Cosmic ray positron excess and neutralino dark matter

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Using a new instrument, the HEAT Collaboration has confirmed the excess of cosmic ray positrons that they first detected in 1994. We explore the possibility that this excess is due to the annihilation of neutralino dark matter in the galactic halo. We confirm that neutralino annihilation can produce enough positrons to make up the measured excess only if there is an additional enhancement to the signal. We quantify the "boost factor" that is required in the signal for various models in the Minimal Supersymmetric Standard Model parameter space, and study the dependence on various parameters. We find models with a boost factor $\gtrsim 30$. Such an enhancement in the signal could arise if we live in a clumpy halo. We discuss what part of supersymmetric parameter space is favored (in that it gives the largest positron signal), and the consequences for other direct and indirect searches of supersymmetric dark matter.

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I. INTRODUCTION

Several years ago the HEAT Collaboration reported an excess of cosmic ray positrons with energies ~ 10 GeV [1]. In the past year they again measured this excess using a new instrument, and found excellent agreement [2]. In this paper we reexamine the possibility that this excess is due to annihilations of weakly interacting massive particles (WIMPs) in the galactic halo, in particular the neutralinos in supersymmetric models. The possibility of detecting positrons as annihilation products of WIMPs in the galactic halo has been discussed previously, both as a continuum and as a monochromatic source [3–8]. We update the results of [7] including the new data, and confirm the conclusions of that paper, finding that neutralino annihilation cannot produce enough positrons to make up the measured excess without an additional enhancement to the signal. Recently, this point has been reiterated in Ref. [9].

In calculating the observed positron flux from annihilations in the halo, we encounter several astrophysical uncertainties. First, cosmic ray propagation is not perfectly understood, although the errors are unlikely to be larger than a factor of two. More importantly, the structure of the galactic dark halo is unknown. Any clumpiness in the halo serves to enhance the signal, whether it is a single nearby clump (or one containing the Earth), or a uniform distribution of clumps. There is no compelling argument for any particular value of the enhancement factor, be it unity or in the thousands or more. In this paper we carefully discuss the possibility that a clumped galactic halo could account for the measured positron excess.

We define B_s to be the boost factor that the WIMP annihilation signal from a smooth galactic halo must be multiplied by to match the HEAT data. We have explored models in the Minimal Supersymmetric Standard Model (MSSM) parameter space to find how large the boost factor must be for each of the models. The lowest boost factor we found is roughly 30 for a WIMP that is primarily a B-ino in content with mass 160 GeV. For $B_s < 100$, we find that the models are gaugino dominated, although some have significant Higgsino fractions. The masses of the models are in the range 150–400 GeV for the most part. For $100 < B_s < 1000$, the masses are as large as 2 TeV, and some very pure Higgsinos become allowed. For both cases there are a significant number of models that have a large contribution to a_μ so that the anomalous magnetic moment of the muon can be explained. We have investigated the dependence of the boost factor on various parameters. There is essentially no dependence on parameters such as $\tan\beta$ or m_0 (the sfermion mass scale). The boost factor does depend strongly on the relic density of WIMPs; the lowest boost factors are required for the models with the smallest relic density without rescaling (defined below).

One can ask the question: even with a large boost factor, can neutralino annihilation produce the "bump" seen in the positron spectrum just above 10 GeV? Even if there is a line signal direct from the annihilation, it gets spread out by the propagation, so that a bump does not get produced. Thus, if

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TABLE I. The ranges of parameter values used in the MSSM scans of Refs. [10,11,16,17,7,18,19].

Parameter	μ	M_2	$\tan\beta$	m_A	m_0	A_b/m_0	A_t/m_0
Unit	GeV	GeV	1	GeV	GeV	1	1
Min	−50000	−50000	1.0	0	100	−3	−3
Max	50000	50000	60.0	10000	30000	3	3

one looks "by eye," one concludes that neutralinos cannot produce the data. However, this is an inappropriate way to ask the question. One should instead study the problem statistically to see if one can find a neutralino model with a good χ^2. With a combination of background and annihilation signal, we are able to find statistically reasonable fits to the spectral shape for boost factors above 30.

II. SUPERSYMMETRIC MODEL

We work in the Minimal Supersymmetric Standard Model. In general, the MSSM has many free parameters, but with some reasonable assumptions we can reduce the number of parameters to the Higgsino mass parameter μ, the gaugino mass parameter M_2, the ratio of the Higgs vacuum expectation values $\tan\beta$, the mass of the CP-odd Higgs boson m_A, the scalar mass parameter m_0 and the trilinear soft supersymmetry-(SUSY-)breaking parameters A_b and A_t for the third generation. In particular, we do not impose any restrictions from supergravity other than gaugino mass unification. For a more detailed definition of the parameters and a full set of Feynman rules, see Refs. [10–12].

The lightest stable supersymmetric particle in the minimal supersymmetric standard model is most often the lightest of the neutralinos, which are superpositions of the superpartners of the neutral gauge and Higgs bosons,

$$\tilde{\chi}_1^0 = N_{11}\tilde{B} + N_{12}\tilde{W}^3 + N_{13}\tilde{H}_1^0 + N_{14}\tilde{H}_2^0. \quad (1)$$

For many values of the MSSM parameter space, the relic density $\Omega_\chi h^2$ of the (lightest) neutralino is of the right order of magnitude for the neutralino to constitute at least a part, if not all, of the dark matter in the Universe (for a review see Ref. [13]). Here Ω_χ is the density in units of the critical density and h is the present Hubble constant in units of 100 km s^{-1} Mpc^{-1}. Present observations favor $h = 0.7 \pm 0.1$, and a total matter density $\Omega_M = 0.3 \pm 0.1$, of which baryons contribute roughly $\Omega_b h^2 \approx 0.02$ [14]. Thus we take the range $0.05 \leqslant \Omega_\chi h^2 \leqslant 0.25$ as the cosmologically interesting region. This region can be narrowed somewhat if we consider the results of cosmic microwave background (CMB) anisotropy measurements (summarized in e.g. [15]), which favor $\Omega_\chi h^2 = 0.14 \pm 0.05$. We are also interested in models where neutralinos are not the only component of dark matter, so we separately consider models with arbitrarily small $\Omega_\chi h^2$.

