Vacuum Stability and inflation in gauged $U(1)_{B-L}$ Model

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Motivation : Shortcomings of Standard Model

SM works beautifully, explaining all experimental phenomena to date with great precision $\rightarrow$ No compelling hints for deviations... 750 GeV.

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SM works beautifully, explaining all experimental phenomena to date with great precision $\rightarrow$ No compelling hints for deviations... 750 GeV.

But many questions remain unanswered:

- Higgs mass is not protected by any symmetry $\Rightarrow$ 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.

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

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

Minimal extension of Standard Model: 3 steps ...

Symmetry group : $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_{B-L}$.

Fermion sector

One Right Handed neutral fermion (ν_R) per generation.

Scalar sector

A complex scalar (S) is required to break $B-L$ symmetry.
Scalar potential:

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

Particle content

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.M *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 Sector of $U(1)_{B-L}$

- SM Higgs and singlet scalar fields after acquiring *vev*

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

- h and H are the mass eigenstates :

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi \\ \phi' \end{pmatrix}$$

$\alpha \rightarrow$ Scalar Mixing Angle

- Mass eigenvalues can be written as :

$$M_h^2 = \lambda_1 v^2 + \lambda_2 v_{B-L}^2 - \sqrt{(\lambda_1 v^2 - \lambda_2 v_{B-L}^2)^2 + (\lambda_3 v_{B-L} v)^2},$$

$$M_H^2 = \lambda_1 v^2 + \lambda_2 v_{B-L}^2 + \sqrt{(\lambda_1 v^2 - \lambda_2 v_{B-L}^2)^2 + (\lambda_3 v_{B-L} v)^2},$$

Gauge and fermion sector

Modification in gauge sector

Addition of new U(1) symmetry : extra gauge field B'_μ.

- Kinetic term : $-\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu}$ where $F'_{\mu\nu} = \partial_\mu B'_\nu - \partial_\nu B'_\mu$.
- Covariant derivative :

$$D_\mu = \partial_\mu + ig_2 T^a W_\mu{}^a + ig_1 YB_\mu + i(\widetilde{g}Y + g_{B-L} Y_{B-L})B'_\mu$$

Fermion sector

SM + 3 RH neutrinos (ν_R).

- Yukawa interaction:

$$-\mathcal{L}_Y = y^l_{ij}\overline{l_{iL}}\,\widetilde{\Phi}\,\nu_{jR} + y^h_{ij}\,\overline{(\nu_R)^c_i}\,\nu_{jR}\,S + h.c.$$

Stability criteria for $U(1)_{B-L}$ model

The quartic potential has the form

$$\lambda_1\,|\Phi|^4 + \lambda_2\,|S|^4 + \lambda_3|\Phi|^2\,|S|^2,$$

and we can easily write this potential as

$$\left(\sqrt{\lambda_1}\,|\Phi|^2 + \frac{\lambda_3}{2\sqrt{\lambda_1}}\,|S|^2\right)^2 + \left(\lambda_2 - \frac{\lambda_3^2}{4\lambda_1}\right)|S|^4.$$

Clearly the above equation is positive definite if

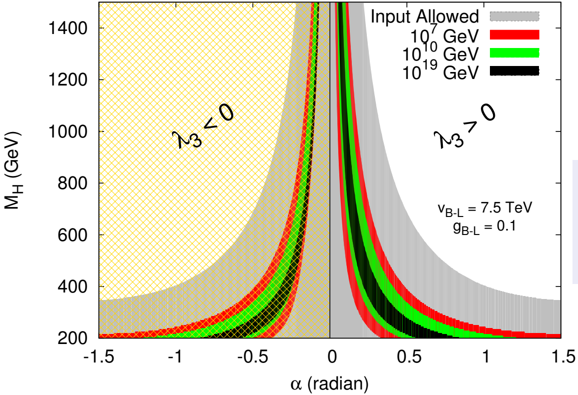
$$\lambda_1 > 0\ ,\quad \lambda_2 > 0,$$
$$4\lambda_1\lambda_2 - \lambda_3^2 > 0.$$

These are the non-trivial vacuum stability conditions.

Results: $U(1)_{B-L}$ model

The unknown parameters in this model (total 5):

$$M_H \ , \ \alpha \ , \ g_{B-L} \ , \ y^h \ \& \ v_{B-L}$$



For fixed values of g_{B-L} , y^h & v_{B-L}.
y^h =0.04

Results: $U(1)_{B-L}$ model

How other parameters affect vacuum stability ?

