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DIRECT VERSUS INDIRECT SEARCHES FOR NEUTRALINO DARK MATTER

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Direct search for neutralino dark matter is analyzed in the framework of the minimal supersymmetric extension of the standard model, using a realistic evaluation of the neutralino relic abundance which also includes radiative corrections to the Higgs masses. Relevance of the present (Ge detectors) experimental data to set constraints on the parameters of the model is discussed and expectations for future experiments which involve neutralino-nucleus coherent processes are investigated. These results are compared to those obtained in a previous paper from indirect search data. In the present analysis particular attention is paid to the theoretical uncertainties due to the different estimates of the Higgs-nucleon coupling strength.

Among the particle candidates for dark matter, SUSY particles provide a very attractive possibility. This is based on the assumption that R-parity is conserved.[1] In fact, in this case the lightest SUSY particle (LSP) is stable; then, if neutral, it may constitute a very interesting candidate for dark matter.

Whereas sneutrino appears to be excluded by present experimental data (at least for the standard value of the local density), the neutralino is still a perfectly viable candidate, largely unconstrained, except for lower bounds on its mass established by accelerator results. The purpose of the present note is to examine where we stand in the search for relic neutralinos and what are the perspectives for future investigations, both in direct and indirect experiments.

Let us first establish a few notations. The stable neutralino is the lowest mass linear superposition of photino, zino and higgsinos

$$\chi = a_1\tilde{\gamma} + a_2\tilde{Z} + a_3\tilde{H}_1^0 + a_4\tilde{H}_2^0 \,. \tag{1}$$

The usual definitions of $\tilde{\gamma}$ and $\tilde{Z}$ in terms of the neutral U(1), SU(2) gauginos ($\tilde{B}$ and $\tilde{W}_3$, respectively) are

$$\tilde{\gamma} = \cos\theta_{\rm W}\tilde{B} + \sin\theta_{\rm W}\tilde{W}_3$$

$$\tilde{Z} = -\sin\theta_W \tilde{B} + \cos\theta_W \tilde{W}_3\,, \tag{2}$$

where θ_W is the Weinberg angle.

Processes involving neutralinos will be discussed in the framework of the Minimal Supersymmetric extension of the Standard Model (MSSM), where the Higgs-boson sector is constituted by two Higgs doublets, whose vev's are v_1 (for the doublet providing mass to the down-type quarks) and v_2 (for the doublet providing mass to the up-type quarks). The independent parameters of the MSSM are chosen to be: the $\tilde{B}$ mass parameter M_1, the $\tilde{W}_3$ mass parameter M_2, the Higgs mixing mass parameter μ, and $\tan\beta = v_2/v_1$; under the assumption (which we are making here) that the MSSM is embedded in a grand unification scheme, the standard relationship $M_1 = \frac{5}{3}M_2\tan^2\theta_W$ holds. Furthermore one has to introduce the masses of the three physical neutral bosons: h, H (CP-even states), A (CP-odd state). As is well known, if the Higgs potential is treated at the tree level, the three masses are related by analytic expressions that only involve the $\tan\beta$ parameter; then, in this case, only one extra independent parameter, say m_h, needs being introduced. However, since it has been recognized[2] that radiative corrections modify the Higgs masses substantially, more parameters come into play; we will come again to this matter later on.

Strategies for detecting relic neutralinos range from direct detection (effects due to neutralino-nucleus scattering in a detector)[3-7] to indirect ways, most notably[8] neutrino signals due to annihilation of neutralinos accumulated in celestial bodies (see Refs. 5, 9 and 10 and references therein), and have been widely discussed in the quoted references.

However, the investigation about actual possibilities for detecting neutralino by the previous means requires a new analysis because of two theoretical points developed recently (a) radiative corrections to the Higgs masses, (b) strength of the Higgs-nucleon coupling.

The relevance of these two points in the case of the neutrino flux produced by neutralino annihilation in the Earth has already been discussed in a previous paper[5]; in the present note we address the issue of the direct neutralino detection in order to establish which constraints can be derived from the available experimental data and which predictions can be made about future experiments. Here particular emphasis is put on the comparison between the capabilities of the direct and the indirect methods and on how the present uncertainties in fundamental physical parameters (Higgs masses and couplings) affect the evaluation of the quantities relevant to neutralino detection.

1. Direct Detection

For the neutralino-nucleus scattering the following processes are pertinent: 1) Z-exchange: this provides a spin-dependent cross-section (the coherent part is missing due to the Majorana character of the neutralino); 2) squark-exchange[11]: this gives a coherent as well as an incoherent cross-section; 3) Higgs boson-exchange: this term gives a coherent cross-section.[12] In the present paper only coherent processes (relevant for the available direct experimental data) are discussed, and then the Z-exchange contribution is disregarded; the Z-exchange process is important for future experiments (for instance with enriched ^{73}Ge) where spin-dependent cross-sections are involved.[6,7] In the present experiments using natural composition of Ge, the role of isotope ^{73}Ge is marginal. Furthermore, the *s*quark-exchange contribution can be safely neglected as compared to the Higgs-exchange one if we take for the Higgs and the *s*quark masses values close to the present experimental lower bounds[13,14]: $m_h = 50$ GeV, $m_{\tilde{q}} = 150$ GeV; indeed, corrections due to inclusion of *s*quark-exchange diagram are $(m_h/m_{\tilde{q}})^2 \sim 0.1$ in this case.

