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Update of the direct detection of dark matter and the role of the nuclear spin

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We update our exploration of the minimal supersymmetric standard model (MSSM) parameter space at the weak scale where new accelerator and cosmological constraints are respected. The dependence of weakly interacting massive particle nucleon cross sections on parameters of the MSSM, uncertainties of the nucleon structure and other theoretical assumptions such as universality and coannihilation are considered. In particular, we find that the coannihilation does not have a significant effect on our analysis in certain regions which are allowed even with coannihilation. The new cosmological constraint on the relic neutralino density used in the form $0.1<\Omega_\chi h_0^2<0.3$ also does not significantly affect the regions of allowed neutralino-nucleon cross sections. We notice that for nuclear targets with spin the spin-dependent interaction may determine the lower bound for the direct detection rate when the cross section of the scalar interaction drops below about 10^{-12} pb.

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I. INTRODUCTION

It is well known (see, for example, Ref. [1]) that the minimal supersymmetric standard model (MSSM), being the most promising extension of the standard model, offers a solution of the hierarchy problem, possesses gauge coupling unification, and naturally proposes a dark matter candidate—the lightest supersymmetric particle (LSP). In the framework of low-energy supersymmetry (SUSY), when SUSY breaking masses lie below a few TeV, sparticles will be copiously produced (and detected) at future colliders such as the Large Hadron Collider (LHC) at CERN. On the other hand, there are several on-going and future projects searching for the LSP as a dark matter particle. One of them even claims a positive signal [2], although the situation remains rather contradictory [3]. The present experimental upper limit on the spin-independent part of the elastic scattering of the LSP on a nucleon is around 10^{-5} pb for 50 GeV$\lesssim m_\chi \lesssim$100 GeV. In any case, it seems very plausible that both SUSY collider signals and LSP dark matter will be found in the future. Such dark matter searches offer interesting prospects for beating accelerators in the discovery of SUSY, particularly during the coming years before the LHC enters operation [4]. In this situation naturally arose the question of how small the event rate of the LSP direct detection can be, provided the LSP is a cold dark matter particle. Searching for the answer different SUSY models were considered (see, for example, Refs. [5–9]).

Recently exciting evidence for a flat and accelerating universe was obtained [10,11]. The position of the first acoustic peak of the angular power spectrum strongly suggests a flat universe with density parameter $\Omega_0=1$ while the shape of the peak is consistent with the density perturbations predicted by models of inflation. The density parameter $\Omega_0=\rho_0/\rho_c$ is the ratio of the current mass density ρ_0 to the critical density $\rho_c=1.88\times10^{-29}\ h_0^2$ g cm^{-3}, with h_0 being the dimensionless Hubble parameter. Data support the straight line $\Omega_0=\Omega_M+\Omega_\Lambda=1$ [12–15], where Ω_M is the matter density in the universe and Ω_Λ is the contribution of the nonzero cosmological constant (the energy density of the vacuum). At the same time one determines $\Omega_M=0.4\pm0.1$, which implies $\Omega_\Lambda=0.85\pm0.2$, a value that has been supported from high-redshifted Supernova data [16]. Since the baryonic matter density is small, $\Omega_B=0.05\pm0.005$, the values for matter density Ω_M give a cold dark matter (CDM) density $\Omega_{\rm CDM}\simeq0.35\pm0.1$, which combined with recent measurements of the Hubble parameter $h_0=0.65\pm0.05$, result in smaller CDM relic densities $\Omega_{\rm CDM}h_0^2\simeq0.15\pm0.07$ [12–15].

Previously we have restricted our analyses to the cosmological constraint for the relic density of the LSP in the range $0.025<\Omega_\chi h_0^2<1$ [17–20], where the neutralino relic density parameter $\Omega_\chi=\rho_\chi/\rho_c$ and ρ_χ is the relic neutralino mass density. In this paper adopting the above-mentioned new cosmological data and going to compare our estimation with literature [4,9,21,22] we constrain the allowed region for the neutralino relic density in the form $0.1<\Omega_\chi h_0^2<0.3$. It is possible that there is more than one component in the cold dark matter, so that $\Omega_\chi<\Omega_{\rm CDM}$, and therefore $\Omega_\chi<0.1$. Although, in general, a decrease of Ω is associated with larger elastic scattering cross sections, the detection rate also must be reduced because of the corresponding reduction in the density of LSP's in the Galactic halo. Here we neglect this possibility and assume that all the cold dark matter is composed of LSP's, so that $\Omega_\chi\geqslant0.1$ [4].