As a scan in MSSM parameter space, we have used the database of MSSM models built in Refs. [10,11,16,17,7,18,19]. The overall ranges of the seven MSSM parameters are given in Table I. While the ranges are extreme, most interesting models fall in a much more modest region of parameter space, with the notable exception that very pure Higgsinos, and thus very large M_2, cannot be ruled out at present. The database embodies one-loop corrections for the neutralino and chargino masses as given in Ref. [20], and leading logarithmic two-loop radiative corrections for the Higgs boson masses as given in Ref. [21]. For all of the MSSM models in the scan of parameter space, the database contains results for expected detection rates of the particles in a variety of neutralino dark matter searches. The database includes the relic density of neutralinos $\Omega_\chi h^2$. The relic density calculation in the database is based on Refs. [11,22] and includes resonant annihilations, threshold effects, finite widths of unstable particles, all two-body tree-level annihilation channels of neutralinos, and coannihilation processes between all neutralinos and charginos. The database also includes the supersymmetric correction to the anomalous magnetic moment of the muon $a_\mu = (g_\mu - 2)/2$ which is important for dark matter searches in light of new data [23] indicating a deviation from the standard model prediction, as discussed by e.g. Ref. [24]. In this paper we will identify models that have a large contribution, $10\times 10^{-10} \leqslant \Delta a_\mu(\mathrm{SUSY}) \leqslant 75\times 10^{-10}$, to the anomalous magnetic moment of the muon as being particularly interesting.

We examined each model in the database to see if it is excluded by the most recent accelerator constraints. The most important of these are the CERN e^+e^- collider LEP bounds [25] on the lightest chargino mass

$$m_{\chi_1^+} > \begin{cases} 88.4 \ \text{GeV}, & |m_{\chi_1^+} - m_{\chi_1^0}| > 3 \ \text{GeV} \\ 67.7 \ \text{GeV} & \text{otherwise}, \end{cases} \quad (2)$$

and on the lightest Higgs boson mass m_h (which ranges from 91.5 to 112 GeV depending on $\tan\beta$) and the constraints from $b\to s\gamma$ [26] (we use the leading order implementation in DARKSUSY [27]).

III. POSITRON FLUX

We obtain the positron flux from neutralino annihilation in the galactic halo following Ref. [7]. The model is a true diffusion model and assumes that the diffusion region of tangled galactic magnetic field is an infinite slab. This approximation is reasonable since most of the positrons are emitted quite nearby so that the outer radial boundary is unimportant. Furthermore, energy losses due to synchrotron radiation and inverse Compton scattering from the cosmic microwave background and from starlight are included. This model roughly agrees with earlier work [4], although the inclusion of inverse Compton scattering from starlight is crucial as it doubles the energy loss rate.

As we will discuss in the following sections, the positron flux from a smooth galactic halo is too low to explain the positron excess, as has been discussed previously [7,9]. However, any deviations from smoothness serve to enhance the annihilation signal, as the annihilation rate is proportional to the neutralino density squared. However, we must be careful that in postulating a boost factor, we do not overproduce the other products of neutralino annihilation, especially antiprotons and gamma rays [28]. We do have some freedom here, in that the boost factors for positrons, antiprotons and gamma rays are not necessarily equal, as their propagation is not the same. For example, a nearby clump would serve to increase the positron flux more than it would increase the antiproton or gamma ray fluxes, as positrons have the shortest range (they have shorter range than the antiprotons because of their rapid energy loss). Many of the antiprotons come from far away, outside the location of the clump, almost a third of them from as far away as the galactic center. Positrons, on the other hand, come from much closer, roughly within a few kiloparsecs.

We will fit the full positron data set of the HEAT experiments (1994 and 1995 combined data [1] and the 2000 data [2]). We use the positron fraction data, as the error bars are smaller and the data cleaner. The full data set consists of 12 independent measurements of the positron fraction at various energies.

We will in the following assume that the standard prediction for the positron background [29,30] is correct to within a normalization factor N. We are aware that cosmic ray propagation is not completely understood, and that even the best efforts to reproduce the observed cosmic ray spectra need to rely on yet-to-be-understood *ad hoc* assumptions on the dependence of the diffusion constant on energy and on the source spectrum [30]. However, we gather from the latter work that the discrepancies between the observed and theoretical positron spectra lie preponderantly at energies smaller than a few GeV, where they can become as large as a factor of 4 in the hundreds of MeV range. At the slightly higher energies where the HEAT bump is, the theoretical models in [30], which cover a wide range of theoretical assumptions, agree to within 20%. While this may give some justification to our use of model 08-005 of Ref. [29] as our standard positron background, we nevertheless stress that it may be possible to explain the positron bump by purely astrophysical means (although we do not know how). Keeping these uncertainties in mind, we proceed with the assumption that the background calculation is correct, and we study the possibility that neutralino annihilation can account for the excess positrons.