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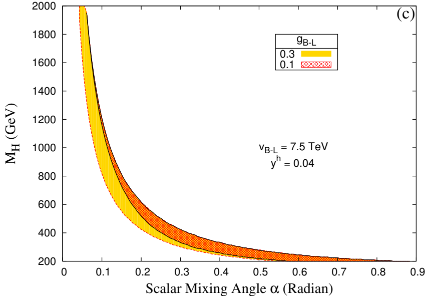
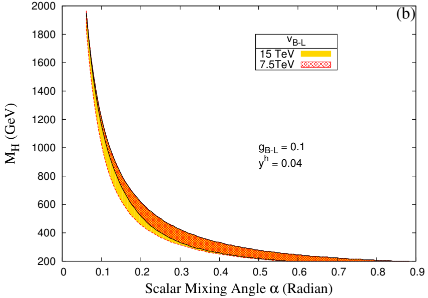
How other parameters affect vacuum stability ?

g_{B-L}



v_{B-L}



High scale breaking of $B - L$ symmetry

- The SM instability scale $\Lambda_I \sim 10^{9-11}$ GeV.
- Any scalar field with mass scale below Λ_I will help to stabilize:

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

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Motivation for these models

It can appear in models which can explain inflationary dynamics.

Example case

We will consider $v_{B-L} = 10^{16}$ GeV and $M_H = 10^8$ GeV.

High scale breaking of $B - L$ symmetry

Threshold Correction

- The model contains another heavy scalar apart from Higgs boson.
- At the mass scale M_H the heavy field has the equation of motion

$$S^\dagger S = \frac{1}{2} v_{B-L}^2 - \frac{\lambda_3}{2\lambda_2} \Phi^\dagger \Phi$$

- Potential becomes

$$V(\Phi)|_{eff} = \lambda_s (\Phi^\dagger \Phi)^2 + m^2 (\Phi^\dagger \Phi), \qquad \lambda_S(M_H) = \lambda_1 - \frac{\lambda_3^2}{4\lambda_2}\Big|_{M_H}$$

- The Higgs quartic coupling gets a tree level shift at M_H scale.
- λ_S will run according to SM RGEs up to M_H scale.
- After M_H scale λ_1 will start evolving.

High scale breaking of $B - L$ symmetry

Stability Conditions

$$\begin{aligned} \lambda_S &> 0 \quad (Q < M_H) \\ \lambda_1 - \frac{\lambda_3^2}{4\lambda_2} &> 0 \quad (Q > M_H) \end{aligned}$$

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Other parameters

- λ_2 and λ_3 starts evolving after the M_H scale.
- The RH neutrino Yukawa (Y_i^N) also affect the scalar RGEs.
- Since $B - L$ breaking *vev* is very high ($\sim 10^{16}$ GeV), light neutrino Yukawa is large ($\mathcal{O}(1)$) and must be implemented.

Inflation in $U(1)_{B-L}$ model

SM Higgs and singlet scalar fields after acquiring *vev*

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

- In this model the heavy scalar ϕ' act as the inflaton.
- After symmetry breaking the inflaton potential:

$$V(\phi') = \frac{1}{4}\lambda_2(\phi'^2 - v_{B-L}^2)^2 + a\,\lambda_2 \log\left(\frac{\phi'}{v_{B-L}}\right)\phi'^4$$

$$a = \frac{1}{16\pi^2\lambda_2}\Big\{20\lambda_2^2 + 2\lambda_3^2 + 2\lambda_2\left((Y_i^{N_R})^2 - 24g_{B-L}^2\right) + 96g_{B-L}^4 - (Y_i^{N_R})^4\Big\}$$

- 'a' determines whether the $B-L$ symmetry is broken through the tree-level potential or radiatively.

