COSMIC ANTIPROTONS FROM NEUTRALINO ANNIHILATION IN THE GALACTIC HALO

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Abstract

We investigate the possibility that the antiproton–to–proton flux ratio which is measured in cosmic rays may be generated by neutralino–neutralino annihilation in the galactic halo. We study the most general compositions for the relic neutralinos. We compare our results with the present experimental sensitivity and find that the theoretical predictions are at the level of the current experimental limits for some regions in the parameter space of the model. We expect that the future measurements of the $\bar{p}/p$ will provide very useful information, complementary to the ones obtainable with other experimental means.

1 Introduction

One of the best motivated particle candidates for cold dark matter is provided by supersymmetry [1]. The lightest supersymmetric particle (LSP), being stable provided R-parity is conserved, is, in a large region of the supersymmetric parameter space, the lightest neutralino (χ). This state is defined as the lowest-mass superposition of the gaugino ($\tilde{B}, \tilde{W^3}$) and the higgsino ($\tilde{H_1}, \tilde{H_2}$) fields :

$$\chi \;=\; a_1\tilde{B} + a_2\tilde{W^3} + a_3\tilde{H_1} + a_4\tilde{H_2} \quad . \tag{1}$$

The possibility of detecting neutralinos in our galactic halo has been studied extensively in many different ways [2]. Direct detection of the nuclear recoil induced by neutralino–nucleus elastic scattering is, both theoretically [3] and experimentally [4,5], under investigation. The indirect detection of high-energy neutrinos coming from the centre of the Earth or the Sun [6], or the indirect detection of exotic components in the primary cosmic rays, such as γ, e^+ and

$\bar{p}$, have been studied in detail [7,8]. Here we examine the latter possibility, and analyse the parameter space of the supersymmetric model taking care of the new experimental limits on supersymmetric particles coming from CERN LEP [9]. We also include some recent progress on the treatment of the propagation of cosmic antiprotons $\bar{p}$ in the Galaxy [10], considering the properties of the diffusion model instead of using the standard leaky box approach.

2 Theoretical framework

We recall in this section only the main features of the model to which we refer: the Minimal Supersymmetric Standard Model (MSSM). For a detailed description of the model and for a discussion on the range of variation of the various parameters that enters in the current analysis see: A. Bottino, these Proceedings.

The neutralino mass and the coefficients a_i of Eq.(1) depend on the parameters: μ (Higgs mixing parameter), M_1, M_2 (masses of $\tilde{B}$ and of $\tilde{W}^3$, respectively) and $\tan\beta = v_u/v_d$ (v_u and v_d are the v.e.v.'s which give masses to up-type and down-type quarks). As for the masses of the particles entering in the amplitudes for the neutralino-neutralino annihilation and for the neutralino-quark scattering (Higgs bosons, sfermions), we do not make use of theoretical assumptions implied by supergravity schemes, but we only take into account constraints due to present experimental limits. In the case of the neutral Higgs bosons (the two CP–even bosons: h, H (of masses m_h, m_H with $m_H > m_h$) and the CP–odd one: A (of mass m_A)) we take m_A as a free parameter only bounded by the present experimental results [11]. As for the sfermion masses and in order to deal with a relatively small number of parameters, we consider a common soft scalar mass m_0 as a free parameter (with the possible exception of the top squark). Another quantity which we take as a free parameter is the top trilinear coupling A_t. Moreover we assume the standard GUT relation among the gaugino masses

$$M_1 : M_2 : M_3 = \alpha_1 : \alpha_2 : \alpha_3 \tag{2}$$

which implies at m_Z scale that $M_1 \simeq 0.5 M_2$.

Once defined our parameter space, we impose the experimental constraints deduced from the new particles searches at accelerators, including the new lower limits on the chargino mass obtained at LEPII[9], and the measurement of the rare decay $b \to s\gamma$[12] from CLEO.

We then compute the neutralino relic abundance in the standard way [13,14,15,16] and we exclude from the parameter space those configurations that do not fulfil the cosmological bounds $\Omega h^2 \leq 1$.