We assume that the positron signal from neutralino annihilation can be rescaled by a normalization factor (boost factor) B_s. We find that the best fit normalization of the background with no signal from neutralinos is $N=1.14$, with $\chi^2=3.33$ per degree of freedom. When adding the signal, we make a simultaneous fit of the normalization of the background N and the normalization of the signal B_s, for each supersymmetric model in the database. We say that a given model "gives a good fit to the positron data" when (1) the background-plus-signal fit fits the data better than the background-only fit with a decrease in χ^2 per degree of freedom greater than unity, namely the background-plus-signal fit has $\chi^2\leq 2.33$ per degree of freedom; (2) the best fit normalization of the background N is between 0.5 and 2.0, namely the calculation of [29] is correct to within a factor of two according to the best fit.

The positron fluxes are more than an order of magnitude smaller than the HEAT measurements, and we find that the best fit normalizations of the signal B_s lie between 30 and 10^{10}. Values of B_s as large as 10^{10} are hardly realistic, but B_s up to 100–1000 might be acceptable given the uncertainties in the halo structure (the halo could e.g. be clumpy [31,28,32]).

A. Antiprotons

In addition, we require that the antiproton flux from annihilations [33,18] not be too large, given the boost factor required for each model. There is a significant correlation between the antiproton and positron fluxes due to neutralino annihilations (see e.g. Fig. 8 of Ref. [7]), so this constraint is important. Following Ref. [28], we take the antiproton flux as

$$\Phi_{\bar{p}}=k(1+0.75B_s)\Phi_{\bar{p}}^{\rm smooth}, \tag{3}$$

where k represents the difference in enhancement factors between the antiprotons and positrons. The factor 0.75 comes from the fact that the antiprotons that reach the Earth on average are produced further away than the positrons. In particular, the antiprotons produced close to the galactic center make a significant contribution to the flux at Earth. In these denser environments, a clumpy distribution enhances the signal less than in our local environment, and hence the different scalings of the positron and antiproton fluxes (see Ref. [28] for more details).

We take the constraint from the combined 1995 and 1997 data of the BESS Collaboration [34]. Note that we use the BESS data rather than the HEAT 2000 antiproton data (the new instrument measures both positrons and antiprotons) for the following reason: the observed antiproton flux rises with momentum to a maximum value and then falls. The spectrum from neutralinos, on the other hand, is flat with momentum and then cuts off before it reaches the observed peak. Hence the strongest constraint on neutralinos comes from lower energy measurements. BESS goes to much lower energy than HEAT 2000 and thus places a stronger constraint. The BESS Collaboration measured the cosmic ray antiproton flux at low energies to be

$$\begin{aligned}\Phi_{\bar{p}}(T=400\text{–}560\ \ \text{MeV})\\ =1.27^{+0.37}_{-0.32}\times 10^{-6}\ \ (\text{cm}^2\ \text{s}\ \text{sr}\ \text{GeV})^{-1}.\end{aligned} \tag{4}$$

Using the central value as the maximum allowed annihilation flux, and taking $k=1$, we find no models with a boost factor $B_s<100$, although there are a handful of models with $B_s<300$, including several with a significant value of a_μ. Taking $k=0.2$, we find the constraint much less punishing, and given the uncertainties, we choose this value instead.

B. Two successful models

In Fig. 1 we plot the positron data from the HEAT 94 +95 and HEAT 2000 experiments, together with the background only fit, and two interesting SUSY models that have good fits as well as large contributions to a_μ. The antiproton constraints have been applied with $k=0.2$. Note that we have

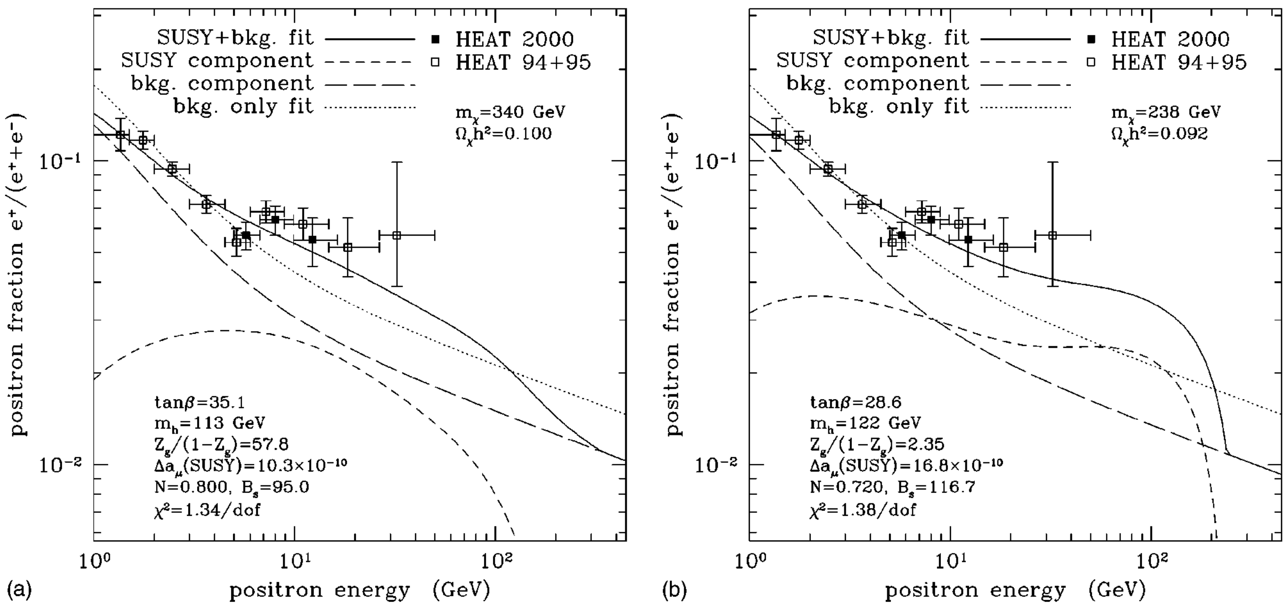

FIG. 1. Positron fraction data and fits. We illustrate positron data from HEAT 94+95 and HEAT 2000, a background only fit, and a SUSY+background fit from two interesting models from the MSSM database. Two additional curves separately display the SUSY and background components of the combined SUSY+background fit. These models are gaugino dominated and have contributions to a_μ in line with the experimental discrepancy. The model in the left panel has positrons primarily from hadronization, while the model in the right panel has hard positrons from direct gauge boson decays.

