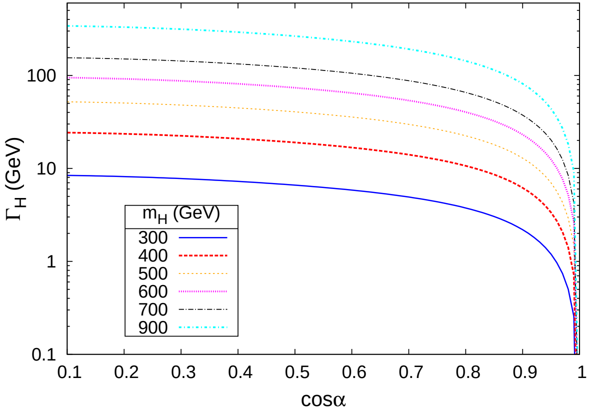
  $$\Phi = \begin{pmatrix} 0 \\ \frac{v+\phi}{\sqrt{2}} \end{pmatrix}, \qquad S = \frac{v_{_{B-L}} + \phi'}{\sqrt{2}}$$

  with v and $v_{_{B-L}}$ real and positive.
- The mass eigenstates are linear combinations of ϕ and ϕ', and written as

  $$\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi' \\ \phi \end{pmatrix}$$

  where, we identify H_2 as the SM-like Higgs boson with mass 125.5 GeV.

Decay Width of Heavy Scalar Boson



Total decay width, Γ_H has strong dependence on the mixing angle $\cos\alpha$ and mass

Fermionic Part of the model

- Yukawa part : important for DM interaction

$$\mathcal{L}_Y = \mathcal{L}_Y^{SM} + \mathcal{L}_{int}$$

and the interaction part is

$$\mathcal{L}_{int} = \sum_{\beta=1}^{3}\sum_{i=1}^{2} y_\beta^i \bar{l}_\beta \tilde{\Phi} N_i - \sum_{i=1}^{3} \frac{y_{n_i}}{2} \bar{N_R^i} S N_R^i$$

where, $\tilde{\Phi} = -i\tau_2\Phi^*$.

- DM interacts with the SM particles via Z'-boson and h, H.
- But, Z'-boson being heavy ($m_{Z'} \geq 2.33$ TeV) $\Longrightarrow$ effectively Higgs-portal

Neutrino mass generation

- Neutrino mass generated via Type-I seesaw mechanism

$$\begin{aligned} m_{\nu_L} &\simeq m_D^T \; m_M^{-1} \; m_D, \\ m_{\nu_H} &\simeq m_M \end{aligned}$$

where, $m_D = (y^j_\beta/\sqrt{2})v$, $(j = 1, 2)$ and $m_{M_i} = -(y_{n_i}/\sqrt{2})v_{B-L}$, $(i = 1, 2, 3)$.

- N^3_R has no Yukawa coupling with the left-handed lepton doublet $\Rightarrow$ the lightest neutrino remains massless.

Dark Matter Observations and Constraints

Relic Abundance

Relic density :

$$\Omega_{DM} h^2 = 1.1 \times 10^9 \frac{x_f}{\sqrt{g^*} m_{Pl} \langle \sigma v \rangle} \mathrm{GeV}^{-1}$$

where $x_f = m_{N_R^3} / T_D$ with T_D as decoupling temperature and

$$\langle \sigma v \rangle = \frac{1}{m^2_{N_{R^3}}} \left\{ w(s) - \frac{3}{2} \left(2w(s) - 4m^2_{N_R^3} w'(s) \right) \frac{1}{x} \right\} \Bigg|_{s=4m^2_{N_R^3}}$$

M. Srednicki *et al.* '88

- $w(s)$ depends on amplitude of different annihilation processes,

$$N_R^3 N_R^3 \longrightarrow b\bar{b},\ \tau^+\tau^-,\ W^+W^-,\ ZZ,\ \text{and}\ \ hh$$

$$w(s) = \frac{1}{32\pi} \sqrt{\frac{s - 4m^2_{final}}{s}} \int \frac{d\cos\phi}{2} \sum_{\text{all possible channels}} |\mathcal{M}|^2$$

