

Improved constraints on supersymmetric dark matter from muon $g-2$

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The new measurement of the anomalous magnetic moment of the muon by the Brookhaven AGS experiment 821 again shows a discrepancy with the standard model value. We investigate the consequences of these new data for neutralino dark matter, updating and extending our previous work [E. A. Baltz and P. Gondolo, Phys. Rev. Lett. **86**, 5004 (2001)]. The measurement excludes the standard model value at 3.0σ confidence, assuming the evaluation using the hadronic e^+e^- cross section (the τ decay evaluation yields only a 1.6σ discrepancy). We analyze a phenomenological set of supersymmetric models with gaugino mass unification imposed but without *a priori* constraints on the Higgs sector. Taking the discrepancy as a sign of supersymmetry, we find that the lightest superpartner must be relatively light and it must have a relatively high elastic scattering cross section with nucleons, which brings it almost within reach of proposed direct dark matter searches. The SUSY signal from neutrino telescopes correlates fairly well with the elastic scattering cross section. The rate of cosmic ray antideuterons tends to be large in the allowed models, but the constraint has little effect on the rate of gamma ray lines. We stress that being more conservative may eliminate the discrepancy, but it does not eliminate the possibility of high astrophysical detection rates.

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I. INTRODUCTION

In early 2001, the Brookhaven AGS experiment 821 measured the anomalous magnetic moment of the muon $a_\mu = (g-2)/2$ with three times higher accuracy than it was previously known [1]. Their result disagreed with the standard model prediction at greater than 2.6σ . However, a sign error in the calculation of the hadronic light-by-light contribution to a_μ [2] was discovered, reducing the discrepancy to 1.6σ [3]. Recently, the same collaboration has released a result with much improved statistics [4], and furthermore, new evaluations of the standard model contributions have appeared [5,6]. Considering only the e^+e^- evaluation (described in more detail below), there is again a discrepancy at the 3.0σ level. Supersymmetric (SUSY) particles can give significant corrections to a_μ [7–9]; thus, the Brookhaven measurement is an important constraint on supersymmetric models. There has been substantial literature on this topic since the announcement of the discrepancy [10,11], discussing various consequences of the older measurement. In this paper, we update the results of [10] concerning the implications of the Brookhaven data for supersymmetric cold dark matter, assuming that supersymmetry is the only relevant physics outside of the standard model.

There are two significant caveats in our discussion. The first is that the standard model prediction for the muon anomalous magnetic moment is somewhat disputed, primarily in the hadronic contribution. This was clearly demonstrated in the sign error discovered in the last year. The hadronic error is a very significant part of the error budget when

comparing the Brookhaven results to the standard model. In fact it has been claimed that the standard model errors have been significantly underestimated [12], but this claim has been refuted [13]. Furthermore, the disagreement between the e^+e^- and τ decay results for hadronic contribution [5] are troubling. The second caveat is that supersymmetry is only one of many possible scenarios providing corrections to a_μ at the weak scale. Theoretical prejudice tends to favor supersymmetry, but other possibilities exist, summarized in Ref. [9].

II. SUPERSYMMETRIC MODEL

In the minimal supersymmetric standard model (MSSM) the lightest of the superpartners (LSP) is often the lightest neutralino. The latter is a superposition of the superpartners of the neutral gauge and Higgs bosons,

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

With R parity conserved, this lightest superpartner is stable. For significant regions of the MSSM parameter space, the relic density of the stable neutralino is of the order $\Omega_\chi h^2 \sim 0.1$, thus constituting an important (and perhaps exclusive) part of the cold dark matter (for a review see Ref. [14]). Note that Ω_χ is the neutralino density in units of the critical density and h is the present Hubble constant in units of $100 \text{ km s}^{-1} \text{ Mpc}^{-1}$. Observations favor $h = 0.7 \pm 0.1$ [15] and a matter density $\Omega_M = 0.3 \pm 0.1$ [16], of which baryons contribute a small amount $\Omega_b h^2 = 0.02 \pm 0.001$ [17]. Cosmic Microwave Background (CMB) anisotropy measurements combined with large scale structure data are consistent with this (summarized in e.g., [18]), favoring $\Omega_M h^2 = 0.12 \pm 0.04$ (95% confidence). We choose to be quite conservative

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TABLE I. The ranges of parameter values used in the MSSM scans of Refs. [20,21,23–25]. We use approximately 80 000 models not excluded by accelerator constraints or the cosmological relic density bound ($\Omega_\chi h^2 < 0.25$) before the a_μ measurement. Approximately 25 000 of these lie in the cosmologically interesting region ($0.05 < \Omega_\chi h^2 < 0.25$).