In terms of the neutralino-nucleus cross-section σ, that will be explicitly given below, the event rate per nucleus is

$$R = \frac{v_\chi \rho_\chi \sigma}{m_\chi}, \tag{3}$$

where m_χ in the neutralino mass and ρ_χ, v_χ are the neutralino local mass density and mean velocity, respectively.

2. Indirect Detection

Relic neutralinos may be captured by celestial bodies (Earth, Sun) and accumulated therein. Their subsequent annihilation in pairs creates a steady flux of neutrinos from the celestial bodies. This process has been recently reanalyzed in Ref. 5, where the predictions are given for the ensuing flux of up-going muons due to ν_μ–μ conversion as ν_μ's pass through the Earth; we refer to this paper for details of the calculations. Here we only remind that the capture rate of neutralinos by the macroscopic bodies is given by Refs. 9, 10, 15–17

$$C = \frac{\rho_\chi}{v_\chi} \sum_i \frac{\sigma_i}{m_\chi m_i} (M_B f_i) \langle v_{\rm esc}^2 \rangle_i X_i \,, \tag{4}$$

where σ_i is the cross-section for the scattering of the neutralino on the nucleus i of mass m_i, f_i is the mass fraction of the element i in the macroscopic body of mass M_B, $\langle v_{\rm esc}^2 \rangle_i$ is the square escape velocity averaged over the distribution of the element i, X_i is a factor which takes into account further neutralino-nucleus kinematical effects.

In the case of capture by celestial bodies, coherent cross-sections play a crucial role, as in the case of the direct detection previously discussed. For the range of parameters (Higgs masses and couplings) considered here these coherent processes make the signal of the up-going muons originated by neutralino annihilation in the Earth much larger than the corresponding signal due to annihilation in the Sun; then, in the following, only the flux from Earth will be discussed.

We note that, when evaluating the intermediate Higgs contribution to the coherent cross-section needed for both direct and indirect detection, a problem arises in the estimate of the Higgs-nucleon coupling. We shall discuss below this question that leads to quite different estimates of the signals.

From the capture rate and the assumption that, at present, equilibrium between neutralino capture and annihilation is attained, the flux of neutrinos at a distance d from the annihilation region is given by

$$\frac{dN_\nu}{dE_\nu} = \frac{R_a}{4\pi d^2}\sum_f B_f \frac{dN_{f,\nu}}{dE_\nu}\,. \tag{5}$$

Here $dN_{f,\nu}/dE_\nu$ denotes the differential distribution of the neutrinos generated by the semileptonic decays of the fermions produced by χ-χ annihilations; B_f are the relevant branching ratios. From Eq. (5) the estimate of the final muon flux can be obtained by well established computations (see, for instance, Ref. 5).

3. Higgs Boson-Nucleon Coupling

For the evaluation of the Higgs-exchange contribution to the coherent cross-section needed for both direct and indirect detection, a reliable estimate of the strength of the Higgs-nucleon coupling is extremely important. Recent theoretical analyzes have in fact shown that the Higgs boson coupling to the sea of the strange quarks contributes significantly to the Higgs-nucleon coupling[18] and then substantially enhances the coherent neutralino-nucleus cross-sections.[10] Unfortunately the theoretical analysis is rather involved and requires a number of approximations in order to derive the coupling from baryonic quantities such as the pion-nucleon sigma term and hyperon mass differences. As a matter of fact a more recent analysis[19] of the problem has led to an estimate for the Higgs-nucleon strength somewhat lower than the previous ones.[18] Due to the relevance of this question to our discussion let us review the derivation of the coupling in some detail.

The low energy neutralino-quark effective Lagrangian due to Higgs exchange can be written as[12]

$$\mathcal{L}_{\text{eff}} = \sqrt{2}\,G_{\text{F}}\frac{m_Z}{m_h^2}F\sum_q k_q m_q \bar{\psi}_\chi \psi_\chi \bar{q}q\,, \tag{6}$$

where ψ_χ is the Majorana spinor for the neutralino, the quantities k_q are given by

$$\begin{aligned} k_q &= \frac{\cos\alpha}{\sin\beta} \equiv k_u \quad \text{for up-type quarks}\\ k_q &= -\frac{\sin\alpha}{\cos\beta} \equiv k_d \quad \text{for down-type quarks} \end{aligned} \tag{7}$$

and F is the Higgs-neutralino coupling divided by the SU(2) gauge coupling, namely

$$F = a_2(a_3\sin\alpha + a_4\cos\alpha)\,. \tag{8}$$

Here α is the mixing angle involved in the diagonalization of the mass matrix for the two neutral CP-even Higgs bosons (h, H); an expression for α is given below.

