Heavy Dirac Neutrino Dark Matter

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Heavy Dirac neutrinos are viable dark matter candidates provided their coupling to the standard model Z is suppressed to satisfy constraints from direct detection experiments.

1 Introduction

Although evidence for dark matter has become very convincing, we still have few clues on what this dark matter could be. On the theoretical side, many candidates have been proposed, in particular weakly interacting massive particles (WIMPS) provide naturally the right amount of relic abundance.

We reexamine the case of a Dirac neutrino with a mass at the electroweak scale but that does not come from the Higgs vev. An example is a vector-like fermion with a Kaluza-Klein mass. In addition, our candidate does not have standard neutrino interactions. Indeed, a heavy fourth-generation purely Dirac neutrino with Standard Model (SM) interactions is excluded as dark matter because it leads to a large cross-ection for scattering on nucleons and a very small value for the relic abundance [2]. Besides, there are strong constraints from EW precision tests if the neutrino mass comes from EW symmetry breaking.

We consider a generic extension of the SM containing a stable heavy neutrino, ν' [3]. We assume that this neutrino is an $SU(2)_L$ singlet but charged under $SU(2)_R$. Electroweak symmetry breaking typically induces a mixing between the Z and the Z', leading to a small effective coupling of ν' to the Z. Examples of this type were studied in warped extra dimensions [4, 5] and in universal extra dimensions [6]. We further assume a discrete symmetry under which all SM fields are neutral and ν' is the lightest new charged particle.

The low energy constraints on additional neutral or charged gauge bosons (Z',W') that might be present in this generic model can be avoided simply by assuming that the new gauge bosons couple only to the fermions of the third generation. Typical mass limits are then $M_{Z'}, M_{W'} > 500$ GeV [3]. We introduce effective couplings of ν' to Z, Z' and H, denoted g_Z, $g_{Z'}$ and g_H respectively:

$$g_Z \overline{\nu'} \gamma^\mu \frac{1+\gamma_5}{2} \nu' Z_\mu \ , \qquad g_{Z'} \overline{\nu'} \gamma^\mu \frac{1+\gamma_5}{2} \nu' Z'_\mu \ , \qquad g_H \overline{\nu'} \nu' H \tag{1}$$

As motivated in higher-dimensional models, only one chirality has non-suppressed couplings to the gauge bosons. However, our results essentially do not depend on the presence or not of the projector. We assume that the remaining new physics which makes the model more complete does not interfere much with our dark matter analysis.

2 Direct detection

The cross section for elastic scattering of a Dirac neutrino on nucleons is dominated by Z exchange and in contrast with Majorana dark matter, the Z exchange contributes to the spin-independent scattering cross section [4]. In order to satisfy limits from direct detection experiments, in particular those of Xenon [7], the ν' coupling to the Z must be suppressed. This means that $g_Z \lesssim 10^{-2} g (g = e/\sin\theta_W)$ for $M_{\nu'} \sim 100$ GeV while for a ν' in the TeV range larger values of g_Z are allowed due to the reduced experimental sensitivity. Suppressed couplings are quite natural in models where the coupling arise from mixing effects and in fact low energy constraints on the Z–Z' mixing can be even more severe than the ones from direct detection [3]. When the ν' has a sizable coupling to the Higgs, the Higgs exchange contributes significantly to the spin independent cross section. The constraints from both Xenon [7] and CDMS [8] in the g/g_Z-$M_{\nu'}$ plane are displayed in Fig. 1 with and without the Higgs contribution (with $m_H = 120$ GeV, $g_H = 0.25$).

3 Relic abundance

The parameter that determines the elastic scattering of Dirac neutrino dark matter on nucleus is the same parameter that drives the annihilation of neutrinos and determines the relic density. The suppressed coupling g_Z that is required from direct detection constraints is nevertheless sufficient to guarantee an annihilation rateresulting in $\Omega_{\nu'} h^2 \approx 0.1$ for three different ranges of neutrino masses. This is illustrated in Fig. 1. First, when $M_{\nu'} \approx M_Z/2$ neutrinos annihilate very efficiently into fermion pairs through Z exchange even if g_Z is small. Second when $M_{\nu'} \approx M_H/2$ the annihilation cross section through Higgs exchange is enhanced significantly provided the ν' couples to the Higgs. Third, for heavier neutrinos, $M_{\nu'} > 700$ GeV, the WW annihilation channel increases significantly, while satisfying unitarity limits. Furthermore, for this range of masses the experimental constraint from direct detection is less severe.

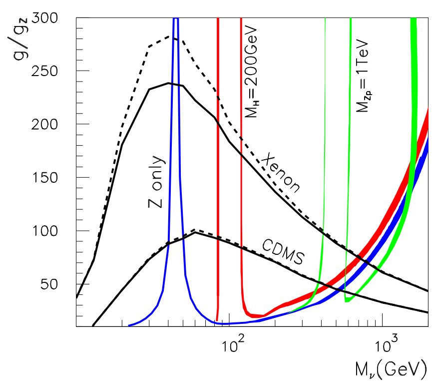

Figure 1: WMAP region, $0.097 < \Omega_{\nu'} h^2 < 0.113$, in the $g/g_Z - M_{\nu'}$ plane including Z-exchange only (blue band), also the Higgs exchange (red band), and the Z' exchange (green band) and region allowed by direct detection (full or dotted). The region above the CDMS/Xenon lines and below the WMAP band is allowed.

The presence of a Z' will in general enhance the annihilation cross section opening the possibility of satisfying both direct detection and relic abundance constraints for $M_{\nu'} \approx M_{Z'}/2$. In particular, a Z' of 1TeV gives quite naturally a viable dark matter candidate in the few hundred GeV range, see Fig. 1. Other new particles introduced in addition to the ν' can also increase the annihilation cross section and make the ν' a viable dark matter candidate in the few hundred GeV range. For example, a W' can contribute via t-channel exchange of a new charged lepton or coannihilation with new heavy leptons or quarks could increase the annihilation cross section without affecting the direct detection rate [3]. The latter mechanism is of course very much dependent on the mass of the new fermions. In summary, the Dirac neutrino is expected to be rather heavy, thus with a limited potential for discovery at colliders, except for small windows around the mass of resonances or when coannihilation effects are important.

4 Collider signatures

Like in other WIMP models, the standard searches rely on pair production of the heavier exotic particles which ultimately decay into the WIMP, leading to signals with energetic leptons and/or jets and missing E_T. Some signatures that are more specific to the neutrino WIMP model include invisible Higgs decay into ν', production of a long-lived charged lepton and production of new colored fermion. The latter is of course model dependent and has been studied for the LHC within the context of a model with warped extra dimensions [9]. Production of long-lived charged leptons, for example a τ' nearly degenerate with ν', is a very distinctive signature of new physics at colliders and has been searched for at LEP and Tevatron. For such a signature to be relevant however requires very special conditions on the parameters of the model, for example a weak $\tau'\nu'W$ coupling and/or a small $\tau' - \nu'$ mass splitting [3]. The invisible Higgs can be probed at LHC via the weak boson fusion process [10]. Sensitivity is best when the Higgs is too light to decay into W pairs. Then, for $g_H > 0.01 - 0.1$ a signal should be observed at LHC [3]. The ILC has however a greater potential to probe the invisible Higgs.

5 Conclusion

A Dirac neutrino is a viable dark matter candidate in the mass range from 40 GeV to a few TeV however special mechanisms such as resonance annihilation or coannihilation are required if the neutrino mass is below 700 GeV. A signal is expected in direct detection experiments in the near future especially in the mass range relevant for searches at the ILC.

6 Acknowledgments

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