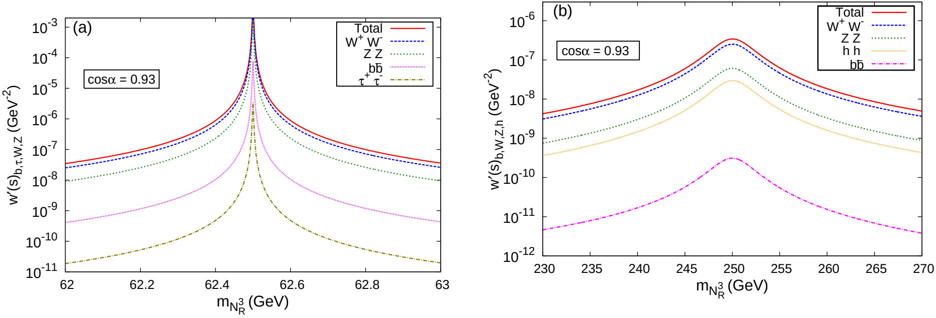
Typical choice of benchmark values :

m_h	m_H	Γ_h	v_{B-L}	g_{B-L}
125 GeV	500 GeV	4.7×10^{-3} GeV	7 TeV	0.1

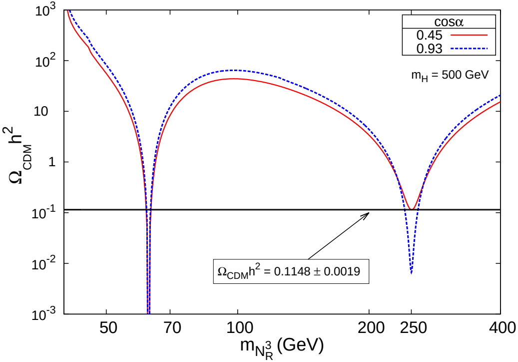
Typical choice of benchmark values :

m_h	m_H	Γ_h	v_{B-L}	g_{B-L}
125 GeV	500 GeV	4.7×10^{-3} GeV	7 TeV	0.1

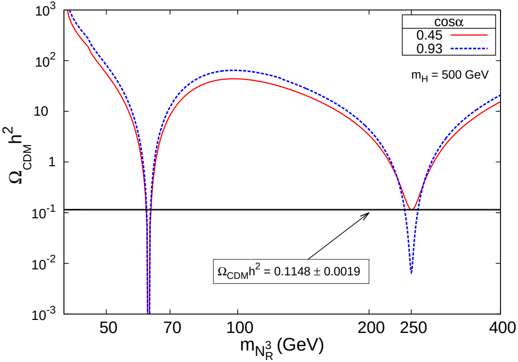
Variation of w(s) near resonance :



Relic abundance as a function of DM mass



Relic abundance as a function of DM mass



Important feature of Higgs-portal DM : Scalar Resonance

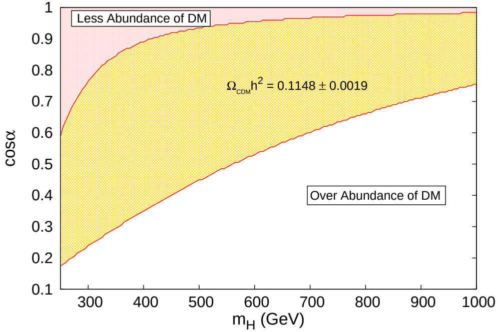
Relic abundance is found to be consistent with the recent WMAP9 and PLANCK data only near scalar resonances, i.e, $m_{N_R^3} = (1/2) m_{h,H}$

Constraints on Parameter space

Perform scan over the entire parameter space of m_H and scalar mixing $\cos\alpha$, consistent with relic abundance

Constraints on Parameter space

Perform scan over the entire parameter space of m_H and scalar mixing $\cos\alpha$, consistent with relic abundance



Relic abundance near the resonance depends on : scalar mixing angle (α), heavy scalar mass (m_H) and decay width (Γ_H).

