

Indirect and direct detection prospect for TeV dark matter in the MSSM-9

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We perform a Bayesian analysis taking into account particle physics constraints, and upper limits on the scattering cross-section from direct detection experiments to investigate the prospects of indirect and direct dark matter searches for the minimal supersymmetric standard model with nine parameters (MSSM-9). We assume that the lightest neutralino provides all the dark matter through the thermal freeze-out mechanism. We find that the Cherenkov Telescope Array, CTA, together with XENON-1T will be able to probe a large fraction of the most probable regions of the MSSM-9: ~ 1 TeV higgsino-like and ~ 3 TeV wino-like neutralinos.

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1. Introduction

The hunt for signatures of physics beyond the Standard Model of particle physics is going on at the LHC. Although there has been no claim of positive signatures, some outstanding conclusions can be drawn from several measurements, in particular for the Minimal Supersymmetric Standard Model (MSSM), one of this consequence comes from the mass measurement of the Higgs boson of about 126 GeV [1, 2]. The rather high reported Higgs mass m_h shifts the scale of supersymmetric masses to higher values with respect to what was expected based on naturalness arguments.

The Galactic center is one of the most promising places to search for signals from WIMP annihilation. Upper limits from modern gamma-ray instruments, such as the Large Area Telescope (LAT) aboard *Fermi* satellite, start to exclude this canonical annihilation cross-section for WIMP masses below 100 GeV [3]. On the other hand the wino dark matter annihilation cross-section is significantly larger than the canonical value for WIMPs due to a non-perturbative effect known as Sommerfeld Enhancement (SE) [4, 5, 6, 7, 8], being already in some tension with searches for gamma-ray lines [9, 10, 11].

In this proceeding we review the main result of the paper [12] where we studied the current status of the MSSM models with nine parameters (MSSM-9) and the prospects for CTA (indirect detection) and for XENON-1T (direct detection) experiments.

2. Bayesian analysis of the MSSM-9

There are several studies that have incorporated the all available experimental measurements to different parameterizations of the Minimal Supersymmetric Standard Model, e.g. Refs. [13, 14, 15, 16, 17, 18, 19, 20]. Various statistical approaches have been used to infer the most probable regions of these scenarios. Interestingly, when performing a proper Bayesian analysis, the fine-tuning penalization arises automatically from very basic statistical arguments, allowing to explore larger regions of the parameter space while taking the notion of naturalness automatically into account Ref. [21]. Electroweak fine-tuning arise as a Jacobian factor after including the Z-boson mass as an experimental value. In the same way fine-tuning associated to all the experimental measurements are included following this approach.

In order to evaluate the sensitivity on dark matter in a more generic context, we parameterize the MSSM with 10 fundamental parameters at the gauge coupling unification scale. After requiring the correct electroweak symmetry breaking, we end up with 9 effective parameters:

$$\left\{ s, M_1, M_2, M_3, m_{\tilde{q}}, m_{\tilde{l}}, m_H, A_0^{\tilde{q}}, A_0^{\tilde{l}}, \tan \beta, \text{sgn}(\mu) \right\}, \quad (2.1)$$

where s represents the SM nuisance parameters, M_1, M_2, M_3 are the gaugino masses, $m_{\tilde{q}}, m_{\tilde{l}}, m_H$ are the squark, slepton, and Higgs masses ($m_H = m_{H_u} = m_{H_d}$), and $A_0^{\tilde{q}}$ and $A_0^{\tilde{l}}$ are the squark and slepton trilinear couplings. The sign of μ is fixed to $+1$. All the soft parameters and μ defined at gauge coupling unification scale.

We take into consideration electroweak precision measurements [22], B-physics observables [23, 24, 25, 26, 27], the Higgs mass [1, 2], and constraints on the WIMP-nucleon scattering cross-section by XENON-100 [28] and LUX [29], implementing the likelihood function as defined in ref. [30]. In particular, for Xenon100 we use the likelihood defined in [31]. The LUX limit is