Parameter	μ	M_2	$\tan \beta$	m_A	m_0	A_b/m_0	A_t/m_0
Unit	TeV	TeV	1	TeV	TeV	1	1
Min	-50	-50	1.0	0	0.1	-3	-3
Max	50	50	60.0	10	30	3	3

here and take the range $0.05 \leq \Omega_\chi h^2 \leq 0.25$ as the cosmologically interesting region; this is roughly the 2σ constraint from separate measurements of Ω_M and h . Models where neutralinos are not the only component of dark matter are also allowed, so we separately consider arbitrarily small $\Omega_\chi h^2 < 0.25$. Even with very small relic densities, such models may be observable in astrophysical contexts [19].

We have explored a phenomenological variation of the MSSM with seven free parameters: 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 SUSY-breaking parameters A_b and A_t for third generation squarks. All of our parameters are fixed at the electroweak scale. Our framework is more general than the supergravity framework, in that we do not impose grand unified theory (GUT) unification of the scalar masses and trilinear couplings. In contrast to supergravity, this allows a highly pure Higgsino LSP and its consequences, namely a SUSY spectrum that can be significantly more massive. For simplicity, we do apply the supergravity constraint on gaugino mass unification, though the relaxation of this constraint would not significantly alter our results. As is typical, we assume R -parity conservation, stabilizing the lightest superpartner. (These models are described in more detail in Refs. [20–22].)

To investigate the MSSM parameter space, we have used the database of MSSM models built in Refs. [20,21,23–25]. Furthermore, for this work we have made special scans emphasizing large positive supersymmetric corrections to a_μ , $\Delta a_\mu(\text{SUSY})$. The overall ranges of the seven MSSM parameters are given in Table I. The database includes one-loop corrections for the neutralino and chargino masses as given in Ref. [26], and leading log two-loop radiative corrections for the Higgs boson masses as given in Ref. [27]. Supersymmetric contributions to the precision quantities a_μ and the $b \rightarrow s\gamma$ branching ratio are also included. The database contains the neutralino-nucleon cross sections and expected detection rates for a variety of neutralino dark matter searches.

Crucial for studies of dark matter, the database includes the cosmological relic density of neutralinos $\Omega_\chi h^2$, based on calculations in Refs. [21,28,29] considering resonant annihilations, threshold effects, finite widths of unstable particles,

all two-body tree-level annihilation channels of neutralinos, and coannihilation processes between all neutralinos, charginos, and sfermions.

Recent accelerator constraints are applied to each model in the database. The most important are as follows. The CERN e^+e^- collider LEP bounds [30,31] on the lightest chargino mass (chargino and neutralino masses are tightly linked) are

$$m_{\chi_1^\pm} > \begin{cases} 103.6 \text{ GeV}, & |m_{\chi_1^+} - m_{\chi_1^0}| > 5 \text{ GeV}, \\ 92.4 \text{ GeV}, & \text{otherwise.} \end{cases} \quad (2)$$

The LEP bounds on the lightest Higgs boson mass m_h range from 91.5 GeV to 112 GeV depending on $\tan \beta$. Finally, measurements of the $b \rightarrow s\gamma$ branching ratio [32] give a significant constraint (DarkSUSY currently only implements the leading-order calculation [33].)

III. MUON ANOMALOUS MAGNETIC MOMENT

Supersymmetric corrections to a_μ are surprisingly large, enhanced relative to typical weak-scale contributions by the parameter $\tan \beta$ [7–9]. This fact makes these precision measurements enticing approaches for searching for supersymmetry. Typically, the supersymmetric corrections are given by

$$\Delta a_\mu(\text{SUSY}) \sim 14 \times 10^{-10} \left(\frac{M_{\text{SUSY}}}{100 \text{ GeV}} \right)^{-2} \tan \beta, \quad (3)$$

where M_{SUSY} is the typical mass of superpartners.

Since the previous experimental announcement, two new evaluations of the standard model contribution have appeared [5,6]. Davier *et al.* perform the evaluation using both data from the hadronic e^+e^- cross section and from hadronic τ decays [5]. Unfortunately, the two evaluations disagree. In the remainder of this paper, we will consider only the e^+e^- evaluation, which might be considered to be better understood simply because of the fact that there is more experience in using such data. Hagiwara *et al.* do an independent evaluation using only the e^+e^- results [6], and are in good agreement with Davier *et al.*