It is worth recalling that, because of the dependence of F on the coefficients a_i (as displayed in Eq. (8)), the effective Lagrangian (6) differs from zero only for neutralinos which are zino-higgsino mixtures.

From Eq. (6) the coherent neutralino scattering cross-section on nucleus i (of mass m_i and mass number A_i) follows[12]

$$\sigma_i = \frac{8G_F^2}{\pi} m_Z^2 \frac{m_i^2 m_\chi^2}{(m_i + m_\chi)^2} A_i^2 \frac{\alpha_H^2}{m_h^4}\,, \tag{9}$$

where

$$\alpha_H = FI\,, \quad I = \sum_q k_q m_q \langle N|\bar{q}q|N\rangle\,. \tag{10}$$

The next step is the evaluation of I. The two important quantities needed are

$$y \equiv \frac{2\langle N|\bar{s}s|N\rangle}{\langle N|\bar{u}u + \bar{d}d|N\rangle} \tag{11}$$

and the sigma term

$$\sigma_\pi N \equiv \frac{m_u + m_d}{2} \langle N|\bar{u}u + \bar{d}d|N\rangle\,. \tag{12}$$

The quantities y and $\sigma_{\pi N}$ are related by the expression (m_N is the nucleon mass):

$$\frac{1}{3}\left(1 - \frac{2m_s}{m_u + m_d}\right)(1 - y)\sigma_{\pi N} = \frac{m_\Lambda^2 - m_\Xi^2}{2m_N} \tag{13}$$

and $\sigma_{\pi N}$ may be derived by phase-shift analysis and dispersion relation techniques from low energy pion-nucleon scattering cross-sections.[18,19]

From (11) and (12) we have

$$m_s \langle N|\bar{s}s|N\rangle = \frac{m_s}{m_u + m_d} y \sigma_{\pi N} \equiv a\sigma_{\pi N}\,. \tag{14}$$

Let us see how the quantities in (11), (12) enter in the expression of I. Since the u, d masses can be neglected, we have

$$I \simeq k_d m_s \langle N|\bar{s}s|N\rangle + \sum_h k_h m_{\text{heavy}} \langle N|\bar{h}h|N\rangle\,, \tag{15}$$

where the sum runs over the heavy quarks (c, b, t). Now, from the heavy quark expansion[20] one knows that the contribution of a single heavy quark is

$$m_h \langle N|\bar{h}h|N\rangle = -\frac{\alpha_s}{12\pi} \langle N|G^a_{\mu\nu} G^a_{\mu\nu}|N\rangle + O(\Lambda^3/m^3_{\text{heavy}})\,, \tag{16}$$

where $G^a_{\mu\nu}$ is the gluon field strength and Λ is the QCD scale factor. Furthermore, for the nucleon mass m_N one has

$$m_N = \sum_q m_q \langle N|\bar{q}q|N\rangle + \frac{\beta(\alpha_s)}{4\alpha_s} \langle N|G^a_{\mu\nu} G^a_{\mu\nu}|N\rangle\,, \tag{17}$$

where as usual

$$\beta(\alpha_s) = \left(-11 + \frac{2}{3}n_q\right)\frac{\alpha_s^2}{2\pi} + O(\alpha_s^3)\,, \tag{18}$$

n_q being the number of the quark flavors.

From (16) and (17), summing over the heavy quarks, one finally obtains

$$\sum_h k_h m_{\text{heavy}}\langle N|\bar{h}h|N\rangle \simeq (2k_u + k_d)\frac{2}{27}[m_N - (1+a)\sigma_{\pi N}] \tag{19}$$

and then, inserting this result and Eq. (14) in (15),

$$I \simeq 2g_h k_u + (g_h + g_s)k_d\,, \tag{20}$$

where

$$\begin{aligned} g_h &= \frac{2}{27}[m_N - (1+a)\sigma_{\pi N}] \\ g_s &= a\sigma_{\pi N}\,. \end{aligned} \tag{21}$$

Now to numbers. We report in Table 1 the evaluations of the relevant quantities given in Ref. 18 (CC) and in Ref. 19 (GLS).

Table 1.

