Inverse Seesaw from dynamical $B-L$ breaking

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The Inverse Seesaw scenario relates the smallness of the neutrino masses to a small $B-L$ breaking parameter. We investigate a possible dynamical generation of the Inverse Seesaw neutrino mass mechanism from the spontaneous breaking of a gauged $U(1)_{B-L}$. To obtain an anomaly free theory we need to introduce additional fermions which exhibit an interesting phenomenology. Additionally, we predict a $Z'$ boson associated to the broken $B-L$ which preferentially interacts with the dark sector formed by the extra fermions making it particularly elusive.

1 Introduction

The observation of non-zero neutrino masses is so far the only laboratory-based evidence for physics beyond the Standard Model. Nevertheless, there are many ways to generate neutrino masses. The probably simplest way is via the Seesaw framework\(^1\),\(^2\),\(^3\),\(^4\),\(^5\),\(^6\) where the smallness of the neutrino masses is explained with a large suppression of the electroweak scale. However, this is not the only possibility to explain the smallness of neutrino masses. The inverse seesaw (ISS)\(^7\) relies on the fact that neutrino masses are protected by the $B-L$ global symmetry. If this symmetry is only mildly broken, neutrino masses will be suppressed by this small $B-L$-breaking parameters. On the other hand, production and detection of the extra ISS right-handed neutrinos at colliders as well as their indirect effects in flavour and precision electroweak observables are not protected by this symmetry hence leading to a rich and interesting phenomenology.

To explore a possible dynamical origin of the ISS pattern we choose to gauge $B-L$ which then gets spontaneously broken\(^8\).

2 The model

In the ISS the masses of the light neutrinos are given by

$$m_\nu \sim v^2 Y_\nu M_N^{-1} \mu (M_N^T)^{-1} Y_\nu^T.$$  

With TeV-scale right handed neutrinos and $O(1)$ Yukawa couplings $\mu \sim O(\text{keV})$. Since a hierarchy of mass scales $\mu/v_H \sim 10^{-6}$ seems to be rather ad hoc we will promote $\mu$ to a dynamical quantity by gauging $B-L$ and identify the $\mu$ parameter with the $B-L$ breaking scalar vev.

For the ISS two copies of right-handed neutrinos ($N_R, N'_R$) with $B-L$ charges +1 and -1 per active neutrino are introduced.

Requiring an anomaly-free theory leads to the introduction of additional chiral fermion content to the model. We find a phenomenologically interesting and viable scenario for the
particle content displayed in tab. 1. The Lagrangian in in the neutrino sector is then given by
\begin{equation}
-\mathcal{L}_\nu = Y_L H N_R + \bar{N}_R^\dagger N_N N_R + \phi_2 \bar{N}_R^\dagger Y_N N_R + \phi_2^c (N_R^\dagger)^c Y_L N_R + \phi_1^c \bar{\chi}_L Y_\chi R + \text{h.c.}.
\end{equation}

The scalar potential of the model can be written as
\begin{equation}
V = \frac{m_H^2}{2} H^\dagger H + \frac{1}{2} \lambda_H (H^\dagger H)^2 + \frac{1}{2} \lambda_1 \phi_1^\dagger \phi_1 + \frac{1}{2} \lambda_2 \phi_2^\dagger \phi_2 + \frac{1}{2} \lambda_1 (\phi_1^\dagger \phi_1)^2 + \frac{1}{2} \lambda_2 (\phi_2^\dagger \phi_2)^2 + \lambda_{12} \phi_1^\dagger \phi_2^\dagger \phi_2 + \frac{1}{2} \lambda_{1H} (\phi_1^\dagger \phi_1) (H^\dagger H) + \frac{1}{2} \lambda_{2H} (\phi_2^\dagger \phi_2) (H^\dagger H) - \eta (\phi_1^\dagger \phi_1 + \phi_2^\dagger \phi_2).
\end{equation}

Minimalisation of the potential yields a vev for \( \phi_2 \)
\begin{equation}
v_2 \simeq \frac{\sqrt{2} m_1^2}{m_2^2},
\end{equation}
which will be identified with the \( \mu \) parameter. To obtain \( v_2 \approx \mathcal{O}(\text{keV}) \), one could have \( m_2 \sim 10 \text{ TeV} \), \( v_1 \sim 10 \text{ TeV} \), and \( \eta \sim 10^{-5} \text{ GeV} \).