There are two main approaches to evaluate the dark-matter-neutralino nucleon cross section and the expected event rate in a detector. The basis of the first approach is the minimal supergravity (MSUGRA) model [23]. This model assumes the minimal supersymmetric standard model to be valid at all energy scales from $M_{\rm weak}$ up to $M_{\rm GUT}\simeq2\times10^{16}$ GeV. The MSUGRA model arises as the low-energy limit of

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a supergravity theory, where supersymmetry is broken in the hidden sector of the model at an energy scale of $M\sim10^{10}$ GeV. Supersymmetry breaking is communicated to the observable sector via gravitational interactions, leading to soft SUSY breaking mass terms of the order of the electroweak scale. At the grand unified theory (GUT) scale this leads to a common mass for all scalars m_0 and a common trilinear coupling A_0. Motivated by the apparent unification of gauge coupling constants, it is also assumed that all gaugino masses are unified to $m_{1/2}$ at $M_{\rm GUT}$. The weak scale sparticle spectrum is derived from renormalization group running of the SUSY soft breaking parameters. Requiring radiative electroweak symmetry breaking allows the determination of the superpotential Higgsino mass squared μ^2, and allows the expression of the soft SUSY breaking bilinear term B in terms of tan β. Thus all sparticle masses and couplings are derived in terms of the minimal parameter set m_0, $m_{1/2}$, A_0, tan β, and sign(μ) [23–25]. From a practical point of view this approach as much as possible relies on theoretical arguments like unification, naturalness, etc. aiming to maximally reduce the set of free parameters and obtain maximally restricted predictions. In this approach [4] the quantum stability of the gauge hierarchy suggests that sparticles weigh less than about 1 TeV [26], which is also the range favored for a cold dark matter particle, and there are indeed generic domains of the MSSM parameter space in which the relic LSP density falls within the range favored by astrophysics and cosmology. The unsuccessful laboratory searches for sparticles impose nontrivial constraints on the MSSM parameter space, suggesting that the LSP neutralino is mainly a U(1) gaugino (B-ino) [27]. In the MSSM the lightest neutralino $\chi\equiv\tilde\chi_1^0$ is a mixture of four superpartners of gauge and Higgs bosons (B-ino, W-ino, and two Higgsinos):

$$\chi=N_{11}\tilde B^0+N_{12}\tilde W^0+N_{13}\tilde H_1^0+N_{14}\tilde H_2^0. \qquad (1)$$

It is commonly accepted that χ is mostly gauginolike if $P\equiv N_{11}^2+N_{12}^2>0.9$ and Higgsino-like if $P<0.1$, or mixed otherwise.

It is due to the B-ino-likeness of the relic neutralinos that the calculated neutralino-nucleon cross sections appeared very small and one usually arrived at the conclusion that it was hardly possible to reach the MSUGRA space by means of direct and indirect searches for dark matter particles [4,5,8,17,24,28–30]. The other side of this conclusion is also well known: when $|\mu|$ decreases, the Higgsino components N_{13} and N_{14} of χ increase (P decreases) and as a result the spin-independent cross section increases. So Higgsino-like (and mixed) neutralino on the other hand increases the prospect for its detection as a dark matter particle [7,22,31,32]. Therefore it seems a crucial question here, to what extent is the neutralino mostly gauginolike, Higgsino-like, or mixed?

A way to look for any possibility of higher cross sections and higher expected rates of detection is to investigate alternate models. The basis of it is a departure from the stringent MSUGRA by means of a relaxation of some unification and other theoretical assumptions aiming to obtain as general predictions for the expected detection rate as possible. A remarkable shift from MSUGRA to more relaxed models was made by Refs. [20], [1], and [9]. It mostly included relaxation of unification of soft scalar mass parameters (so called nonuniversal soft symmetry breaking) as well as gaugino mass nonuniversality. The large tan β regime was also considered as a source of higher cross sections. Indeed in canonical MSUGRA it was pointed out [33–35] that the large tan β regime allows regions where $\sigma_{\chi p}\approx10^{-6}$ pb. Besides, with nonuniversal soft scalar masses, it was also found that $\sigma_{\chi p}\approx10^{-6}$ pb for small values of tan β. In particular, this was obtained for tan $\beta\gtrsim25$ (tan $\beta\gtrsim4$) working with universal (nonuniversal) soft terms in Ref. [35]. These analyses were performed assuming (non)universality of the soft breaking terms at the unification scale, $M_{\rm GUT}\approx10^{16}$ GeV, which can be obtained within superstring theories [36,37] and heterotic M theory [36,38].