	CC	GLS
$\sigma_{\pi N}$	60 MeV	45 MeV
y	0.47	0.28
a	5.9	3.5
g_h	39 MeV	54 MeV
g_s	354 MeV	157 MeV

It is worth noting that the different determinations of y and $\sigma_{\pi N}$, which entail different values for g_h and g_s, modify the cross-section (9) by an overall factor which is independent of M_2 and μ. This feature is due to the fact that in Eq. (9) the dependence on the a_i's and the dependence on the g's are factorized; also, we note that this would not be the case for the $\tilde{q}$-exchange cross-section. The values of the ratio $\sigma_{(\text{CC})}/\sigma_{(\text{GLS})}$ for the cross-section of Eq. (9) are given in Table 2 for a few sample values of the other parameters. The values of the ratio $\sigma_{(\text{CC})}/\sigma_{(\text{SVZ})}$ where $\sigma_{(\text{SVZ})}$ refers to the old evaluation[20] (SVZ) where the contribution of the quark s was neglected are also reported in Table 2.

Table 2.

$\tan\beta$	m_h (GeV)	$\sigma_{(\text{CC})}/\sigma_{(\text{GLS})}$	$\sigma_{(\text{CC})}/\sigma_{(\text{SVZ})}$
2	50	2.5	7.6
8	50	3.4	29
8	80	3.1	22

4. Radiative Corrections to the Higgs Masses

As was mentioned before, it has recently been proved that radiative corrections modify in a sizeable way the Higgs phenomenology and in particular the relations among the masses of the three neutral Higgs particles in the MSSM.[2] Indeed, under some simplifying assumptions, the mass matrix for the two neutral CP-even Higgs scalars (h, H) may be written in a simple way in terms of a single quantity

$$\varepsilon = \frac{3\alpha_W m_t^4}{2\pi M_W^2 \sin^2\beta} \log\left(1 + \frac{m^2}{m_t^2}\right) \tag{22}$$

which incorporates the one-loop radiative corrections due to the top quark (of mass m_t) and its scalar SUSY partners (of mass m). Diagonalization of the 2×2 Higgs mass matrix leads to the mass relations

$$m_{h,H}^2 = \frac{1}{2}[m_A^2 + M_Z^2 + \varepsilon \pm \Delta] \tag{23}$$

and to the following expression for the relevant mixing angle[21] α

$$\cos(2\alpha) = \frac{(m_Z^2 - m_A^2)\cos(2\beta) - \varepsilon}{\Delta}\,. \tag{24}$$

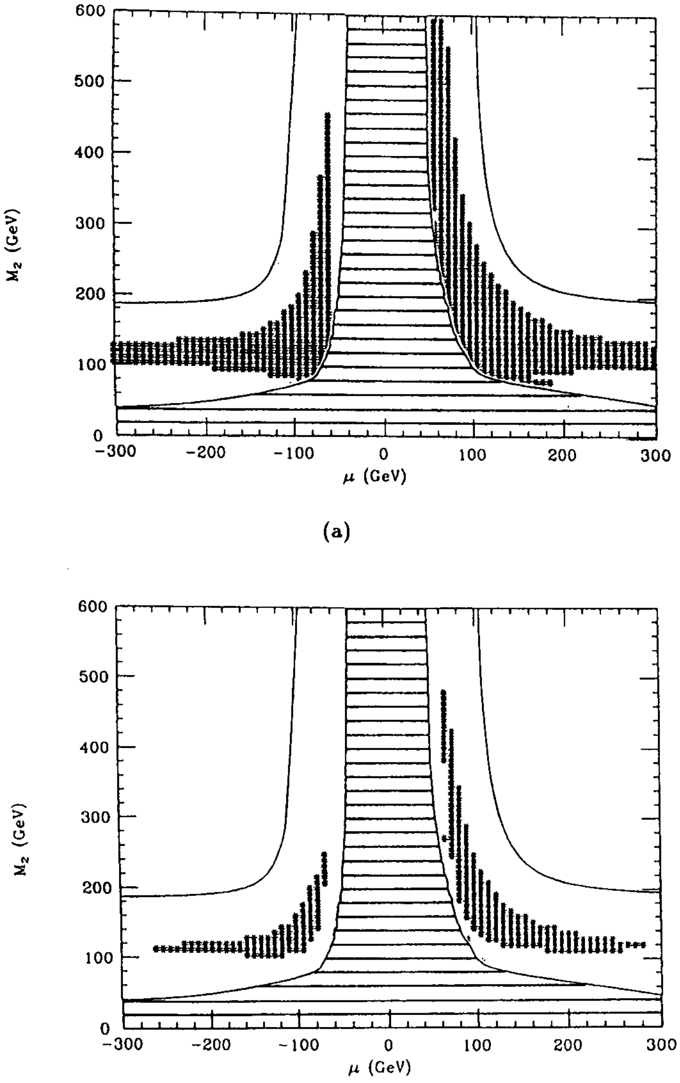
In the two last formulae Δ is given by

$$\Delta = [(m_A^2 + M_Z^2 + \varepsilon)^2 - 4m_A^2 M_Z^2 \cos^2 2\beta - 4\varepsilon m_A^2 \sin^2\beta - 4\varepsilon M_Z^2 \cos^2\beta]^{1/2}\,. \tag{25}$$

The general feature of the corrections is then to modify the tree-level mass values by an amount which depends very strongly on m_t. In the evaluation of the quantities discussed in the present paper we have introduced the radiatively corrected values for the Higgs masses. As was emphasized in Ref. 5, these radiative effects are indeed important in the evaluation of the χ–χ annihilation cross-section and of the relic abundance Ωh^2 (Ω is the ratio of the neutralino matter density to the critical density and h the normalized Hubble parameter), since in these instances Higgses are exchanged in the s-channel.