found the boost factor to be only weakly dependent on $\tan\beta$, so that the values of $\tan\beta$ in the figure do not play any important role (except that $\tan\beta$ is correlated with the SUSY contribution to a_μ). For other models see Fig. 7 of Ref. [7].

The apparent sharp increase in the positron fraction around 7 GeV is not evident in any of our SUSY models, even before the smoothing effects of energy loss on the spectrum. In principle, positrons from direct gauge boson decays have a perfectly flat spectrum (before propagation) with cutoffs at

$$E_\pm = \frac{m_\chi}{2}\left(1 \pm \sqrt{1-\frac{m^2}{m_\chi^2}}\right), \tag{5}$$

where m is the gauge boson mass. For $W^\pm$, a feature at 7 GeV would thus be obtained for $m_\chi = 238$ GeV. However there are also positrons from hadronizations at least from the hadronic gauge boson decays, and possibly from direct annihilations to quark-antiquark pairs. The hadronic component is dominant at the lower cutoff (but not always at the upper cutoff), which means that we cannot reproduce a sharp bump at 7–8 GeV as indicated by the data, but rather a smoother bump over a larger energy range as seen in Fig. 1.

A way to sharpen the neutralino annihilation positrons into a bump is to have them all come from a nearby clump which is smaller than the propagation length. Then a line signal would not be smeared out. This problem has not yet been treated in depth. It requires a different solution of the diffusion equation and is the subject of future work.

IV. FAVORED REGION IN SUPERSYMMETRIC PARAMETER SPACE

Having computed the positron flux and required enhancement factors to give a good fit to the positron data, we can now study the supersymmetric parameter space and identify the favored regions. The composition of the neutralino, namely if it is gaugino or Higgsino, is perhaps its most interesting property. As our indicator of composition, we use the gaugino to Higgsino ratio

$$\frac{Z_g}{1-Z_g} = \frac{|N_{11}|^2+|N_{12}|^2}{|N_{13}|^2+|N_{14}|^2}. \tag{6}$$

In Fig. 2 we plot this ratio vs the neutralino mass separately for models with $B_s < 100$ and $100 < B_s < 1000$, good χ^2, good background normalization as discussed in the previous section, and also a relic density in the region favored by the CMB, $\Omega_\chi h^2 = 0.14 \pm 0.05$. For $B_s < 100$, we find that the models are gaugino dominated, although some have significant Higgsino fractions. The masses of the models are in the range 150–400 GeV for the most part. For $100 < B_s < 1000$, the masses are as large as 2 TeV, and some very pure Higgsinos become allowed. For both cases there are a significant number of models that have a large contribution to a_μ.

V. BOOST FACTOR

It is instructive to study the best fit boost factor as a function of the supersymmetric parameters of the models under discussion. As in the previous sections, we will restrict ourselves to models that provide a good fit to the HEAT data, have a relic density in line with CMB data, and do not produce an overabundance of antiprotons.

We first study the dependence of the relic density on the boost factor in these models. To do so we will of course neglect to apply the constraint on relic density, although we retain all other constraints. We will show two cases, first