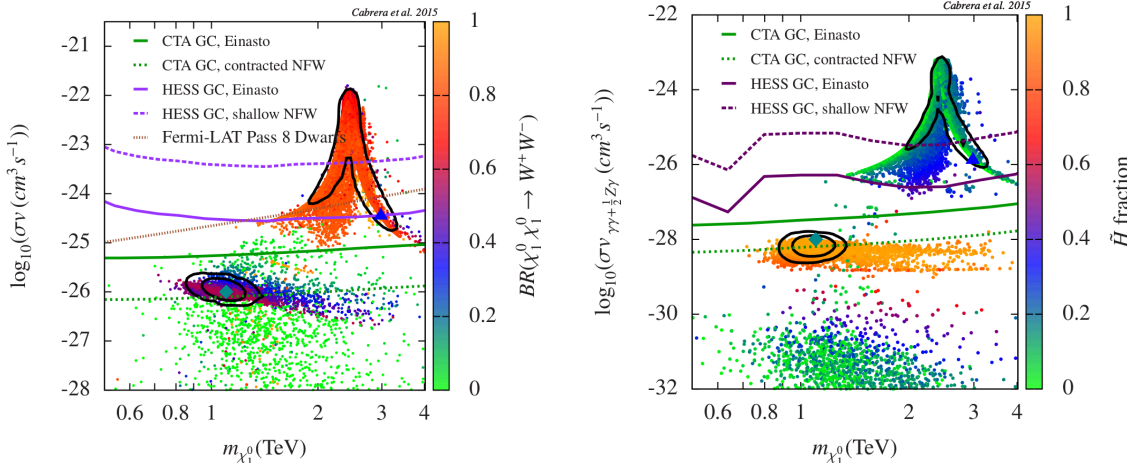


Figure 1: The contours represent 68% and 95% posterior probability credible regions in the plane neutralino mass versus total annihilation cross section (left) and annihilation into monochromatic photons (right). Colored points reproduce all the experimental observables within 2σ of confidence level. The cyan diamond represent the pure higgsino case from [41, 6], and the blue triangle the pure wino case from [9, 33].

applied as a step function only for the 2σ confidence level points. The Z-boson mass is effectively included adding a Jacobian factor.

In addition, we assume a scenario with a single dark matter component that is produced thermally in the early Universe, by including the measured relic density according to the *Planck* results [32]. For the relic density and $\langle\sigma v\rangle$ computation, we take the SE into account by creating a grid of the enhancement in the M_2 - μ plane using the Hryczuk et al. computation method implemented in DarkSE [8, 33]. For the computation of $\langle\sigma v\rangle$ in the present day we implemented a function in DarkSE to extract the enhancement for $v = 10^{-3}$ from the Hryczuk *et al.* computation (we validated the results with the pure-wino case showed in [33]).

For the priors of the parameters, we adopted both standard and ‘improved’ log priors (S-log and I-log, respectively), defined in Refs. [13, 18]. In the following, we show results for the I-log priors only¹.

For the numerical analysis, we use the SuperBayeS code [34], which uses the nested sampling algorithm implemented in Multinest [35], and integrates SoftSusy [36], SusyBSG [37], SuperIso [38], DarkSusy [39], MicrOMEGAs [40], and DarkSE [8] for the computation of the experimental observable.

3. Results

Left panel of Fig. 1 shows two-dimensional contours that represent 68% and 95% credible regions of the most relevant parameters for CTA: the dark matter neutralino mass and annihilation cross-section. The posterior has two peaks in the mass distribution. The largest peak locates

¹The results obtained with S-log priors are very similar. Since the data, in particular the relic density constraint combined with the Higgs mass, turns out to be very constraining in the MSSM-9 when taking into account naturalness arguments into account.

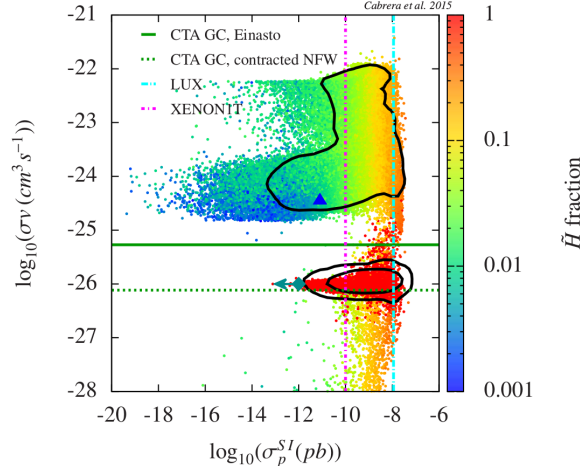


Figure 2: Similar to Fig. 1, but showing the total annihilation cross-section against the WIMP-proton spin-independent cross-section. The blue triangle and the cyan arrow are the theoretical values of the pure wino and pure higgsino case. The arrow indicates that the value of σ_p^{SI} is a theoretical upper limit. Sensitivity lines from CTA and XENON-1T for $m_{\chi_1} = 1$ TeV.

around 1 TeV, where the neutralino mostly consists of higgsino. There is a weaker peak around 3 TeV, where it is mostly wino.

Left panel of Figure 1 also shows, as points, regions in the parameter space that reproduce all experimental observables within 2σ of confidence level. The 68% and 95% credibility regions show that it is much more likely to find neutralinos with a mass of ~ 1 TeV and ~ 3 TeV, however, these contours not necessarily cover all the regions that respect the experimental observables. The scattered points outside the contours show regions that require more tuning to reproduce the experimental observables and, therefore, their integrated probability is small.