5. Results and Conclusions

We discuss now the constraints that can be put on the parameters of the model discussed in this paper by employing the present data from direct and indirect experiments. As for the indirect measurements we will use the results from Kamiokande,[22] which turn out to be the most stringent ones among those available.[22,23] For what concerns the direct measurements, the data from Ge detectors are the most interesting ones. The results provided by different groups[24,25] are virtually equivalent for our discussion; for definiteness we will refer here to the data published most recently (Ref. 25).



(b)

Fig. 1. Indirect detection of neutralino (χ–χ annihilation in the Earth) by signals of up-going muons in the M_2–μ parameter space for $\tan\beta = 8$, $m_h = 50$ GeV and radiative corrections with $m_t = 100$ GeV and $m = 1000$ GeV. The neutralino density is fixed at the local value $\rho_\chi = 0.3$ GeV cm^{-3}. The figures refer to the following cases: (a) Higgs-nucleon coupling value obtained from the evaluations by T. P. Cheng and H. Y. Cheng (Ref. 18): $g^h = 39$ MeV, $g^s = 354$ MeV (hereafter referred to as CC value); (b) Higgs-nucleon coupling value obtained from the evaluations by Gasser, Leutwyler and Sainio (Ref. 19): $g^h = 54$ MeV, $g^s = 157$ MeV (hereafter referred to as GLS value). The regions denoted by stars are excluded (at 95% C.L.) by the experimental results of Kamiokande (Ref. 22) if the value $\rho_\chi = 0.3$ GeVcm^{-3} is used. The horizontally hatched region is excluded by LEP (Ref. 28).

The common feature of the present experimental data, both of direct and indirect type, is that up to now no signal is detected which may be attributed to dark matter neutralino. How these data may constrain the model parameters depends very sensitively on the values assigned to the parameters g_h, g_s and to some of the physical quantities, such as ρ_χ and v_χ, which enter in the crucial formulae, Eqs. (3) and (4).

By way of illustration, let us suppose that for ρ_χ and v_χ the standard values $\rho_\chi = 0.3$ GeV cm^{-3}, $v_\chi = 300$ km s^{-1} are taken. In this case, one would obtain the exclusion plots of Figs. 1 and 2. In these figures the excluded regions are shown in the M_2–μ parameter space for some fixed values of the other parameters, $\tan\beta$, m_h, m_t and m. In Fig. 1 the exclusion regions have been obtained using the experimental data of Kamiokande and assigning to the Higgs-nucleon coupling either the CC value (Fig. 1a) or the GLS estimate (Fig. 1b); we notice how sensitive are the excluded areas to the Higgs coupling strength. In Fig. 2a a similar comparison is presented, employing now the direct data of Ref. 25; in Fig. 2b the relevant maximum values of the neutralino-Ge cross-section are given as functions of the neutralino mass, when M_2 and μ are varied over the parameter space shown in Fig. 2a, at fixed values of the other parameters: $\tan\beta = 8$, $m_h = 50$ GeV, $m_t = 100$ GeV and $m = 1000$ GeV.

Let us now turn to a point which was put forward in Ref. 10 and taken up in Ref. 5. This concerns the fact that the evaluation of the direct and indirect signals for dark matter neutralinos have to take explicitly into account the values of the neutralino relic abundance Ωh^2. Indeed evaluations of the χ relic abundance[a,26] show that in large regions of the parameter space Ωh^2 turns out to be too small to allow for the neutralino to provide the total amount of invisible matter of the galactic halo.

To take into account this last point we have derived new exclusion plots following the procedure[5,10] of rescaling ρ_χ by the factor $\Omega h^2/0.05$, whenever the neutralino relic abundance turns out to be less than 0.05. Some examples of our results are reported in Figs. 3–5. In Fig. 3a the region marked by stars denotes the parameter domain excluded by the Kamiokande data if the CC estimate is used; by comparing this figure with Fig. 1a one notes how the excluded regions shrink because of the ρ_χ rescaling. The dotted domain in Fig. 3a denotes the parameter region which could be explored with future set-ups of much larger surfaces; more specifically, in this domain the signal would produce a 4σ effect in a neutrino telescope of 10^5 m^2 after a running time of two years, by measuring up-going muons of energy above 2 GeV within a cone of 30° half-aperture around the Earth center. In Fig. 3b analogous results are given using the GLS estimate for the Higgs coupling; in this case the constraints due to the Kamiokande data are marginal.