The new results of Brookhaven AGS experiment E821 [4] for the anomalous magnetic moment of the muon, $a_\mu = (g - 2)/2$, compared with the predicted standard model value (we quote Davier *et al.* [5]) are

$$a_\mu(\text{exp}) = 11\,659\,203(8) \times 10^{-10}, \quad (4)$$

$$a_\mu(\text{SM}, e^+e^-) = 11\,659\,169.1(7.8) \times 10^{-10}, \quad (5)$$

$$a_\mu(\text{SM}, \tau) = 11\,659\,186.3(7.1) \times 10^{-10}, \quad (6)$$

$$\Delta a_\mu(e^+e^-) = 33.9(11.2) \times 10^{-10} \quad [3.0\sigma], \quad (7)$$

$$\Delta a_\mu(\tau) = 16.7(10.7) \times 10^{-10} \quad [1.6\sigma]. \quad (8)$$

This situation is not ideal, as the e^+e^- data indicate a 3.0σ discrepancy (quite significant), while the τ data indicate only

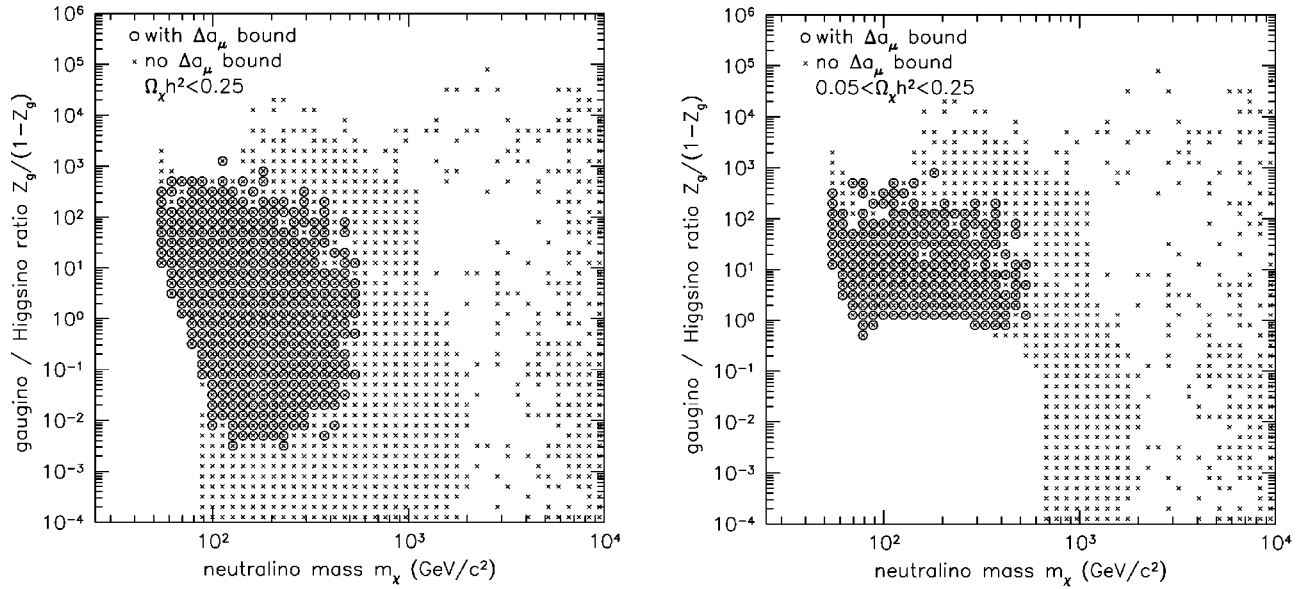


FIG. 1. Gaugino or Higgsino fraction versus mass for the lightest neutralino. In the left panel, we plot all models not excluded by cosmological arguments. In the right panel, only models with an interesting relic density are plotted. Crosses indicate models allowed before applying a constraint on $\Delta a_\mu(\text{SUSY})$, and crossed circles indicate models allowed after imposing the $\Delta a_\mu(\text{SUSY})$ bound.

a 1.6σ discrepancy (not very significant). As mentioned previously, we will proceed by simply ignoring the τ evaluation.

To investigate the implications for the supersymmetric parameter space, we will assume that supersymmetry is the only source of corrections to a_μ outside of the standard model. Considering a 95% (2σ) confidence region for the supersymmetric contribution, we accept the following range of $\Delta a_\mu(\text{SUSY})$:

$$11.5 \times 10^{-10} \leq \Delta a_\mu(\text{SUSY}) \leq 56.3 \times 10^{-10}. \quad (9)$$

We have used the full calculation in Ref. [8] to compute $\Delta a_\mu(\text{SUSY})$ for the models in the database.

