Dark Matter candidates in a baryogenesis inspired scenario

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Abstract. It has recently been shown that the electroweak baryogenesis mechanism is feasible in Standard Model extensions containing extra fermions with large Yukawa couplings. We show that the lightest of these fermionic fields can naturally be a good candidate for cold dark matter. We find regions in the parameter space where the thermal relic abundance of this particle is compatible with the dark matter density of the Universe as determined by the WMAP experiment. We study direct and indirect dark matter detection for this model and compare with current experimental limits and prospects for upcoming experiments. We find, contrary to the standard lore, that indirect detection searches are more promising than direct ones, and they already exclude part of the parameter space.

1. Introduction
The Standard Model (SM) of elementary particles is extremely accurate in describing the fundamental interactions up to the energy scale probed so far at accelerators. However the SM fails to provide a pattern to embed all features emerging from recent data on precision cosmology: in particular, it doesn’t provide a mechanism to explain the origin of the matter-antimatter asymmetry in the Universe, and it doesn’t accommodate a candidate for non-baryonic cold dark matter.

In a recent paper Carena \textit{et al.} [1] have shown that in order to strengthen the electroweak phase transition it is not strictly required to consider models with light extra bosonic degrees of freedom, but that models with extra fermions can be equally successful provided that large Yukawa couplings are introduced. A simple implementation of this idea involves adding to the Standard Model doublet and triplet fermions, such as \textit{e.g.} Higgsinos and gauginos, which can carry new charge- and color-neutral particles, the lightest of which can be the dark matter candidate. These extra-fermions, beside the ordinary gauge interactions, are coupled to the Higgs boson through the Lagrangian:

\[
\mathcal{L} = H^\dagger \left( h_2 \sigma_a \tilde{W}^a + h'_2 \tilde{B} \right) \tilde{H}_2 + H^T \epsilon \left( -h_1 \sigma_a \tilde{W}^a + h'_1 \tilde{B} \right) \tilde{H}_1 \\
+ \frac{M_2}{2} \tilde{W}^a \tilde{W}^a + \frac{M_1}{2} \tilde{B} \tilde{B} + \mu \tilde{H}_2^T \epsilon \tilde{H}_1 + h.c.,
\]
with $\epsilon = i \sigma_2$. Since, in order to obtain baryogenesis an extra CP-violating source is required, a complex $\mu$ is considered.

Carena et al. discuss in details the Bino decoupling setting: $|M_1| \gg |\mu|, |M_2|$ and $h_{1,2}' = 0$, then fix $\mu = -M_2 e^{i\phi}$ \(^1\) and explicitly show that it can indeed provide electroweak baryogenesis, provided that the five free parameters, $|\mu|$, $\phi$, $h_+ = \frac{1}{2} (h_1 + h_2)$, $h_- = \frac{1}{2} (h_1 - h_2)$ and the SM Higgs mass $m_H$, are in the range: $50 \text{GeV} \lesssim |\mu| \lesssim 500 \text{GeV}$, $1.5 \lesssim h_- \lesssim \sqrt{4\pi}$, $m_H \lesssim 300 \text{GeV}$.

In this setup the Lightest Neutralino (LN) is an almost pure Higgsino state with mass settled by $|\mu|$, while the mass of the Lightest Chargino (LC) is settled by $h_+$, contrary to MSSM where the Higgsino-like LN and LC are degenerate. We compute the LN relic density \(^2\) and compare it with the latest determination of the CDM component of the Universe by the WMAP experiment \([3]\) for some choice of the free parameters. The result is shown in the left panel of Figure 1 where we also implemented the bounds on the LEP measurement of the $Z$ width. In this panel we can distinguish three different zones. The first is the one where annihilations are dominated by fermions in the final state via $Z$ boson s-channel exchange originating the oblique branch of the isolevel curves. The second zone is dominated by neutralino annihilations in gauge bosons and originates the horizontal branch. The third is sensitive to the Higgs mass value giving the different behavior in the two green isolevel lines. As final remark we note that the constraint we impose on the parameters space select a “light” spectrum, since $m_{LN} \sim O(100) \text{GeV}$, and $m_{LC} \sim 200 \text{GeV}$.

2. Detection Rates
We systematically go through all WIMP detection techniques to illustrate those that already exclude models within our framework and what are the detection prospects for the future.

Since in this framework LN is a very pure Higgsino state, and the coupling with the $Z$ boson increase as the mixing increase, the spin-independent cross section is negligible and in fact is out the reach of the future experiments \([2]\), while, since the LN has a non negligible coupling with the $Z$ boson, the spin-dependent cross section is in the reach of projected sensitivity of the SuperCDMS \([4]\).

A very promising indirect detection technique is the search for neutrinos produced by the annihilation of neutralinos trapped in the core of the gravitational well of the Sun, since it has a very distinctive signature, and potentially induced fluxes may be large. In the central panel of Figure 1, we present results in terms of muon-induced fluxes, above the threshold of 1 GeV, and compare them to the current limits from the SUPER-KAMIOKANDE Collaboration \([5]\) and with the future projected sensitivity of the IceCube experiment \([6]\). From this analysis we see that SUPER-KAMIOKANDE already rules out a portion of parameter space, while IceCube will remarkably improve the scanning. In this experimental setup is very difficult to test model with $h_- \sim 0$ since the neutralino-$Z$ boson coupling and then the Sun capture rate is very small.

The prospects for antideuteron searches with the GAPS experiment \([7]\) are shown in the right panel of Figure 1. Note that through this detection method, all models are essentially found to be detectable when one considers the most favorable halo profile \([8]\). Taking the very conservative Burkert \([9]\) profile the rates are shifted down by a factor 10; also with this halo choice large portions of parameter space, including part of the $h_- = 0$ regime, are testable.

3. Conclusions
We studied the setup introduced in Ref. \([1]\) to strengthen the electroweak phase transition and achieve baryogenesis. We have foliated the parameter space retaining all the models with

\(^1\) Condition which maximizes the number of degrees of freedom contributing to strengthening the electroweak phase transition.

\(^2\) Details can be found in \([2]\).
\( \Omega_{LN} h^2 \) in agreement with both the WMAP determination and the Z boson width measurement at LEP. Bounds coming from the thermal relic abundance select a light spectrum: the LC mass is typically of the order of 200 GeV, a favorable case for detection at upcoming colliders. We computed rates for direct and indirect detection. Spin-independent elastic scattering cross-sections are very small and they are not within the projected sensitivity of planned detectors. On the other hand the spin-dependent cross-sections may be detected by future experiments. Indirect detection techniques look more promising. In fact using data on the neutrino flux from the center of the Sun we are able to rule out part of the parameter space. The induced antimatter components in cosmic rays give complementary and promising signals. In particular we predict that for most models the antideuteron flux will be detectable with GAPS, regardless on the assumptions on the dark matter distribution in the Galaxy. Hence, in this setup, contrary to the standard lore, indirect detection techniques seem the more promising strategies to detect dark matter.

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