As for the data from direct measurement we notice that, even if our exclusion regions (at $\rho_\chi = 0.3$ GeV cm^{-3}), reported in Fig. 2a, are larger than the ones

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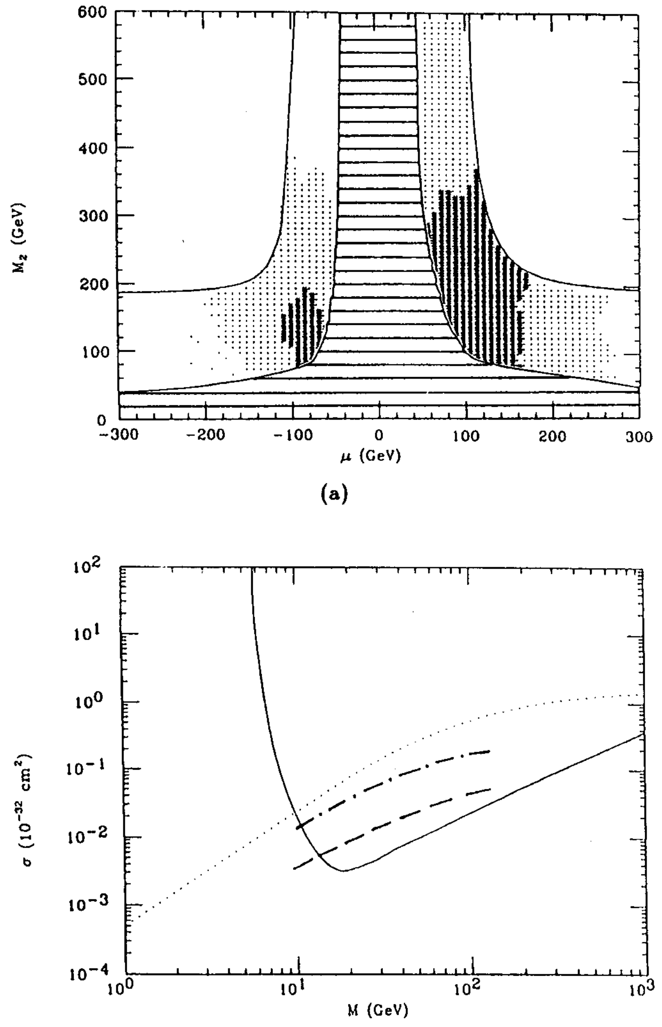
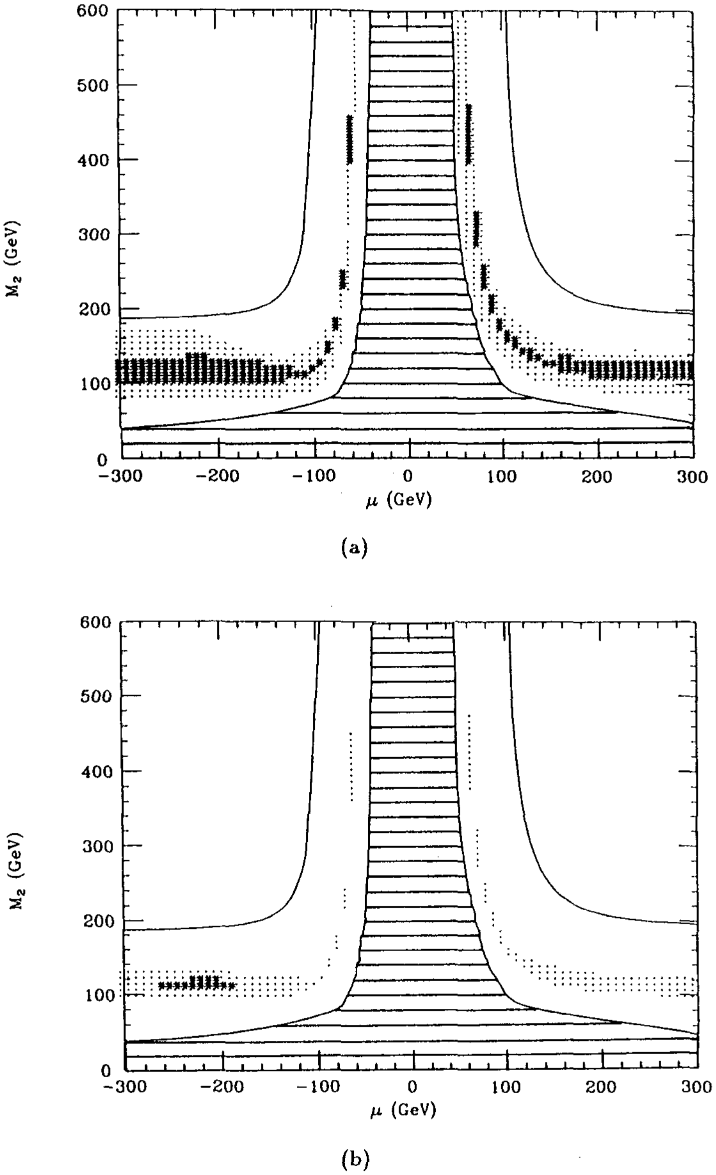
[a] In the following we will use the Ωh^2 values given in Ref. 5. For other evaluations see Ref. 26 and references quoted in Refs. 5 and 10.