The astrophysical phenomenology of neutralinos depends strongly on the ratio of gaugino and Higgsino fractions, defined as

$$\frac{Z_g}{1 - Z_g} = \frac{|N_{11}|^2 + |N_{12}|^2}{|N_{13}|^2 + |N_{14}|^2}. \quad (10)$$

We plot this ratio against the neutralino mass for each model in the database in Fig. 1. For clarity, the models have been binned along both axes. In the left panel, we only require that $\Omega_\chi h^2 < 0.25$, and on the right we apply the more stringent constraint that the neutralino could make up all of the dark matter, $\Omega_\chi h^2 = 0.15 \pm 0.1$. Models allowed before the new $\Delta a_\mu(\text{SUSY})$ constraint are plotted as crosses, and models respecting the new $\Delta a_\mu(\text{SUSY})$ constraint are plotted as crossed circles.

As has been discussed at length previously [10,11], a $\Delta a_\mu(\text{SUSY})$ bound that excludes zero from the positive side gives an upper limit on the mass of the neutralino, in this case 650 GeV. This is a large improvement over the cosmological bound based on the neutralino relic density not being too large, an upper limit in excess of 10 TeV (going above

the 7 TeV bound of Ref. [21] requires a significant degeneracy between neutralinos and sfermions). However, if the standard model value is included in the allowed region by e.g., considering a 3σ confidence interval or using the τ decay standard model calculation, there is no bound on neutralino mass. If the more favorable evaluation is considered, the mass bound becomes 450 GeV.

The $\Delta a_\mu(\text{SUSY})$ bound has interesting consequences for the neutralino composition too. If the neutralino has a large enough relic density to make up all of the cold dark matter, another effect appears, namely that the neutralino cannot be very purely Higgsino-like in composition, requiring at least a 5% mixture (in quadrature) of gaugino states. Even without requiring neutralino dark matter, the $\Delta a_\mu(\text{SUSY})$ bounds disfavor Higgsino-like neutralinos with a maximum purity in excess of 99.7% [$Z_g = 0.003$; see Fig. 1(a)].

Orthogonal to the neutralino mass and composition but equally important to the value of $\Delta a_\mu(\text{SUSY})$ are the parameters $\tan\beta$ (the ratio of vacuum expectation values) and m_0 (the scalar mass parameter). In Fig. 2 we plot these parameters for the database of models, again indicating the effects of the constraint on $\Delta a_\mu(\text{SUSY})$. The constraint forces the scalar mass parameter to be small, but the upper bound increases with increasing $\tan\beta$.

IV. ASTROPHYSICAL DARK MATTER SEARCHES

There is a large community pursuing the goal of detecting dark matter particles, neutralinos especially, in various astrophysical contexts. The possibilities can be broken up along the lines of “direct” and “indirect” detection. Direct detection means detecting the rare scatterings of neutralinos in our galactic halo with nuclei in a sensitive low background apparatus. Indirect detection means detecting the products of rare annihilations of galactic neutralinos, such as antiprotons,