2.1 Relic density

The neutralino relic abundance $\Omega_\chi h^2$ is evaluated following the standard procedure, which gives essentially $\Omega_\chi h^2 \propto < \sigma_{\rm ann} v >_{\rm int}^{-1}$, where $< \sigma_{\rm ann} v >_{\rm int}$ is the thermally–averaged annihilation cross section, integrated from the freeze–out temperature to the present temperature. The standard expansion $< \sigma_{\rm ann} v > = a + bx + ...$ may be employed, with $x = T/m_\chi$, except at s–channel resonances (Z, A, H, h) or at the opening of a new final state channel, where a more precise treatment has to be used for the thermal average[14]. In the evaluation of $< \sigma_{\rm ann} v >$ the full set of annihilation final states ($f\bar{f}$ pairs, gauge–boson pairs, Higgs–boson pairs and Higgs–gauge boson pairs), as well as the complete set of Born diagrams, are taken into account[16]. We note that the constraint $\Omega_\chi h^2 \leq 1$ can be very effective in cutting the parameter space especially for small and intermediate values of $\tan\beta$, but is not really restrictive for large values of $\tan\beta$.

3 The antiproton spectrum

Let us turn now to the evaluation of the antiproton signal due to neutralino annihilation in the galactic halo. The differential rate (per unit volume and per second) for the production of antiprotons from χ–χ annihilations is given by

$$S(E_{\bar{p}}) \; = \; \langle\sigma v\rangle f(E_{\bar{p}}) \left(\frac{\rho_\chi}{m_\chi}\right)^2 \quad , \tag{3}$$

in which $E_{\bar{p}}$ denotes the antiproton energy, σ is the χ–χ annihilation cross section and v is the neutralino velocity in the galactic halo. The neutralino density ρ_χ is a function of the position $\vec{r}$ in the galactic halo. For a single annihilation, the antiproton energy spectrum is

$$f(E_{\bar{p}}) \equiv \frac{1}{\sigma} \frac{d\sigma(\chi\chi \to \bar{p} + X)}{dE_{\bar{p}}} = \sum_{F,f} B^{(F)}_{\chi f} \left(\frac{dN^f_{\bar{p}}}{dE_{\bar{p}}} \right) , \tag{4}$$

where F describes the χ–χ annihilation final state and $B^{(F)}_{\chi f}$ is the branching ratio into the quarks or gluons f in the channel F. The differential distribution of the antiprotons generated by the hadronization of quarks (with the exception of the top quark) and of gluons, is denoted by $dN^f_{\bar{p}}/dE_{\bar{p}}$ and depends on the nature of the species f. In Eq.(3), $\langle \sigma v \rangle$ and $f(E_{\bar{p}})$ depend on the neutralino properties. The antiproton production rate also depends on the distribution ρ_χ of neutralinos inside the galactic halo.

For the $\bar{p}$ differential distribution $f(E_{\bar{p}})$, we have evaluated the branching ratios $B^{(F)}_f$ for all annihilation final states that may produce antiprotons, i.e. direct production of quarks and gluons, generation of quarks through the intermediate production of Higgs bosons, gauge bosons and the top quark. The distributions $dN^f_{\bar{p}}/dE_{\bar{p}}$ from the hadronization of quarks (with the exception of the top quark) and gluons have been computed by using the Monte Carlo code JETSET 7.2[17].

The neutralino halo distribution ρ_χ is taken to be spherically symmetric and is given by the standard expression:

$$\rho_\chi(r) = \rho_\chi(\odot) \frac{a^2 + r^2_\odot}{a^2 + r^2} , \tag{5}$$

where $a = 3$ kpc is the core radius of the dark matter halo. Particular care must be taken about the local neutralino density $\rho_\chi(\odot)$, which depends on on the distribution of dark matter in the galactic halo as well as on the LSP properties. On the one hand the presence of a clumpy structure over the smooth distribution 5 may well enhance the expected signal[18]. On the other hand if the big-bang relic density $\Omega_\chi h^2$, which we evaluate following the method previously discussed, is too small to account for the cosmological dark matter, the density of neutralinos in the galactic halo should be corrected by a factor of ξ. The latter deals with the fact that the neutralino density is less than the halo density whenever $\Omega_\chi h^2$ is smaller than a minimal value of, say, $(\Omega h^2)_{min} = 0.03$, which is compatible with the observed rotation curve of the Galaxy. At cosmological distances, this ratio is given by