Lagrangian for effective interaction

- Effective lagrangian for spin-independent interaction :

$$L_{eff} = f_p \bar{N}_R^3 N_R^3 \bar{p} p + f_n \bar{N}_R^3 N_R^3 \bar{n} n$$

where, $f_{p,n}$ is the hadronic matrix element.

$$f_{p,n} = \sum_{q=u,d,s} f_{Tq}^{(p,n)} a_q \frac{m_{p,n}}{m_q} + \frac{2}{27} f_{TG}^{(p,n)} \sum_{q=c,b,t} a_q \frac{m_{p,n}}{m_q}$$

a_q is the effective coupling constant between DM and the quark.

- SI-scattering cross section of DM off a nucleon :

$$\sigma_{scalar} = \frac{4 m_r^2}{\pi} f_{p,n}^2$$

→ m_r is the reduced mass of the nucleon.

Approximate form of a_q

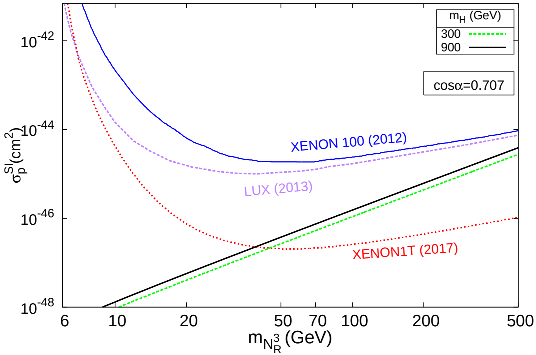
- The analytical form of a_q can be derived as,

$$\frac{a_q}{m_q} = \frac{y_{n_3}}{v\sqrt{2}}\left[\frac{1}{m_h^2} - \frac{1}{m_H^2}\right]\sin\alpha\cos\alpha$$

  where, $y_{n_3} = \sqrt{2} m_{N_R^3}/v_{B-L}$ is the Yukawa coupling.

- Spin-independent scattering cross-section of DM off a nucleon is maximum for $\cos\alpha = 0.707$, and maximum σ_p depends on the value of heavy scalar mass.

Spin-independent Cross-Section and XENON 100 Limits



E. Aprile *et al.* '12; Akerib *et al.* '13; T. Basak *et al.* '14

σ_p^{SI} is well below the XENON100 and LUX exclusion limits for DM mass ranging from 5 – 500 GeV.

Fermi-LAT upper bound on $\sigma v_{\gamma\gamma}$

- The RH-neutrino dark matter N_R^3 can also annihilate into two photon final state mediated by scalar bosons (h and H)
- $w(s)_{\gamma\gamma}$ for massless final product is defined as,

$$w(s)_{\gamma\gamma} = \frac{1}{32\pi} \sum_{spins} |\mathcal{M}_{N_R^3 N_R^3 \to \gamma\gamma}|^2$$

where,

$$\begin{aligned}\sum_{spins} |\mathcal{M}_{N_R^3 N_R^3 \to \gamma\gamma}|^2 \quad &= \quad y_{n_3}^2 (s - 4 m_{N_R^3}^2) \Big\{ \frac{|\mathcal{M}_{h \to \gamma\gamma}|^2 \sin^2\alpha}{(m_h^2 - s)^2 + m_h^2 \Gamma_h^2} + \frac{|\mathcal{M}_{H \to \gamma\gamma}|^2 \cos^2\alpha}{(m_H^2 - s)^2 + m_H^2 \Gamma_H^2} \\ &+ \frac{|\mathcal{M}_{h \to \gamma\gamma}||\mathcal{M}_{H \to \gamma\gamma}| \sin\alpha \cos\alpha \{(m_h^2 - s)(m_H^2 - s) + m_h m_H \Gamma_h \Gamma_H\}}{((m_h^2 - s)^2 + m_h^2 \Gamma_h^2)((m_H^2 - s)^2 + m_H^2 \Gamma_H^2)} \Big\}\end{aligned}$$