Inflation in $U(1)_{B-L}$

Case I : Negligible radiative correction

- Mass of the inflaton : $m_{\phi'} = \sqrt{\lambda_2} v_{B-L}$
- Slow roll parameters :

$$\epsilon_V = \frac{1}{2} M_{\rm Pl}^2 \left(\frac{V'}{V} \right)^2 = \frac{8 M_{\rm Pl}^2}{\phi'^2}, \quad \eta_V = M_{\rm Pl}^2 \left(\frac{V''}{V} \right) = \frac{12 M_{\rm Pl}^2}{\phi'^2}.$$

- Inflation ends when $max(\epsilon_V, |\eta_V|) \sim 1.$

$$\Rightarrow \phi'_{end} \approx 3 M_{\rm Pl}.$$

Inflation in $U(1)_{B-L}$

Case I : Negligible radiative correction

- Number of e-foldings:

$$N_k = \frac{1}{\sqrt{2}M_{\rm Pl}} \int_{\phi'_{\rm end}}^{\phi'_k} \frac{d\phi'}{\sqrt{\epsilon_V}}, \quad \phi'_k : \text{field value at scale k}$$
$$= \frac{1}{8M_{\rm Pl}^2}(\phi'^2_k - \phi'^2_{\rm end}).$$

- $N_k \simeq 65 \Rightarrow \phi_{0_k} \sim 23M_{\rm Pl}$.

- In a single field scenario

$$r = 16\epsilon_V = \frac{128M_{\rm Pl}^2}{\phi'^2_k}$$
$$\Rightarrow r \simeq 0.24 \qquad \text{too large !}$$

Inflation in $U(1)_{B-L}$

Case II : Radiative correction to the rescue

$$V_{\phi'} = \frac{1}{4}\lambda_2\phi'^4\left[1 + 4a\, ln\left(\frac{\phi'}{v_{B-L}}\right)\right]$$

This gives

$$\epsilon_V = \frac{8M_{\rm Pl}^2}{\phi'^2}\left[\frac{u^2}{(u-1)^2}\right], \quad \eta_V = \frac{12M_{\rm Pl}^2}{\phi'^2}\left[\frac{u+4/3}{u-1}\right].$$

where, $u = \frac{1}{a}\left[1 + a + 4a\, ln\left(\frac{\phi'}{v_{B=L}}\right)\right]$.

- a$\to 0 \Rightarrow u \to \infty$: ϕ^4 inflation.
- We now have two cases:
  - $|u| \gg 1 \Rightarrow$ radiative correction negligible: ϕ^4 Branch
  - $|u| \ll 1 \Rightarrow$ radiative correction term is important : Hilltop

Inflation in $U(1)_{B-L}$

Case II : Radiative correction to the rescue

$$r = \frac{128 M_{\rm Pl}^2}{\phi'^2} \frac{u^2}{(u-1)^2}, \qquad n_s = 1 - \frac{8 M_{\rm Pl}^2}{\phi'^2} \frac{3u^2 - u + 4}{(u-1)^2}.$$

Set $\phi' = 23 M_{\rm Pl}$. Solve for $n_s = 0.9603$.

Two solutions exists:

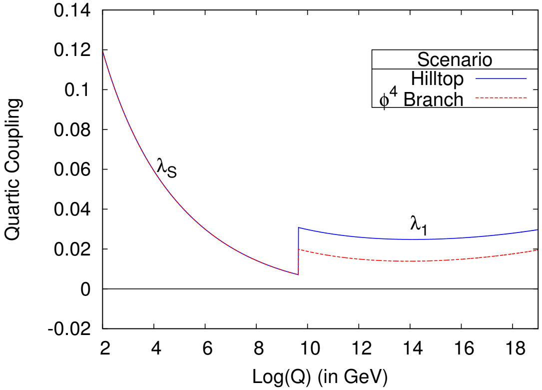
- $u = -0.333 \;\Rightarrow$ Hilltop scenario
- $u = -11.001 \;\Rightarrow$ ϕ^4 scenario

Inflation in $U(1)_{B-L}$

Case II : Radiative correction to the rescue

Parameter	Hilltop	ϕ^4
u	-0.333	-11.001
a	-0.028	-0.022
ϕ'_{end}	$0.71 M_{\mathrm{Pl}}$	$2.6 M_{\mathrm{Pl}}$
r	0.015	0.203
λ_2	1.89×10^{-13}	3.6×10^{-13}
λ_3	3×10^{-8}	3×10^{-8}
$m_{\phi'}$	4.3×10^{9} GeV	6×10^{9} GeV

Vacuum Stability in $U(1)_{B-L}$ Model



Dark Matter in $U(1)_{B-L}$

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 ($m_{Z'} \geq 3$ TeV) $\Longrightarrow$ effectively Higgs-portal