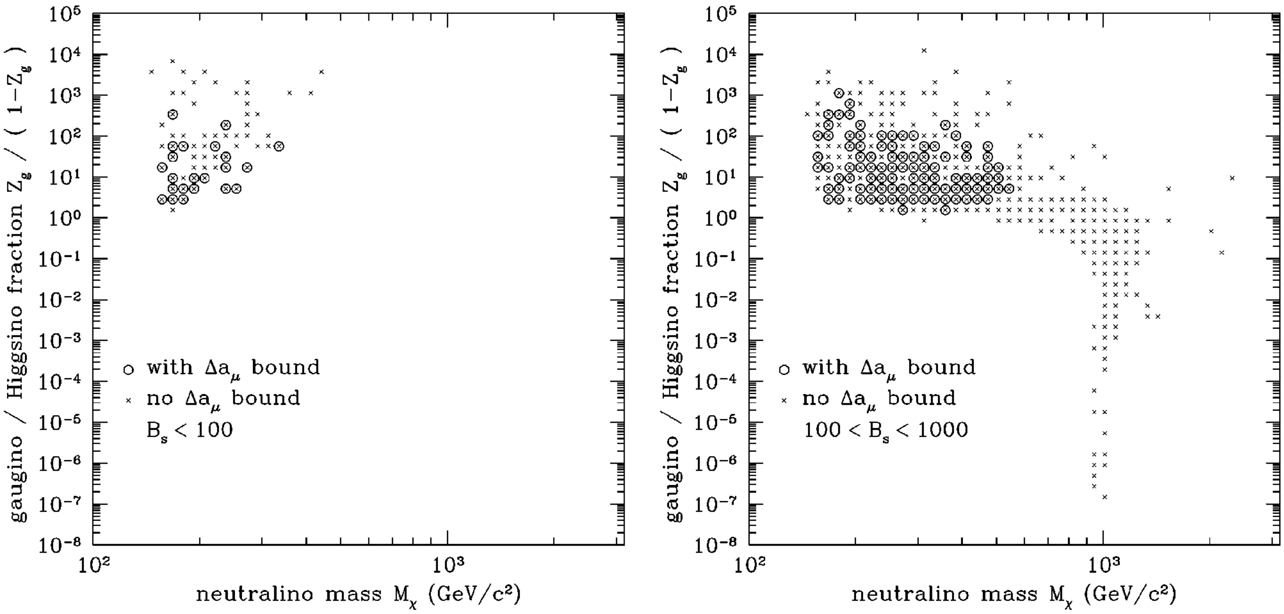

FIG. 2. Neutralino composition vs mass for well-fitting models. For $B_s<100$ these are mixed and gauginos, mostly from 150–400 GeV. For $100<B_s<1000$ the masses extend to 2 TeV, and very pure Higgsinos are also allowed. In both cases many of the models have a contribution to a_μ in line with the measured discrepancy.

assuming that the dark halo density is independent of the relic density, and second applying a rescaling. This rescaling is applied for models whose relic density is less than $\Omega_\chi h^2 = 0.09$, the lower value in the CMB range, and is defined as follows. For low relic densities, neutralinos would make only a fraction of the dark halos of galaxies, and in principle that fraction should be proportional to the relic density,

$$\rho_{\chi,\mathrm{gal}} = \left(\frac{\Omega_\chi}{\Omega_{\mathrm{CDM}}}\right)\rho_{\mathrm{CDM,gal}}. \tag{7}$$

Here, the subscript "gal" indicates that the density is that inside the Galaxy and the subscript "CDM" refers to the dominant matter component (cold dark matter). As annihilation depends on the square of the density, we rescale as the square of the fraction. The rescaling affects the best fit boost factor and the antiproton flux as follows:

$$B_s \rightarrow B_s\left(\frac{\Omega_\chi h^2}{0.09}\right)^{-2}, \tag{8}$$

$$\Phi_{\bar{p}}^{\mathrm{smooth}} \rightarrow \Phi_{\bar{p}}^{\mathrm{smooth}}\left(\frac{\Omega_\chi h^2}{0.09}\right)^{2}. \tag{9}$$

In Fig. 3 we plot the boost factor versus the relic density for both cases, not rescaled and rescaled. Without rescaling, there is a clear trend that B_s increases linearly with $\Omega_\chi h^2$. This is expected because the relic density is inversely proportional to the annihilation cross section, and so is the boost factor. When taking the rescaling into account, we find that the lowest boost factors are required for the models with the smallest relic density without rescaling, that is with $\Omega h^2 = 0.09$ according to our choice.

We take two main points from Fig. 3. First, our preferred region depends somewhat sensitively on the cuts we make in the relic density. Enlarging our definition of the region of cosmological interest would have a significant effect on the number of allowed models in the database. Our conclusions would however be broadly similar. Second, and more importantly, we see the fundamental problem of explaining the positron excess with neutralino annihilation. Given the observed value of the dark matter density, the expected annihilation cross section is too small to explain the observed excess of positrons without some boost due to clumping or some other mechanism (for example some models discussed in Refs. [9,35]). This point is independent of the specific model for the WIMP, and relies only on the fact that the relic density is due to a thermal freeze-out of a stable (or very long-lived) species, and reasonable annihilation branching fraction to hadrons.

Concerning the other supersymmetric parameters, we find that the boost factor is only weakly dependent on $\tan\beta$ and m_0, the sfermion mass scale. We see a rough trend that models with heavy neutralinos need larger boost factors, but this is simply related to the fact that the number density scales as the inverse of the mass and thus the annihilation rate scales as the inverse square of the mass.

Since the constraint from the antiproton flux is so important, we now show how this quantity depends on the required boost factor. Of course we now neglect to apply the constraint on antiproton flux, but we retain all other constraints. In Fig. 4 we plot the boost factor vs the antiproton flux in the 400–560 MeV bin for easy comparison with the BESS experiment, shown as the hatched band. That small antiproton fluxes imply large boost factors is another statement of the fact that the antiproton and positron fluxes are significantly correlated. Furthermore, we see the advantage of allowing