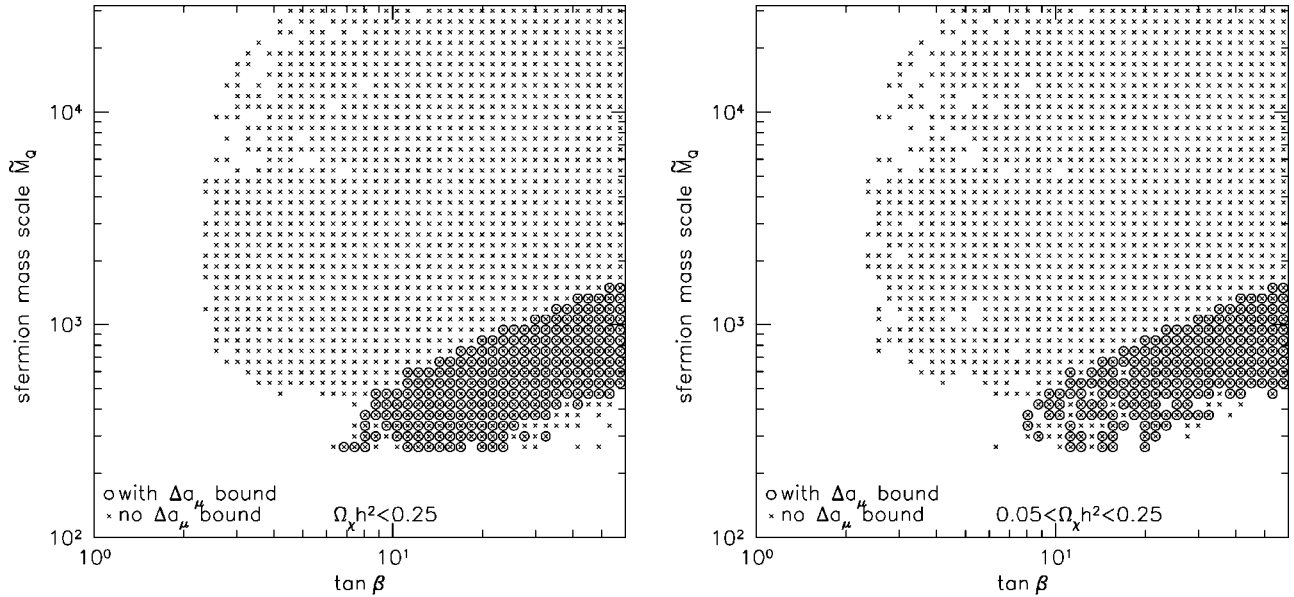


FIG. 2. Sfermion mass scale versus $\tan \beta$. As in Fig. 1, in the left panel, we plot all models not excluded by cosmological arguments and in the right panel we plot only models with an interesting relic density. Crosses indicate models allowed before applying a constraint on $\Delta a_\mu(\text{SUSY})$, and crossed circles indicate models allowed after imposing the $\Delta a_\mu(\text{SUSY})$ bound. The small “inlet” at $\tan \beta \sim 4$ and $m_0 \sim 400$ GeV is due to the constraint on the Higgs boson mass. It is clear that the relic density cut has little effect on the allowed region.

antideuterons, positrons, gamma rays, and neutrinos.

Perhaps the most promising of the astrophysical neutralino searches is the direct detection program [34]. Experiments such as CDMS [35], DAMA [36], and EDELWEISS [37] have pushed exclusion limits down to spin-independent neutralino-nucleon cross sections as small as 10^{-6} pb. As has been noted before, the neutralino-nucleon elastic scattering cross section exhibits a significant correlation with $\Delta a_\mu(\text{SUSY})$ [38,10], thus a large positive $\Delta a_\mu(\text{SUSY})$ is exciting for direct searches. Direct detection is promising even in the case where the neutralinos have a small relic density and thus are only a small component of the dark matter. In this case we perform a conservative rescaling of the galactic neutralino density as

$$\rho_\chi \rightarrow \rho_\chi \left(\frac{\Omega_\chi h^2}{0.25} \right), \tag{11}$$

where $\Omega_\chi h^2 = 0.25$ is the current upper limit on the relic density. In the top left panel of Fig. 3, we plot the spin-independent neutralino-proton scattering cross section, rescaled according to Eq. (11). The constraint due to $\Delta a_\mu(\text{SUSY})$ is intriguing, as it bounds the rescaled cross section at around 10^{-11} pb. In the top right panel of Fig. 3, we perform no rescaling, and only consider models with cosmologically interesting relic densities. Here the minimum cross section is around 10^{-10} pb. The inlet at 100 GeV and 10^{-9} pb is due to the lower limit $\Omega_\chi h^2 > 0.05$. These bounds indicate that there is considerable hope for the next generation of experiments, such as CDMS II and CRESST II [39]. The latter bound is perhaps reachable by future experiments with one ton target masses such as GENIUS [40], CryoArray [41], and XENON [42]. Finally, it is important to note that in the case where the significance of the a_μ discrepancy is re-

duced, the lower bound on the cross section disappears. However, there is *not* an upper bound on the cross section. Large cross sections are still possible with $\Delta a_\mu(\text{SUSY})$ consistent with zero. In the bottom panels of Fig. 3 we plot the spin-dependent cross sections on protons: all models with rescaling on the left and only cosmologically interesting models on the right. Experiments using NaI (both sodium and iodine have unpaired protons) are sensitive to this. Current limits from the UKDMC [43] and ELEGANT V [44] are plotted along with the future reach of the NAIAD detector [45]. The DAMA Xenon results are similar [46], though the relevant cross section is that on neutrons rather than protons which complicates plotting them on the same graph [47]. Other targets such as fluorine compounds have been used by the Tokyo(LiF) group [48] and by SIMPLE [49].

