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Neutralino dark matter with a Light Higgs

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We examine the neutralino dark matter (DM) phenomenology in supersymmetric scenarios with nonuniversal Higgs masses (NUHM) at the gauge coupling unification scale that can acommodate a light Higgs boson, where the correct relic density is obtained mostly through the annihilation into a pseudoscalar A. Our analysis shows that most part of the A pole region can produce detectable gamma-ray and antiproton signals. We further focus on uncertainties influencing the results in indirect and mainly direct detection.

1 Introduction

1.1 The model

One of the major experimental constraints on the constrained-MSSM parameter space comes from the LEP-2 limits on the lightest higgs boson mass. In particular, LEP-2 set a lower bound of 114.4 GeV for this mass [1], excluding the largest part of the model's viable parameter space. However, strictly speaking, this bound only applies to the SM. It comes mostly from searches in the Higgsstrahlung channel, which in the case of the MSSM is actually not identical to the SM one. In particular, $\sigma_{\rm MSSM}(e^+e^- \to hZ) = \sin^2(\beta-\alpha)\sigma_{\rm SM}(e^+e^- \to hZ)$ [2,3]. Hence, the LEP2 bound $m_h \gtrsim 114$ GeV applies to the MSSM only if $\sin^2(\beta-\alpha) = \mathcal{O}(1)$. This is the case in cMSSM/mSUGRA scenarios.

This limit can actually be partially circumvented once some of the cMSSM constraints are relaxed. In particular, it has been pointed out [4,5,6] that relaxing the requirement for higgs mass universality at the GUT scale can effectively reduce the $\sin^2(\beta-\alpha)$ factor, leading to a smaller cross-section and thus to weaker bounds on the lightest higgs mass.
Our particular model [7] is characterised by the following parameters

$$m_{1/2},\ A_0,\ \mathrm{sign}(\mu),\ \tan\beta,\ m_0,\ m^2_{H_u},\ m^2_{H_d} \qquad (1)$$

where the GUT-scale common scalar mass m_0 concerns all scalars but the two Higgs bosons.

We examined the neutralino dark matter - related phenomenology of this model, notably the behavior of the relic density over some region of the parameter space, the prospects for indirect detection as well as the constraints coming from direct DM detection experiments. Viable parameter space points have to satisfy a number of constraints:
- Higgs boson mass limit: In the *non decoupling* region where the A boson becomes very light the lower limit of m_h goes down to 93 GeV or even lower. We consider that the parameter space with $\sin^2(\beta-\alpha) < 0.3$ (or, $\sin(\beta-\alpha) \lesssim 0.6$), and $93 < m_h < 114$ is in agreement with the LEP2 limit [1]. Consequently, the coupling of the heavier Higgs boson to the Z boson

($g_{ZZH} \propto \cos(\beta-\alpha)$) becomes dominant and this makes the heavier Higgs boson SM - like, so the LEP-2 114 GeV limit starts applying for the heavier CP-even higgs boson. On the other hand, in the decoupling region $\sin(\beta-\alpha) \sim 1$, which means that the 114 GeV limit applies to the lightest higgs. Given the fact that there exists an uncertainty of about 3 GeV in computing the mass of the light Higgs boson [8], we accept a lower limit of 111 GeV.

- **$Br(b \to s\gamma)$ constraint:** We demand [9,10] $2.77 \times 10^{-4} < Br(b \to s\gamma) < 4.33 \times 10^{-4}$.

- **$Br(B_s \to \mu^+\mu^-)$ constraint:** We further impose the important $Br(B_s \to \mu^+\mu^-)$ constraint coming from CDF, [11] $\mathrm{Br}(B_s \to \mu^+\mu^-) < 5.8 \times 10^{-8}$ (at 95 % C.L.), which has recently been improved to $< 4.3 \times 10^{-8}$ at 95% C.L [12].

- **WMAP constraint :** In computing the relic density constraint, we consider the 3σ limit of the WMAP data [13] $0.091 < \Omega_{CDM}h^2 < 0.128$. Here $\Omega_{CDM}h^2$ is the dark matter relic density in units of the critical density and $h = 0.71 \pm 0.026$ is the Hubble constant in units of 100 Km s^{-1} Mpc^{-1}. We use the code micrOMEGAS [14] to compute the neutralino relic density.