$$\xi = \frac{\Omega_\chi h^2}{(\Omega h^2)_{min}} . \tag{6}$$

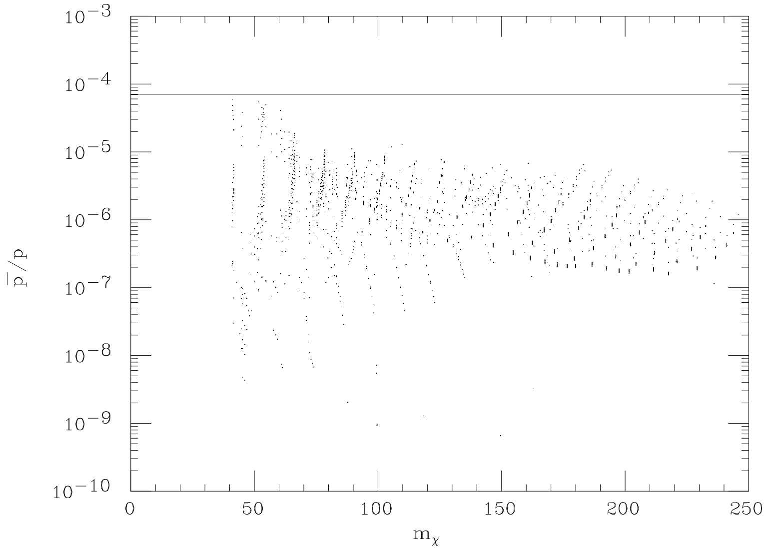

Figure 1: The ratio $\bar{p}/p$ as a function of the neutralino mass for the simple scan of the parameter space as described in the text. The horizontal line represent the current experimental upper bound [20].

The antiproton flux expected at Earth can be written as

$$\Phi_{\bar{p}}(E_{\bar{p}}) = \frac{1}{4\pi} < \sigma v > f(E_{\bar{p}}) \left(\frac{\bar{\rho}_\chi}{m_\chi}\right)^2 v_{\bar{p}} \tau_{\bar{p}}(E_{\bar{p}}) \qquad (7)$$

where $v_{\bar{p}}$ and $\tau_{\bar{p}}(E_{\bar{p}})$ are the $\bar{p}$ velocity and confinement time.

As far as $\tau_{\bar{p}}(E_{\bar{p}})$ is concerned we employ the results of Ref.[10] and we introduce an energy dependence of $\tau_{\bar{p}}$ as deduced from a detailed calculation a diffusion model to treat the $\bar{p}$ propagation.

To compare predictions with experimental data we have to take into account the solar modulation of the antiprotons as well as the modulation of the primary protons. We have used the results of Ref. [19] changing the values of the parameters of the modulation model in order to properly compare with the experiments [20].

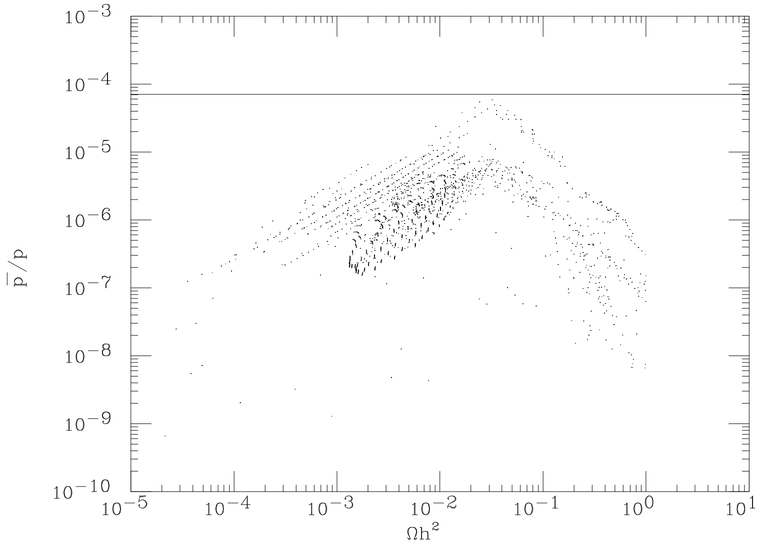

Figure 2: The ratio $\bar{p}/p$ as a function of the neutralino relic density $\Omega_\chi h^2$ for the simple scan of the parameter space as described in the text. The horizontal line represent the current experimental upper bound [20].