(a)

(b)

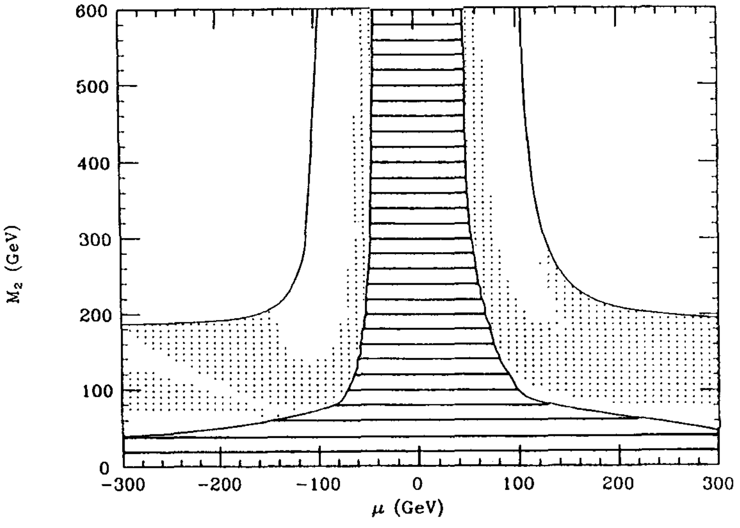
Fig. 2. Direct detection of neutralino by neutralino-Ge cross-section measurements in the M_2–μ parameter space for $\tan\beta = 8$, $m_h = 50$ GeV and radiative corrections with $m_t = 100$ GeV and $m = 1000$ GeV. The neutralino density is fixed at the local value $\rho_\chi = 0.3$ GeVcm^{-3}. (a) The regions excluded by using the CC value for the Higgs-nucleon coupling are denoted by dots; those excluded by using the GLS value for the Higgs-nucleon coupling are denoted by stars. The horizontally hatched region is excluded by LEP; (b) Cross-sections for the coherent interaction of dark matter candidates on a nucleus of Germanium vs the mass of the dark matter particle: solid line: experimental limit (Ref. 25; similar exclusion plots have been obtained by UCSB/LBL/UCB and by UZ/USC/PNL collaborations (see Ref. 24)); dotted line: Dirac neutrino-Ge cross-section; dash-dotted line: for each mass value, the maximum value of the neutralino-Ge cross-section in the M_2–μ parameter space ($0 < M_2 < 600$ GeV, -300 GeV $< \mu < 300$ GeV) is plotted. The CC value for the Higgs-nucleon coupling is used; dashed line: the same as for dash-dotted line except for the use of the GLS value for the Higgs-nucleon coupling instead of the CC value.



(a)

(b)

Fig. 3. In direct detection of neutralino (χ–χ annihilation in the Earth) by signals of up-going muons in the M_2–μ parameter space for $\tan\beta = 8$, $m_h = 50$ GeV and radiative corrections with $m_t = 100$ GeV and $m = 1000$ GeV. The neutralino density is rescaled according to the value of Ωh^2. The regions denoted by stars are excluded (at 95% C.L.) by the experimental results of Kamiokande; in the dotted regions the signal would produce a 4σ effect in a neutrino telescope of the size 10^5 m^2 in two years (muon threshold energy of 2 GeV). The figures refer to (a) the CC value and (b) the GLS value for the Higgs-nucleon coupling. The horizontally hatched region is excluded by LEP.



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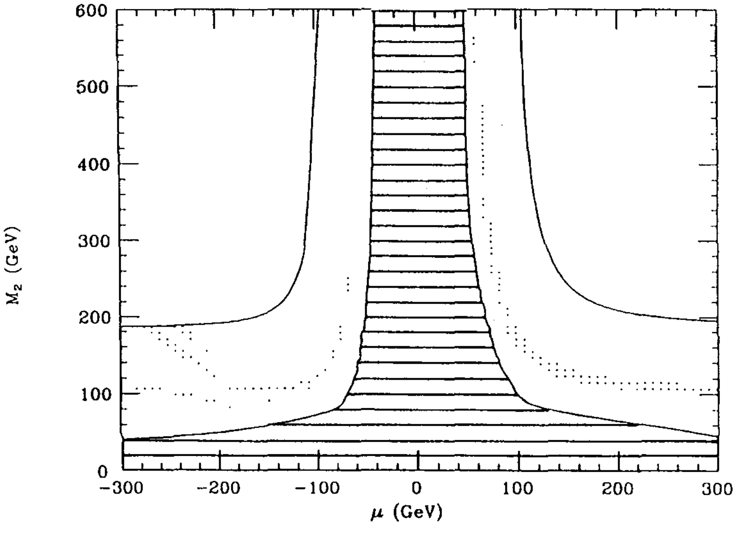