Fermi-LAT upper bound on $\sigma v_{\gamma\gamma}$

- The RH-neutrino dark matter N_R^3 can also annihilate into two photon final state mediated by scalar bosons (h and H)
- $w(s)_{\gamma\gamma}$ for massless final product is defined as,

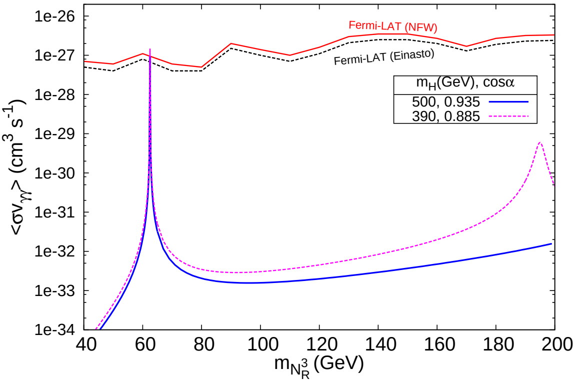
$$w(s)_{\gamma\gamma} = \frac{1}{32\pi} \sum_{spins} |\mathcal{M}_{N_R^3 N_R^3 \to \gamma\gamma}|^2$$

where,

$$\sum_{spins} |\mathcal{M}_{N_R^3 N_R^3 \to \gamma\gamma}|^2 = y_{n_3}^2 (s - 4m_{N_R^3}^2) \Big\{ \frac{|\mathcal{M}_{h\to\gamma\gamma}|^2 \sin^2\alpha}{(m_h^2 - s)^2 + m_h^2\Gamma_h^2} + \frac{|\mathcal{M}_{H\to\gamma\gamma}|^2 \cos^2\alpha}{(m_H^2 - s)^2 + m_H^2\Gamma_H^2} + \frac{|\mathcal{M}_{h\to\gamma\gamma}||\mathcal{M}_{H\to\gamma\gamma}| \sin\alpha\cos\alpha \{(m_h^2 - s)(m_H^2 - s) + m_h m_H \Gamma_h \Gamma_H\}}{((m_h^2 - s)^2 + m_h^2\Gamma_h^2)((m_H^2 - s)^2 + m_H^2\Gamma_H^2)} \Big\}$$

Caution : Monochromatic γ-ray line !!!

The gamma-ray continuum spectra produced due to W^+W^- , ZZ final state supersaturate the 130 GeV monochromatic γ-ray line feature.



Ackerman *et al.* '12; T. Basak *et al.* '14

Clear coincidence between theoretical plots and Fermi-LAT data near resonance point where, $m_{N_R^3} \sim (1/2)\, m_h$.

Summary

- We adopt the minimal $U(1)_{B-L}$ extension of SM with an additional Z_2-symmetry imposed.
- One of the right-handed neutrino, being odd uder Z_2, qualified as the DM candidate.
- Relic abundance of the DM is found to be consistent with the latest WMAP9 and Planck data only near scalar resonances.
- SI-scattering cross-section is well below the XENON100 and LUX exclusion limits for DM mass ranging from $5 - 500$ GeV.
- Neutrino mass can be generated in this kind of model via Type-I seesaw mechanism.

Summary

- We adopt the minimal $U(1)_{B-L}$ extension of SM with an additional Z_2-symmetry imposed.
- One of the right-handed neutrino, being odd uder Z_2, qualified as the DM candidate.
- Relic abundance of the DM is found to be consistent with the latest WMAP9 and Planck data only near scalar resonances.
- SI-scattering cross-section is well below the XENON100 and LUX exclusion limits for DM mass ranging from $5-500$ GeV.
- Neutrino mass can be generated in this kind of model via Type-I seesaw mechanism.

Thank you