1.2 Dark matter detection

There exist two main modes of dark matter detection, usually referred to as "indirect" and "direct". Indirect detection is based on the principle that if DM can annihilate (or decay), in the early universe in order to give the measured relic density, this process should also occur today throughout the galaxy (and beyond), so we could hope to detect its annihilation products: gamma-rays, positrons, antiprotons and neutrinos. Direct detection of DM relies on the fact that WIMPs may interact with (scatter on) ordinary matter. This scattering is an in principle measurable effect and indeed a huge effort is currently being developped worldwide to measure potential signals coming from DM scatterings upon large underground detectors.

Concerning indirect detecion, in this work we compute the gamma-ray signals at intermediate galactic latitudes [15] in the spirit of elliminating as much as possible uncertainties coming from the DM "halo profile" (i.e. its distribution in the galaxy) as well as background contributions to the spectrum. These gamma-rays can be detected by the Fermi satelite [16]. For the case of antiprotons, we compute the prospects for detection in the AMS-02 mission [17]. We adopt a semi-analytical treatment of the diffusion equation [18,19,20], presenting results for the so-called MAX propagation model.

Finally, we compare the neutralino-nucleon spin-independent scattering cross-section to some of the tightest bounds available in the literature[21,22,23]. As it has been pointed out, uncertainties are not absent in direct detection as well. These can be of a twofold nature: First of all, when giving exclusion bounds on the $(m_\chi, \sigma_{\chi(p,n)})$ plane, a set of astrophysical assumptions (as well as some assumptions on the passage from the nuclear to the nucleonic level) have already been made. These assumptions are thought to have a small impact on the results, the mangitude of which depends, among other factors, on the considered mass range [24,25,26,27,28]. Secondly, there are often uncertainties in the cross-section computations performed by theorists in specific models. In our case, what is of relevance is one of the parameters entering the passage from the partonic to the the WIMP-nucleon scattering cross-section, denoted by f_{T_s}. This parameter is actually related to the strange quark content of the nucleon. Its value can be either measured or estimated through lattice QCD methods. The DarkSUSY [29] code, which was used to compute the cross-section, adopts a default value of $f_{T_s} = 0.14$. However, recent lattice simulations [30,31] point towards much lower values, of the order of 0.02, being even compatible with zero. The effect of this uncertainty has been quantified [32] and is known to range from negligible to very large, depending on the specific mechanism driving the scattering cross-section. In what follows we shall quantify the effect of this uncertainty showing that it is really crucial in assessing the viability of our models.

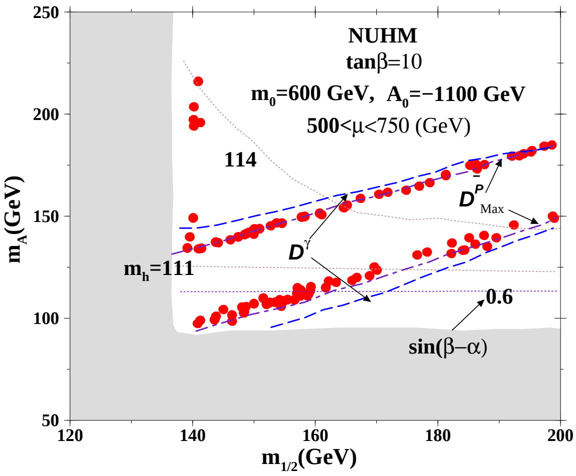

Figure 1: Viable points in the $m_{1/2} - m_A$ plane. Neutralino masses of $\sim 55-65$ GeV correspond to the *Light Higgs Boson* region. Detectability of the photon and anti-proton signals are represented by D^{γ} and $D^{\bar{p}}_{Max}$ lines.