(b)

Fig. 4. The dotted regions denote the domains in the M_2-μ parameter space where neutralino-Ge experiments with a detector whose sensitivity is 10 times the present one could measure a signal. Parameters are here taken to be $\tan\beta = 8$, $m_h = 50$ GeV and radiative corrections with $m_t = 100$ GeV and $m = 1000$ GeV. The neutralino density is rescaled according to the value of Ωh^2. The figures refer to (a) the CC value and (b) the GLS value for the Higgs-nucleon coupling. The horizontally hatched region is excluded by LEP.

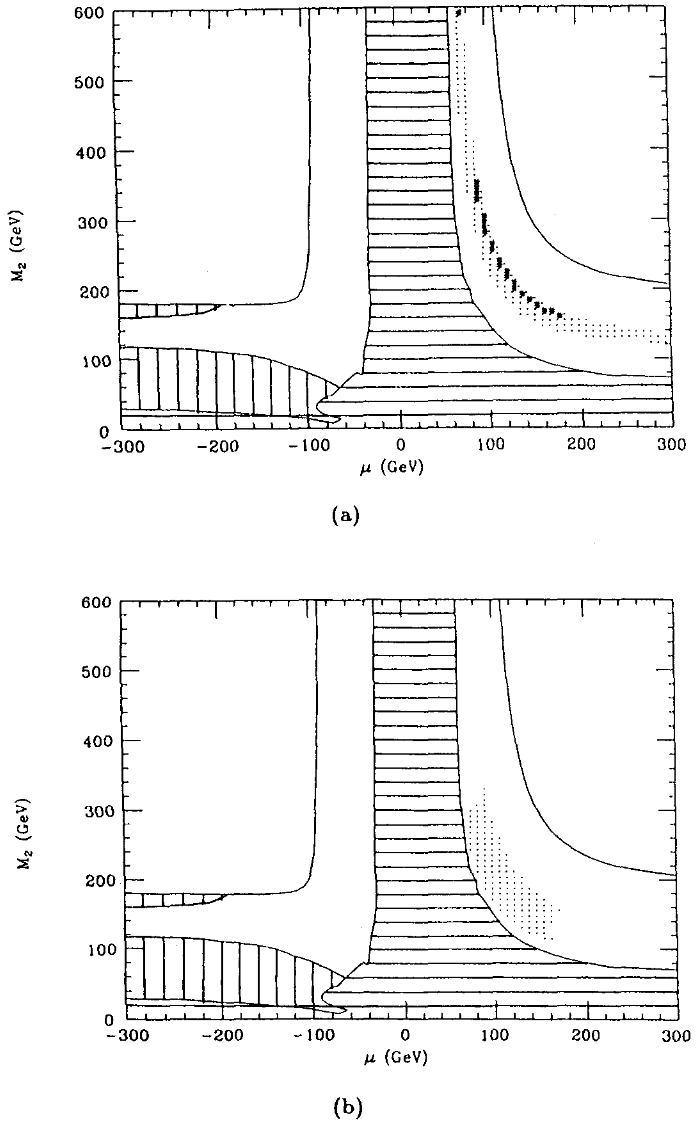

Fig. 5. Signals of indirect (Fig. 5a) and direct (Fig. 5b) neutralino measurements in the M_2–μ parameter space for $\tan\beta = 2$, $m_h = 50$ GeV and radiative corrections with $m_t = 100$ GeV and $m = 1000$ GeV. The neutralino density is rescaled according to the value of Ωh^2. The GLS value is used for the Higgs-nucleon coupling. The figures refer to the following cases: (a) signals of up-going muons. The regions denoted by stars are excluded (at 95% C.L.) by the experimental results of Kamiokande; in the dotted regions the signal would produce a 4σ effect in a neutrino telescope of the size 10^5 m^2 in two years (muon threshold energy of 2 GeV); (b) signals of direct neutralino-Ge cross-section measurements for a detector whose sensitivity is 10 times the present one. The horizontally hatched region is excluded by LEP; in the vertically hatched region overclosure occurs beyond the LEP excluded region.

given in Ref. 10, they completely disappear from the M_2-μ plot, when ρ_χ is properly rescaled. It then follows that present direct measurements with Ge detectors give no constraint on neutralino dark matter (for the parameter ranges considered here). How the situation could change in the case of a substantial improvement in the sensitivity of this class of experiments is illustrated in Fig. 4; here the dotted regions denote the domains which could be explored by these experiments under the hypothesis of an increase in sensitivity by a factor of 10. Again the size of the regions dramatically depends on the theoretical inputs. Finally, by way of example in Fig. 5 we report two sample plots for a different value of $\tan\beta$, $\tan\beta = 2$.

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