Neutrino telescopes such as at Lake Baikal [50], Super-Kamiokande [51], in the Mediterranean [52], and the south pole [53] are a promising technique for indirect detection. Neutralinos in the galactic halo scatter into orbits around the Earth or Sun, and can then rapidly sink to the cores of these bodies by additional scatterings, resulting in a large density enhancement. This can produce a detectable annihilation signal in neutrinos at high (GeV) energies [54]. It is the capture rate that governs the neutrino flux, and is strongly correlated with the neutralino-nucleon cross section. This places a lower bound on the detection rate, though at small neutralino mass there are threshold effects that remove it [24]. To illustrate, we plot the rate of neutrino-induced through-going muons from the Sun along with the unsubtractable background (from cosmic rays incident on the Sun’s surface) in the top left panel of Fig. 4. It is clear that the $\Delta a_\mu(\text{SUSY})$ bound cuts away much of the undetectable parameter space, but not all of it. In the top right panel we repeat the calcula-

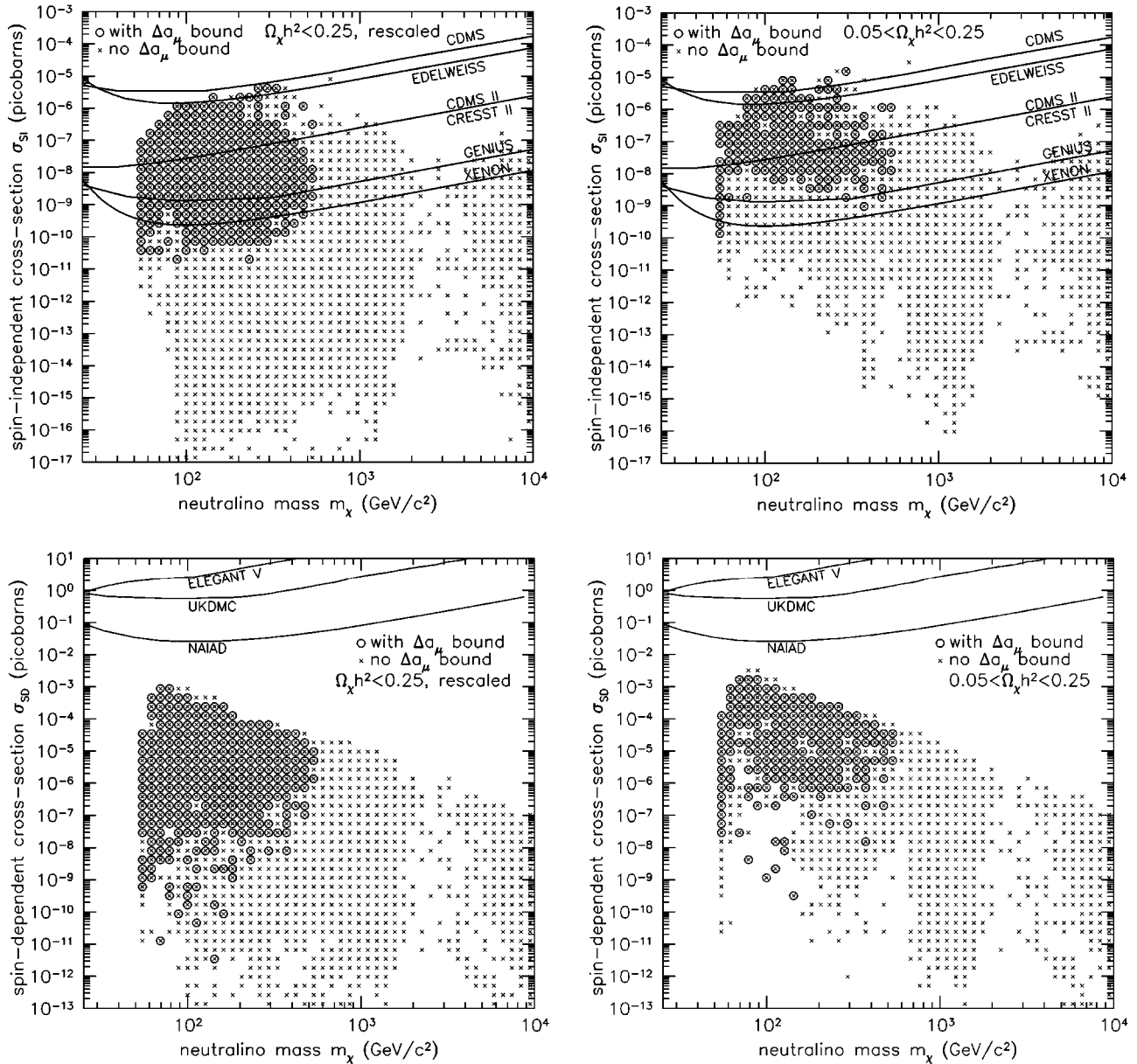


FIG. 3. Neutralino-nucleon elastic scattering cross section versus neutralino mass. Crosses indicate models allowed before applying a constraint on Δa_μ (SUSY), and crossed circles indicate models allowed after imposing the Δa_μ (SUSY) bound. In the left panels, we have only applied the upper constraint on relic density, and rescaled the effective cross section to account for a low galactic density of low relic density neutralinos. In the right panels we plot only those models that could account for all of the dark matter, and we do not perform a rescaling. The top panels illustrate the spin-independent cross section, together with the current limits from CDMS and EDELWEISS, and the future reach of CDMS II, CRESST II, GENIUS and XENON. The inlet at 100 GeV and 10^{-9} pb is due to the lower limit $\Omega_\chi h^2 > 0.05$. For completeness we illustrate the spin-dependent cross section on protons in the bottom panels, together with current bounds from UKDMC and ELEGANT, and the future reach of the NAIAD detector.

tion for neutrinos from the center of the Earth, where the prospects are much less promising.