An additional region around hundreds GeV, corresponding to bino-like neutralino, is not shown in the figure. This region has small statistical weight and is not well explored in our scan, for this reason we show $m_{\chi_1^0}$ larger than 500 GeV in our figures.

The colored points in left panel of Fig. 1 show the branching fraction of the lightest neutralino annihilating into W^+W^- . The colored points in right panel of Fig. 1 show the higgsino fraction of the lightest neutralino. Note that points inside the 95% contour are dominantly higgsino-like and wino-like neutralinos.

4. Prospects of Detection

Figure 1 shows the predicted annihilation cross-section into continuum photons (dominated by W^+W^- , ZZ and $\bar{q}q$ final states) and gamma-ray lines, respectively, compared to different experimental limits and reaches. Our fiducial density profile is given by an Einasto profile (with parameters $\alpha = 0.17$, $\rho_\odot = 0.4 \text{ GeV/cm}^3$ and $r_s = 20 \text{ kpc}$). The current upper limits on the Galactic center from HESS searches for gamma rays from $\bar{b}b$ final states (left panel of Fig. 1) [42] [43] and for gamma-ray lines (right panel of Fig. 1) [43] are already very tight. We find that the wino dark matter region around 3 TeV is almost completely excluded by the HESS upper limits.

However, that upper limits are still subject to uncertainties mainly related to the density profile [9]. To illustrate this point, we show in Fig. 1 how the HESS limits weaken when a shallower dark matter profile is adopted. To this end, we use a generalized NFW profile with an inner slope of $\gamma = 0.7$ (and $r_s = 20 \text{ kpc}$, $\rho_\odot = 0.4 \text{ GeV/cm}^3$), which is still in agreement with kinematic and microlensing observations [44]. In this case, the limits indeed are weakened and part of the wino best-fit region is still allowed. A similar effect will occur for cored profiles.

In left panel of Fig. 1, we also show the *Fermi*-LAT limits, corresponding to $\chi_1^0 \chi_1^0 \rightarrow b\bar{b}$ (limits for W^+W^- final states are very similar), from the observation of dwarf spheroidal galaxies from Ref. [45], which already include the uncertainties in the dark matter profile and can be hence considered robust (i.e., this represent the upper end of the uncertainty band). They exclude most of the wino parameter space.

The CTA sensitivities for both the total annihilation cross section derived for $\bar{b}b$ final states and 100h observation time, assuming 1% systematics, [46] and for the gamma-ray lines [47] are shown in Fig. 1. These figures show that, for standard Einasto profiles, it will be challenging for CTA to reach the 1-TeV higgsino parameter space, unless background systematics are under control at the sub-percent level [46]. However, as explained above, baryonic effects could potentially increase the chances for a CTA discovery of higgsino dark matter as baryons can drag dark matter towards the Galactic center during their cooling, leading to a more cuspy profile [48]. To illustrate this effect, we additionally show in left panel of Fig. 1 the reach of CTA when a slightly contracted NFW profile, with an inner slope of $\gamma = 1.3$ (and otherwise parameters as above), is adopted. In this case, CTA has the potential to rule out (or discover) a large part of the best-fit higgsino dark matter region.

Fig. 2 shows the most probable regions plotted for the annihilation cross-section and the spin-independent scattering cross-section σ_p^{SI} at tree level. We also show higgsino neutralino (cyan diamond) and wino neutralino (blue triangle) one-loop computation performed by [49, 50]. In the pure higgsino case, the perturbative QCD and hadronic input 1σ -uncertainties allow only to set a maximum value for σ_p^{SI} , which is represented in the figure by an arrow. The colored points in Fig. 2 represent the higgsino composition of the lightest neutralino, and show how the value of σ_p^{SI} decreases with the higgsino fraction in the wino-like region. In the region where σ^{SI} is smaller than $\sim 10^{-11} \text{ pb}$ and $\sigma\nu$ larger than $10^{-25} \text{ cm}^3 \text{ s}^{-1}$, the tree level σ^{SI} does not give a realistic value, after including higher order corrections we would expect that those points will get σ^{SI} values of $\sim 10^{-11} \text{ pb}$.

Figure 2 also shows the sensitivities of XENON-1T [51] and CTA [46] corresponding to $\chi_1^0 \chi_1^0 \rightarrow b\bar{b}$, both for $m_{\chi_1^0} = 1 \text{ TeV}$, showing that both direct and indirect searches are very important for the potential discovery of TeV dark matter. Note also that the region around the almost-pure and pure wino and higgsino neutralinos will be probed by CTA only.

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