2 Results

2.1 Indirect detection

We performed [7] two scans in the model's parameter space:
- In the first one, we fix $\tan\beta (= 10)$, $m_0 = 600$ GeV, $A_0 = -1100$ GeV, sign$(\mu) > 0$. Then, we vary the mass parameters m_{h_u} ($0 < m_{h_u} < m_0^2$) and m_{h_d} ($-1.5m_0^2 < m_{h_d} < -0.5m_0^2$) to obtain light neutralino dark matter consistent with light Higgs masses ($m_{H,A} \leq 250$ GeV) at the electroweak scale. μ and m_A are derived quantities. We note that the high μ parameter values obtained in this scenario correspond to an essentially pure bino LSP.
- In our second scan, we fix m_0 at the very similar value $m_0 = 600$ GeV, while $A_0 = -1000$ GeV is chosen to make $b \to s\gamma$ less restrictive. We set m_{h_u} ($= 2.4m_0^2$) and vary m_{h_d} ($-0.3m_0^2 < m_{h_d} < 0.1$) with $m_{1/2}$ to obtain the WMAP-compatible regions for neutralinos. Our scan renders very small μ values ($150 < \mu < 300$), consequently the LSP can have large Higgsino components.
In both cases, we look for points satisfying the relic abundance requirement while passing all constraints previously mentioned. The viable points are then scattered on the $m_{1/2} - m_A$ plane as red dots.

Our results can be seen in figures 1 and 2. Appart from the WMAP-compliant points, we demonstrate in the same plots regions excluded by other constraints (gray regions), higgs mass isocontours, as well the parameter space regions that can be probed during a 3-year data acquisition period for Fermi and AMS-02: all points lying inside the two parallel lines in the case of fig.1 and on the left or below the lines in fig.2 can -in principle- be probed.

In the first set of scenarios, there are mainly two mechanisms that can generate the correct relic density: quasi-resonnant annihilation through a A or H pole, extending along the direction of the line where $2m_{\chi_1^0} \approx m_A, m_H$, or the light Higgs pole at low $m_{1/2}$ and along the m_A direction.

In the second set of scenarios the neutralino self-annihilation cross-section is enhanced kinematically as before (i.e. we are once again sitting near the A pole), but moreover the neutralino acquires a non-negligible higgsino component which enhances its couplings to the higgs bosons.

In both scenarios, we see that the detection prospects are quite good. Significant portions of the viable parameter space can be probed.

In the first case, perspectives are actually good along the A-pole. On the contrary, we see that the light higgs pole seems to be completely invisible in both channels. This is due to

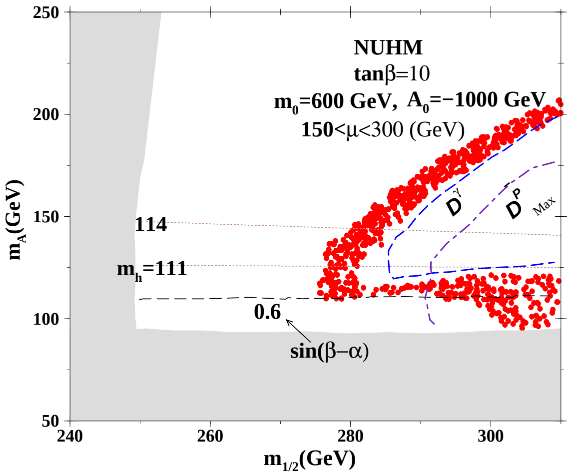

Figure 2: Same as Fig.1, except that the *light Higgs boson* zone is shifted to larger neutralino mass values.