In addition, neutralinos can annihilate in the galactic halo. The relevant rates are quite small, but the enormous mass of the halo compensates, and the annihilation products may be detectable. Gamma rays propagate essentially freely, thus the expected rate is largest towards the galactic center where the dark matter density is largest [55]. Charged particles are trapped by the galactic magnetic field and effectively diffuse, so these annihilation products would originate more nearby [56].

The detection of the gamma ray lines from direct annihilations either to two photons, or to a photon and a Z boson would be a gold-plated signature of neutralinos in the galactic halo [57]. Gamma ray experiments such as the atmospheric Cerenkov telescopes (ACTs) Whipple [58], HEGRA [59], STACEE [60], MILAGRO [61], CELESTE [62], CANGAROO [63], VERITAS [64] and MAGIC [65], and the GLAST [66] satellite hope to detect these lines. Assuming that the galactic halo is an isothermal sphere with a 1 kpc core, we plot the reach of these experiments in the bottom left panel of Fig. 4. Note that with this assumption the emis-

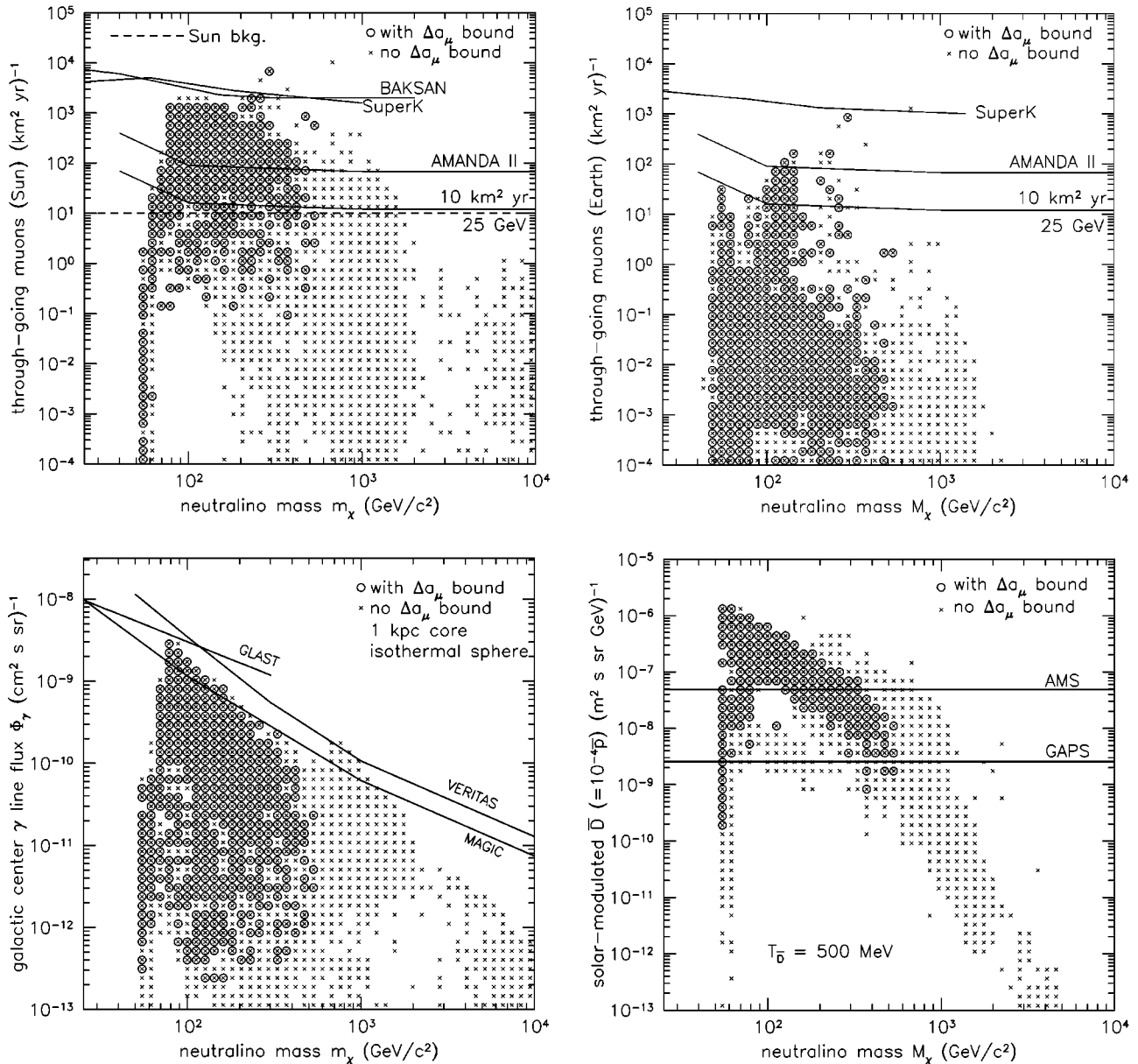


FIG. 4. Indirect detection of neutralinos. In all plots, small crosses indicate cosmologically interesting models ($0.05 < \Omega_\chi h^2 < 0.25$), and crossed circles indicate such models that pass the $\Delta a_\mu(\text{SUSY})$ cut. In the top left we plot the rate of through-going muons in a neutrino telescope for the annihilations in the Sun, with the BAKSAN and SuperKamiokande bounds, and the expected reach of both AMANDA II and a km^2 telescope. The unsubtractable background from cosmic rays impinging on the Sun's atmosphere is also plotted as the dashed horizontal line. In the top right, we plot a similar rate for neutrinos from the center of the Earth. In the bottom left we plot the flux in the gamma ray lines from the galactic center, assuming a 1 kpc core isothermal sphere halo. The future reach of the GLAST, VERITAS, and MAGIC experiments is included. In the bottom right we plot the flux of antideuterons at a kinetic energy of 500 MeV, together with the future sensitivity of the AMS and GAPS detectors.

sion enhancement from around the black hole at the galactic center is insignificant [67], so we neglect it. We notice that applying the $\Delta a_\mu(\text{SUSY})$ bound has little effect on the prospects for these experiments. It appears that the detection of the gamma ray lines is quite difficult. Other assumptions, including clumping of the dark matter [68] or a lack of a central core lead to significantly higher predictions [23,67].

The intensity of cosmic ray positrons [69] from neutralino annihilation is not much affected by the constraint on $\Delta a_\mu(\text{SUSY})$.