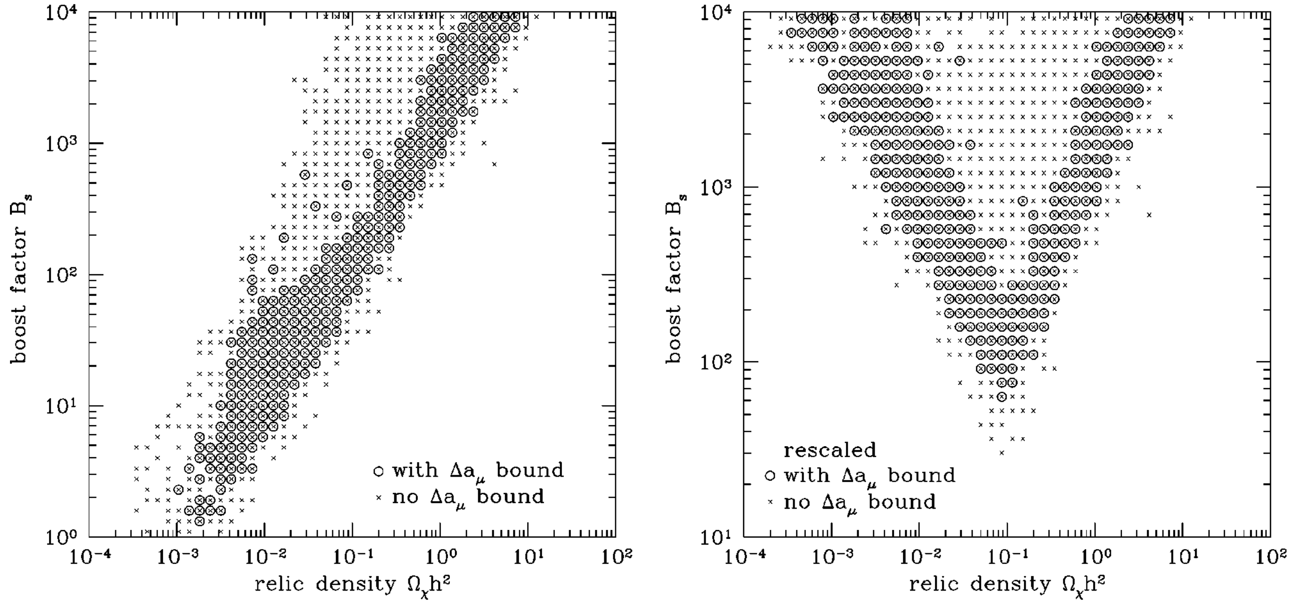

FIG. 3. Boost factor versus relic density. In the first panel, no rescaling is done. The trend that small boost factor indicates small relic density is clearly seen. In the second panel, the rescaling is performed for models whose relic density is less than $\Omega_\chi h^2 = 0.09$, and it is clear that the smallest boost factors come from the smallest relic densities that require no rescaling.

$k<1$, as the bound on the antiproton flux is at $1.27^{+0.37}_{-0.32}\times 10^{-6}$ $(\mathrm{cm}^2\,\mathrm{s}\,\mathrm{sr}\,\mathrm{GeV})^{-1}$. Even for $k=0.5$, a significant number of models becomes allowed, especially with boost factors $B_s<300$.

Finally, we comment on the feasibility of the required boost factors, $B_s>30$. It is well known that dark matter is clumpy in a large range of length scales; such clumps are clusters, galaxies, dwarf galaxies, etc. On such large scales the enhancement factor is in excess of 100 according to simulations of large scale structure [32]. The question for us is whether such clumps persist at scales smaller than several kiloparsecs, which is the size of the emission region for positrons detectable at the Earth. Unfortunately, there are really no data at these distance scales, either observational or from simulations. Without evidence to the contrary, we must allow such enhancements to be possible.

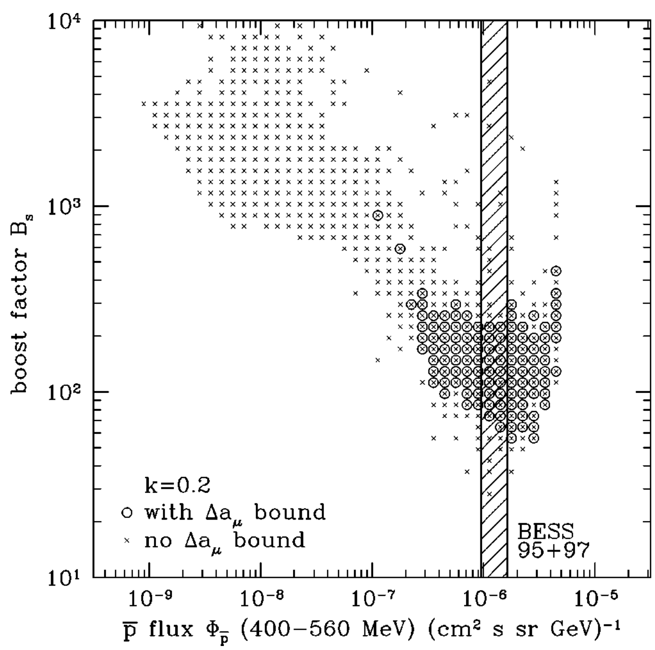

FIG. 4. Boost factor versus antiproton flux. The trend that models with small antiproton fluxes require large boost factors in the positron signal reiterates the statement that there is a significant correlation between the antiproton and positron fluxes. The hatched band indicates the BESS measurement [34].

In obtaining a boost factor, we have assumed that we can average over a volume containing many small clumps. If the halo is not smooth, but we can average over a large volume (relative to the propagation length of positrons from several clumps), then we can pull out an enhancement factor. In other words, we can use the results of the DARKSUSY code for a smooth halo and just multiply the result by a boost factor.

VI. OTHER DARK MATTER SEARCHES

In order to be convinced of an exotic interpretation of cosmic ray data, we would like confirmation by some other technique. In this section we discuss other dark matter search techniques that might give us more confidence that the positron excess really is due to an exotic primary component. In particular, we discuss direct detection of neutralinos by elastic scattering, indirect detection by gamma ray lines, and furthermore by neutrinos from capture and annihilations in the centers of the Earth and Sun.

A. Direct detection

Direct detection of galactic halo neutralinos is one of the most promising techniques for detecting dark matter, and there are several experimental collaborations undertaking