With the conventions \( \phi_j = (v_j + \varphi_j + i a_j)/\sqrt{2} \) the mixing angles \( \alpha_1 \) and \( \alpha_2 \) between \( h - \varphi_1 \) and \( \varphi_1 - \varphi_2 \), respectively, are given by
\begin{equation}
\tan \alpha_1 \simeq \frac{\lambda_{1H} v}{\lambda_1 v_1}, \quad \text{and} \quad \tan \alpha_2 \simeq \frac{2 v_2}{v_1}.
\end{equation}
With \( v_1 \approx \text{TeV} \) and the quartics \( \lambda_1 \) and \( \lambda_{1H} \) are \( \mathcal{O}(1) \), the mixing \( \alpha_1 \) is expected to be small but non-negligible. Due to this mixing the couplings of the Higgs to gauge bosons and fermions get diminished. Relative to the SM couplings they are
\begin{equation}
\kappa_F = \kappa_V = \cos \alpha_1,
\end{equation}
which is constrained to be \( \cos \alpha_1 > 0.92 \) (or equivalently \( \sin \alpha_1 < 0.39 \)) \(^9\).

The \( Z' \) gauge boson associated to the broken \( B - L \) obtains a mass
\begin{equation}
M_{Z'} = g_{BL} \sqrt{v_1^2 + 4 v_2^2} \simeq g_{BL} v_1.
\end{equation}
As the largest particles with the largest \( B - L \) charges are in the dark sector of the model (the massless Weyl fermion \( \omega \) and \( \chi_R \), \( \chi_L \) which will form a Dirac pair), the \( Z' \) is very elusive and has a large BR of 70% to invisibles.

The Dirac fermion \( \chi \) is stable since it is protected by an accidental \( U(1) \) symmetry in the dark sector, hence it is a good DM candidate. Its main annihilation channels are \( \chi \bar{\chi} \to f \bar{f} \) via the \( Z' \) boson exchange and \( \chi \bar{\chi} \to Z'Z' \) - if kinematically allowed.

The DM \( Z' \) interaction leads to a spin-independent scattering in direct detection experiments. With the current experimental bound on the spin-independent cross section we can derive a lower bound on the vev of \( \phi_1 \):
\begin{equation}
v_1 \text{[GeV]} > \left( \frac{2.2 \cdot 10^9}{\sigma_{\chi}^{\text{DD}} \text{[pb]}} \right)^{1/4}.
\end{equation}
This bound pushes the DM mass to be $m_\chi \gtrsim$ TeV. For example, for $g_{BL} = 0.25$ and $m_{Z'} = 10$ TeV, a DM mass $m_\chi = 3.8$ TeV is needed to have $\sigma_{\chi}^{DD} \sim 9 \times 10^{-10}$ pb. In turn, this bound translates into a lower limit on the vev of $\phi_1$: $v_1 \gtrsim 40$ TeV (with $Y_\chi \gtrsim 0.1$).

Since the main annihilation channel of $\chi$ is via the $Z'$ which couples dominantly to the dark sector, the bounds from indirect detection searches turn out to be subdominant.

The massless fermion $\omega$ contributes to the relativistic degrees of freedom in the early universe. Comparing the Hubble expansion rate of the Universe with the interaction rate leads to a freeze out temperature of $\omega$ (for values that satisfy the correct DM relic abundance) of $T_\omega \sim 4$ GeV, before the QCD phase transition.

This means that the SM bath will heat significantly after $\omega$ decouples which suppresses the contribution of $\omega$ to the number of degrees of freedom in radiation:

$$\Delta N_{\text{eff}} \approx 0.026$$

which is one order of magnitude smaller than the current uncertainty on $N_{\text{eff}}^{\text{exp}} = 3.04 \pm 0.33$. Nevertheless, this deviation from $N_{\text{eff}}$ could be detected by EUCLID-like survey and would be an interesting probe of the model in the future.

More details on the model can be found in.

3 Summary of the results

Our results are summarised in fig. 1 for different DM masses of $m_\chi = 1$ TeV and 10 TeV.

The red region to the left is constrained by recasted LHC $Z' \rightarrow e^+e^-, \mu^+\mu^-$ resonant searches. In the blue region the relic abundance is too large and the orange region displays the excluded regions from current direct detection experiments, the dashed lines show the sensitivity of near future experiments (XENON1T (projected sensitivity assuming 2t · y), the long-dashed line the future constraints from LZ (projected sensitivity for 1000d of data taking)). For gauge couplings above the grey dashed line perturbativity will be lost ($g_{BL} \cdot q_{\text{max}} \leq \sqrt{2\pi}$ with largest $B-L$ charge $q_{\text{max}} = 5$).
In summary, we have presented a dynamical realisation of the inverse seesaw scenario which predicts a DM candidate at the TeV scale which can lead to the correct relic abundance while evading all current direct and indirect detection constraints, a massless fermion which contributes to $N_{\text{eff}}$, an elusive $Z'$ at the TeV scale and two scalars with masses around 10 TeV. Additionally, our model exhibits the phenomenology of the right-handed neutrinos of the usual inverse seesaw.

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