The final possibility we mention is that antideuterons may be an interesting annihilation product to search for [70]. The background from mundane cosmic ray processes should be relatively smaller (a smaller fraction of the annihilation signal) at low energies than for antiprotons. A signal may be detectable in experiments such as AMS [71] and GAPS [72], as seen in the bottom right of Fig. 4. It is interesting that the $\Delta a_\mu(\text{SUSY})$ constraint eliminates the models with the lowest rates, and furthermore that most of the parameter space is covered for neutralino masses between 100 GeV and 500

GeV. Separating a signal from the background with antideuterons may be difficult however.

V. CONCLUSIONS

In this paper we have discussed the recently improved measurement of the anomalous magnetic moment of the muon [4]. New theoretical evaluations of this quantity in the standard model are troublesome: the evaluation of the hadronic vacuum polarization using data from the $e^+e^- \rightarrow$ hadrons cross section disagrees from that using data from hadronic τ decays. We proceed using the arguably better understood e^+e^- evaluation which indicates a discrepancy with the standard model at the 3.0σ level, updating and expanding the results of Ref. [10].

Assuming that supersymmetry is responsible for the discrepancy, we have investigated the consequences for astrophysical dark matter searches. We have confirmed that the constraint significantly improves the prospects for direct detection experiments trying to measure the rare scatterings of galactic neutralinos. Neutrino telescopes are also helped by this result. The prospects for the detection of gamma ray lines from neutralino annihilations at the galactic center are

not much affected. The prospects for detecting cosmic ray antideuterons as neutralino annihilation products are also significantly improved. In all cases, if the discrepancy disappears, there remain supersymmetric models with detectable rates for all of these experiments.

The constraint on $\Delta a_\mu(\text{SUSY})$ used in this paper is slightly stronger than that used in our previous work [10]. Nevertheless we find slightly larger allowed regions for two main reasons. First, our scanning of the region of large $\Delta a_\mu(\text{SUSY})$ is much more complete, which expands the allowed region slightly for either the old or new constraint. Second, we have included sfermion coannihilations in the relic density calculation. The more complete calculation indicates that some previously excluded models in fact have an acceptable relic density.

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