4 Results

In Fig.1 we display the ratio $\bar{p}/p$ as a function of the neutralino mass for a simple scan of the parameter space, where $\tan\beta = 1.1$ and $\tan\beta = 55$, and $m_A = 500$ GeV and $m_A = 50 - 60$ GeV. This choice represents almost the two boundaries for the range of variation of these parameters. The horizontal line represents the present level of sensitivity in the energy range $0.25 \text{ GeV} \leq T \leq 1$ GeV as measured by the IMAX collaboration [20], that is

$$\left(\frac{\bar{p}}{p}\right) \leq 7.1 \times 10^{-5} \; 95 \text{ \% C.L. } . \tag{8}$$

We notice that for some configurations of the model we are at the level of the experimental result.

In Fig.2 we show the $\bar{p}/p$ flux versus the cosmological relic density $\Omega_\chi h^2$. This plot illustrates the dependence of the signal on the rescaling procedure we have adopted, here we recall that the value $(\Omega h^2)_{min} = 0.03$ has been used.

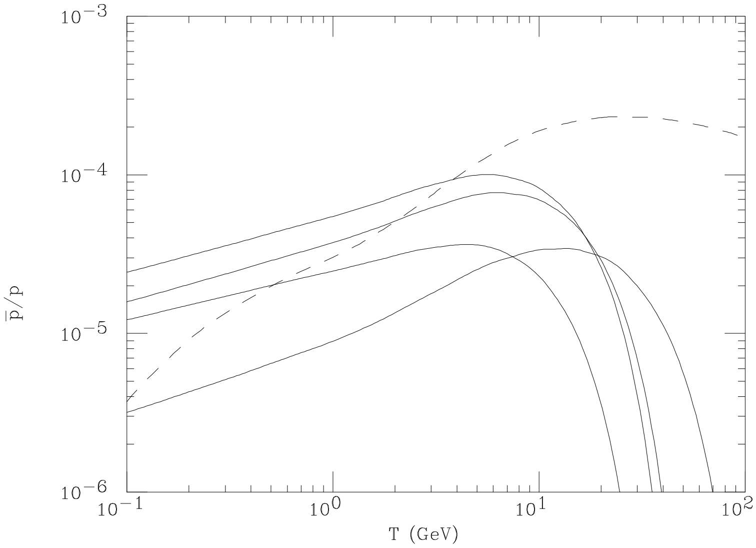

Figure 3: The ratio $\bar{p}/p$ as a function of the kinetic energy T. The solid line represent four different values of the χ mass (from left to right: 40 GeV, 50 GeV, 60 GeV, 120 GeV). The dashed line represent the expected background due to secondary production of $\bar{p}$ [10].

In Fig.3 we display the $\bar{p}/p$ ratio as a function of the kinetic energy T. The different curves represent four different neutralino masses and compositions. In the same plot is shown, as a dotted line, the expected $\bar{p}/p$ background of the secondary production by spallation of the primary cosmic ray flux (taken from Ref. [10]).

A possible clear signature to discriminate signal over background is the energy dependence of the two fluxes on T: the former being a milder function of T at low energies with respect to the latter, as it is clearly seen in Fig. 3. This methods will be useful at the forthcoming generation of experiments such as AMS [21] or PAMELA [22] that will collect a much larger number of $\bar{p}$ with respect to the present experimental situation.

In summary we have shown that the production of $\bar{p}$'s from χ-χ annihilation in our galactic halo is, in some regions of the MSSM parameter space, at the level of the present experimental sensitivity. The forthcoming generation of detectors will be able in the near future to investigate large regions of the MSSM by discriminating the signal over the background with an analysis of the energy dependence of the measured $\bar{p}/p$.

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