Dark Matter Observations and Constraints

Relic Abundance

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

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

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

- $w(s)$ 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

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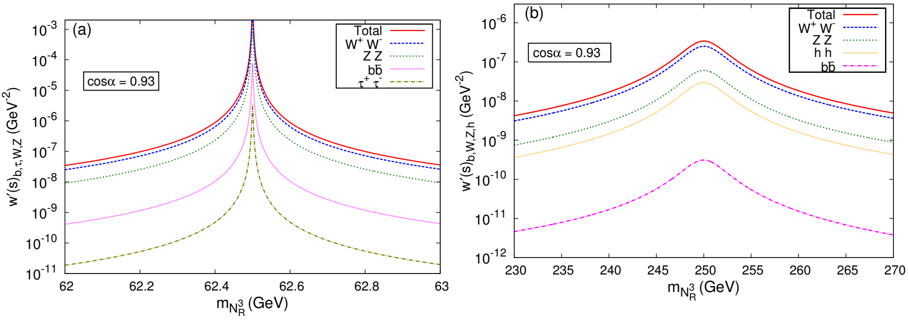
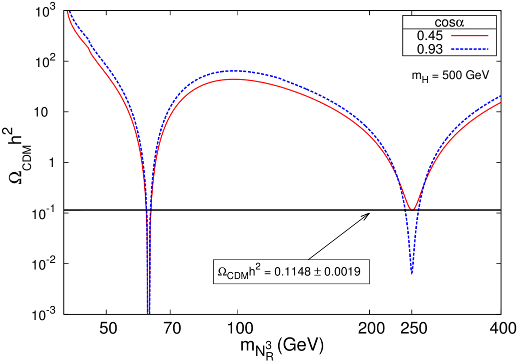
Variation of w(s) near resonance :



Relic abundance as a function of DM mass



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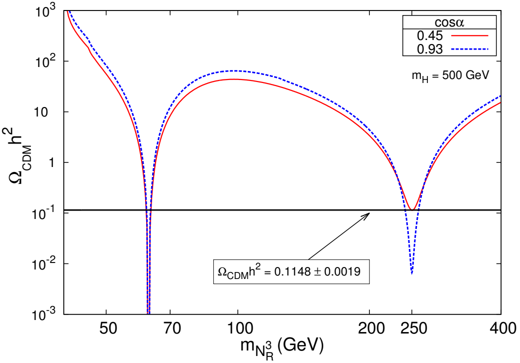

Important feature of Higgs-portal DM : Scalar Resonance

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

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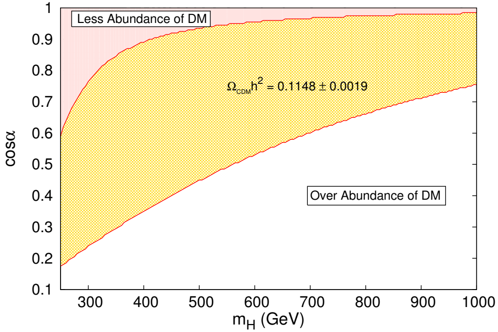
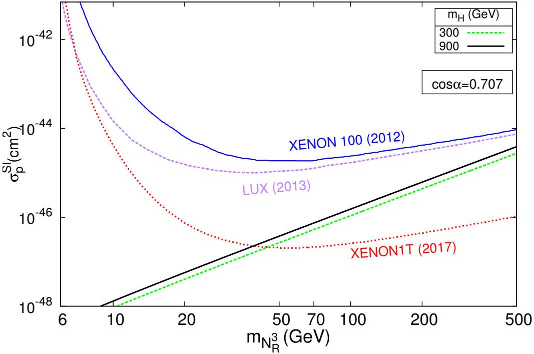


Relic abundance near the resonance depends on : scalar mixing angle (α), heavy scalar mass (m_H) and decay width (Γ_H).

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.

Conclusion

- We have studied $U(1)_{B-L}$ Model : the triply minimal extension of the SM.
- Vacuum stability is restored in this model.
- Presence of heavy scalar adds a threshold correction to the SM Higgs quartic coupling which helps to attain the EW stability.
- Radiative correction term in the inflaton potential can modify the scalar to tensor ratio.
- One of the right-handed neutrinos, 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.

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Thank you