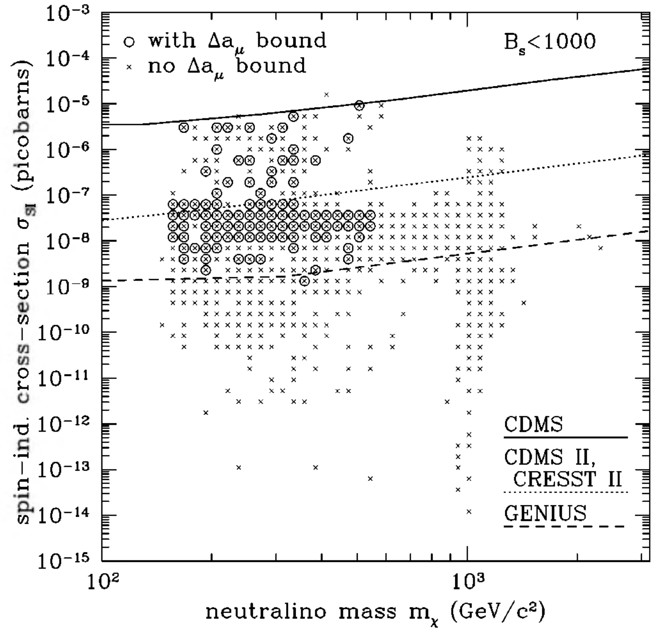

FIG. 5. Neutralino-nucleon elastic scattering cross section. We only show models passing the goodness of fit cuts and require $B_s < 1000$. The current CDMS exclusion [37] (solid line) is plotted along with the expected reach of the CDMS, CRESST [38] (dotted line) and GENIUS [41] (dashed line) experiments.

this program, e.g. DAMA [36], CDMS [37], CRESST [38], EDELWEISS [39], Cryoarray [40], GENIUS [41], IGEX (CanFranc) [42], HDMS [43], MIBETA, ROSEBUD [44], LiF/TOKYO [45], UKDMC [46], SACLAY, ELEGANT V [47], and Baksan. In the next ten years it is expected that neutralinos with elastic scattering cross sections on nucleons as low as 10^{-9} pb or perhaps even lower can be probed [40,41]. The rates in detectors depend only on the local halo density at present, so they will not put any severe constraints on the clumpiness of the halo as a whole. These rates can of course be enhanced if we happen to be inside a clump at present [48].

Direct detection is especially exciting in light of the measurement of a possible discrepancy in the anomalous magnetic moment of the muon [23]. Models with large contributions to a_μ tend to also have large elastic scattering cross sections [24], and we find that many of the models that can explain the positron excess with boost factors $B_s < 1000$ also have large contributions to a_μ. We plot the scattering cross section in Fig. 5.

B. Neutrinos from the Earth and Sun

Another possible method to detect neutralino dark matter is neutrino telescopes, such as at Lake Baikal [49], Super-Kamiokande [50], in the Mediterranean [51], and at the South Pole [52]. Neutralinos in the galactic halo undergo scatterings into bound orbits around the Earth and Sun, and subsequently sink to the centers of these bodies, possibly giving a detectable annihilation signal in neutrinos at GeV and higher energies [53]. The detectability of this signal is strongly correlated with the neutralino-nucleon cross section. As discussed in Ref. [28], the signal is not likely to be sensitive to the clumpiness in the halo. This statement assumes that equilibration time between capture and annihilation is relatively long and that, averaging over the lifetime of the Galaxy, the average local density is neither overdense nor underdense.

C. Gamma rays

Gamma rays from annihilations, both a continuum component [54] and a monochromatic component [55], may provide another handle on neutralinos in the galactic halo. Experiments such as the GLAST satellite [56] and Atmospheric Čerenkov Telescopes (ACTs), such as VERITAS [57], STACEE [58], CANGAROO-III [59], and MAGIC [60], may have the necessary sensitivity to detect annihilation photons in our galaxy above the background [61].

To minimize the impact of the halo model and of experimental uncertainties, we concentrate on the flux at high latitudes, $b > 60°$ and $0° < l < 360°$ ($\Delta\Omega = 0.84$ sr), although we also consider the flux toward the galactic center. A modified isothermal profile gives

$$J(90°) = 0.93(1 + 1.8B_s), \tag{10}$$

where the gamma ray flux is given by

$$\Phi_\gamma = 1.878 \times 10^{-13} \ (\mathrm{cm^2\,s\,sr})^{-1} \times \frac{N_\gamma \langle \sigma v \rangle}{10^{-29}\ \mathrm{cm^3\,s^{-1}}} \left(\frac{m_\chi}{100\ \mathrm{GeV}} \right)^{-2} J. \tag{11}$$

There is only a very weak halo model dependence in this result for J at high galactic latitude [28]. We might exclude models which have too high a gamma ray flux as compared with the measured value at high latitude [61],

$$\Phi_\gamma(E > 1\ \mathrm{GeV}) = (1.0 \pm 0.2) \times 10^{-6}\ (\mathrm{cm^2\,s\,sr})^{-1}, \tag{12}$$

although with boost factors $B_s < 100$ the antiprotons are always more powerful [28]. However, boosting the signal of the gamma ray lines may allow their detection, which would be a clear confirmation of the neutralino halo.

The sensitivities of gamma-ray detectors to the gamma ray lines can be computed following Ref. [16]. First the exposure is determined as a function of energy, as the ACTs in particular have an effective collection area that depends on energy. For the ACTs we consider, these are of order 10^8 cm^2 near threshold and rising to 10^9 and more at TeV energies. ACT integration times of 500 h are assumed, while a 2 year GLAST integration is assumed. The GLAST exposure is taken to be a constant 1800 cm^2 sr, which simply multiplies the 2 yr integration, the fraction of time pointing toward a target already accounted for. The angular field of view for the ACTs is taken to be 0.01 sr, a circle 3.5° in radius. Based on these exposures, the number of background events is determined from the extragalactic gamma ray background, and additionally for ACTs, the backgrounds of cosmic ray electrons and misidentified hadrons. In fact the photon background is unimportant for ACTs:

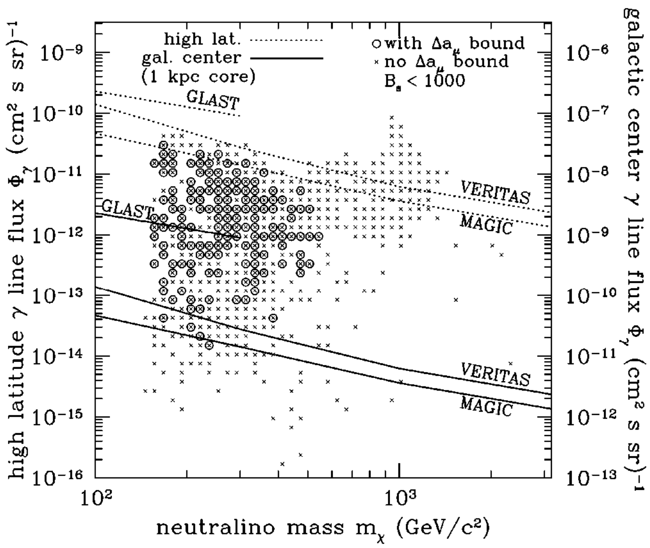

FIG. 6. Gamma ray line flux. We include the expected sensitivity (solid lines) of the VERITAS [57], MAGIC [60] and GLAST [56] experiments. The left axis is the flux from high galactic latitude (dotted sensitivity curves), and the right axis is the flux from the galactic center for an isothermal halo with a 1 kpc core (solid sensitivity curves). We show only models passing the goodness of fit cuts and require $B_s < 1000$.

$$\Phi_{\rm had} = 1.0\times 10^{-2}\left(\frac{E}{\rm GeV}\right)^{-2.7} ({\rm cm^2\,s\,sr\,GeV})^{-1}, \quad (13)$$

$$\Phi_{e^-} = 6.9\times 10^{-2}\left(\frac{E}{\rm GeV}\right)^{-3.3} ({\rm cm^2\,s\,sr\,GeV})^{-1}, \quad (14)$$

$$\Phi_{\gamma} = 6.0\times 10^{-5}\left(\frac{E}{\rm GeV}\right)^{-2.7} ({\rm cm^2\,s\,sr\,GeV})^{-1}. \quad (15)$$

We note that the background flux for a gamma ray line at a specific energy need only be integrated over the energy resolutions of the experiments, taken to be fractionally 0.15 for ACTs and 0.015 for GLAST.

The signal is obtained from Eq. (11), taking care to properly average J over the field of view. For high galactic latitudes and for ACTs toward the galactic center this is a minor consideration as J changes little over the field of view, although for GLAST we find that at the galactic center the averaged value is about ten times smaller than the central value. We require a 5σ excess above background to claim a detection.

In Fig. 6 we plot the flux from the gamma ray lines at high latitude for models with $B_s < 1000$, appropriately boosted by B_s. We include the expected sensitivity of the VERITAS [57] and MAGIC [60] ACTs as well as the GLAST [56] satellite. Furthermore, we include a prediction appropriate to the galactic center, assuming an isothermal halo with a 1 kpc core, which has a signal roughly 1000 times larger, $J\sim 1600 B_s$ (this value is decreased by a factor of 10 when averaged over the GLAST field of view). At high latitude, a more sensitive experiment is probably required, although toward the galactic center, many models would give detectable fluxes in the gamma ray lines.

VII. CONCLUSIONS

The cosmic ray positron excess is intriguing, as there is no simple astrophysical model that can explain it. We are left to consider a primary component, such as from neutralino annihilations. We summarize here our conclusions concerning this scenario.

First, the observed value of the dark matter density implies (assuming thermal production) an annihilation cross section that is too small to reproduce the positron excess without some form of enhancement. This is a general statement, not tied to a specific model. We thus resort to enhancing the signal; fortunately such an enhancement is natural as the dark halo is expected to be clumpy. This leads to a second difficulty, namely that one cannot enhance the positron signal without enhancing other signals, especially antiprotons which would also be produced by annihilation. Hence antiprotons provide a further constraint on this scenario. Indeed lowering the antiproton flux is a further, albeit small, price to pay in the neutralino annihilation scenario. (Note that antiprotons come from much farther away than the positrons, so their fluxes are not always directly correlated.) In addition, in order to obtain a positron spectrum that matches all the data, we had to adjust the normalization of the background (another price we had to pay). We had to choose a positron background a factor of 2 lower than the standard fit to the positron data with background alone. The reason for this lowered background normalization is that one cannot overshoot the data at energies 1–3 GeV. In reality the background is not terribly well understood, and although it cannot by itself explain the upturn in the data at 10 GeV, one wonders if perhaps the boost factor might not be plausibly lower than the values we have found. However, we find this possibility unlikely. We should mention here that the propagation uncertainties make the change in background normalizations and relative boosts between antiprotons and positrons (the $k=0.2$ vs $k=1$ issue) more plausible, and we do not believe these to be serious concerns with our analysis.

Second, assuming that the boost factor is between 30 and 100, we find gaugino-dominated SUSY models that satisfy all constraints, have neutralino masses in the 150–400 GeV range, and have a large contribution to the anomalous muon magnetic moment a_μ. Allowing boost factors as large as 1000 extends the mass range to 2 TeV, and furthermore allows Higgsino-dominated neutralinos. Such boost factors are certainly plausible, and with no evidence to the contrary, we must take this possibility seriously.

Confirmation of the annihilation hypothesis could come from several approaches. The direct detection of halo neutralinos would certainly be a powerful indicator, as would neutrinos from the center of the Earth and Sun. Antiprotons and gamma rays could help study the clumpiness of the galactic halo, helping to determine if it is in fact as large as in the scenario we have presented. In particular, boosting the intensity of gamma ray lines may allow their detection, which would be a clear confirmation of a neutralino halo. The next several years will be an exciting time for particle dark matter searches.

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