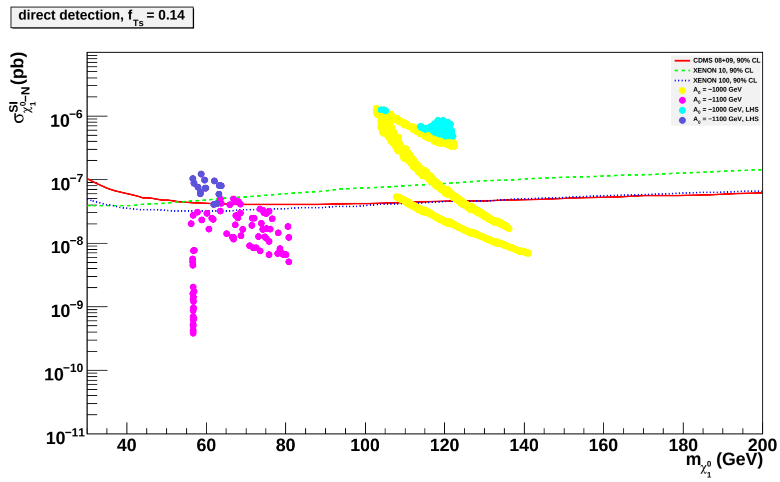

Figure 3: $(m_{\chi_1^0}, \sigma^{SI}_{\chi_1^0 - N})$ combinations along with the relevant exclusion limits from direct detection experiments for $f^{(p,(n))}_{Ts} = 0.14$. Points lying above the lines are excluded according to the published limits. The light blue and the dark blue points represent the *light Higgs boson* regime for the two scenarios at stake.

the fact that whereas resonnant annihilation is an efficient mechanism in the early universe, the cross-section for this process tends to zero as the neutralino velocity does so [33,34]. This is actually the case at present times, which are of relevance for indirect detection. On the other hand, annihilation through a pseudoscalar is not that sensitive to changes in the WIMP velocity [33], so the cross-section remains relatively high even at present times.

In the second set of scenarios, the prospects are actually even better. On the one hand, any interference of CP-even higgs bosons is negligible. Moreover, the fact that in this case the neutralino has a significant higgsino component enhances its couplings to the higgs sector, an effect which is practically insensitive to velocity changes. So, the cross-section remains quite stable at present times.

2.2 Direct detection and associated uncertainties

As a final step, we computed the spin-independent neutralino-nucleon scattering cross-section. The results can be seen if figures 3 and 4, for two different values of the f_{T_s} parameter, namely the default DarkSUSY value of 0.14 and a reduced value of 0.02 respectively.

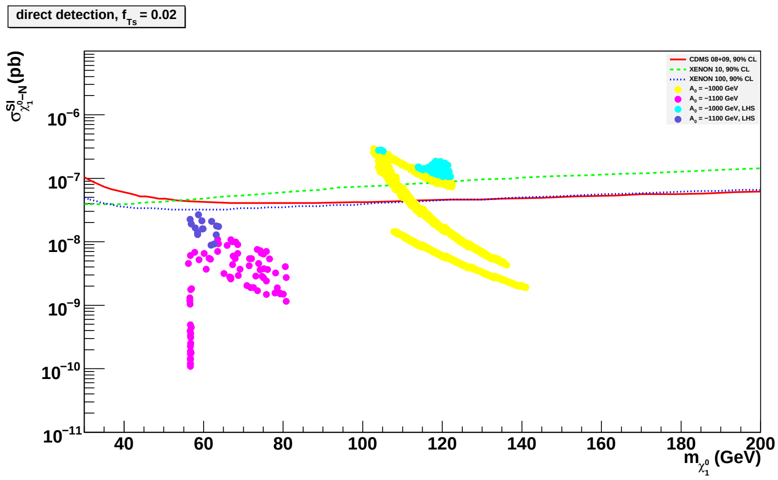

Figure 4: As in fig.3 but for $f_{Ts}^{(p,(n))} = 0.02$.

From fig.3 we see that our NUHM model seems to be hopelessly excluded, especially when it comes to the Light Higgs Scenarios. The situation seems to be however quite different once we look at fig.4.

A comparison of the two figures demonstrates the importance of the uncertainty in the value of f_{T_s}. We see that once we reduce its value from the default one towards lower values the cross-section is reduced by something like an order of magnitude. We further remind that f_{T_s} estimates are even compatible with zero. Moreover, once a set of astrophysical or nuclear uncertainties is taken into account (local density, velocity distribution, nuclear form factors), the experimental limits may be considered to bare an additional uncertainty of a factor $3-4$. We thus see that stating whether a model is excluded by direct detection data or not may be a tricky issue. All potential sources of uncertainty should be examined before definitively ruling out a model. Fortunately, a large effort is being devoted by several groups in quantifying these uncertainties and incorporating them in a systematic manner, both in the limits published by experimental collaborations and in the calculations performed by theorists.

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