Completely new possibilities have also been discussed. For example, it is found that in supersymmetry models multi-TeV scalar masses can exist consistent with naturalness on a certain branch of the radiative breaking of the electroweak symmetry [39]. A similar phenomenon appears in the so-called focus point supersymmetry models where one also avoids naturalness constraints with multi-TeV scalars [31,40,41] and in models with moving intermediate unification scale [32].

It was noticed that the assumptions concerning universality of the scalar masses $m_i(M_{\rm GUT})\equiv m_0$, and the trilinear scalar couplings $A^{l,u,d}(M_{\rm GUT})\equiv A_0$, are not very solid, at least from phenomenological point of view, since, universality might occur at a scale higher than $M_{\rm GUT}\sim10^{16}$ GeV [42], or according to string models at a scale M_I smaller than $M_{\rm GUT}\sim10^{16}$ GeV [32,43]. It was realized that the string scale may be anywhere between the weak scale and the Planck scale. For instance, D-brane configurations allow these possibilities in type-I strings [44–47]. Similar results can also be obtained in type-II strings [48] and weakly and strongly coupled heterotic strings [49,50]. Moreover the M_I might be anywhere between the weak scale and the Planck scale [32], with significant consequences for the size of the neutralino-nucleon cross section. The case of nonuniversal gaugino masses was analyzed in Refs. [6], [7], [51], and [35] and with respect to direct detection of the superlight dark matter neutralinos in Ref. [19]. Schemes with CP violating phases one can find in Ref. [52].

Therefore due to the large uncertainties involved in the choice of the scale M_I and going to obtain as much as general predictions it appeared more convenient to work within a phenomenological SUSY model whose parameters are defined directly at the electroweak scale as, for example, in Refs. [6], [8], and [53–56] and which is denoted as an effective scheme of MSSM (effMSSM) in Ref. [22].

Obviously, this way much larger expected event rates were obtained and optimistic conclusions concerning the possibility to constrain significantly the SUSY parameter space with dark matter experiments were drawn [8,22,31,32,53,57].

In our previous calculations in effMSSM [6,18,19,58] we have adopted an (effective) scheme (with nonuniversal scalar masses and with nonuniversal gaugino soft masses) which has supplied us with large relatively direct detection rates of dark matter neutralinos, practically independent of what is the neutralino composition. In most of the MSSM parameter space we, in agreement with others, have obtained at the detectable level mostly gauginolike neutralinos, but always existed small Higgsino admixtures (at a level less than 1–5 %) which managed to produce large enough cross sections and rates.

In 1994 we claimed that nuclear spin is not important for detection of dark matter particles, provided the detection sensitivity does not exceed 0.01 events/day/kg, which was considered that time as unreachable [58]. Now the situation has changed and we would like to notice that for targets with spin-nonzero nuclei it might be the spin-dependent interaction that determines the lower bound for the direct detection rate when the cross section of the scalar interaction, which is usually assumed to be the dominant part, drops below 10^{-12-13} pb [6].

New updated parameters of the nucleon structure involved in the evaluation of the elastic neutralino nucleon scattering have become available [4] and one expects that they will affect the cross sections of neutralino nucleon scattering. At least significant cancellations may occur for some values of tan β for scalar- and spin-dependent cross sections (at least for tan $\beta < 10$ [4]).

The above considerations stimulated us to perform a recalculation of our previous analysis.

II. APPROACH

A dark matter event is elastic scattering of a relic neutralino from a target nucleus producing a nuclear recoil which can be detected by a suitable detector [59]. The differential event rate in respect to the recoil energy is the subject of experimental measurements. The rate depends on the distribution of the relic neutralinos in the solar vicinity and the cross section of neutralino-nucleus elastic scattering. In our analysis we use the total event rate R which is integrated over recoil energies and useful for searching for domains with extreme rates. We follow our papers [18,19], where one can find all relevant formulas and astrophysical parameters. We consider only a simple spherically symmetric isothermal distribution and do not go into details of any possible uncertainties (and/or modulation effects) of the Galactic halo weakly interacting massive particle (WIMP) distribution [60–66].

To calculate the event rate we use for the relic neutralino mass density and for the escape neutralino velocity commonly accepted values 0.3 GeV/cm^3 and 600 km/s, respectively. Their experimental variations can slightly change R but leave the dependence of R on the MSSM parameters unaffected. To compare our results with other calculations and sensitivities of different dark matter experiments we calculate also the total cross section for relic neutralino elastic scattering on the nucleon. The scalar (spin-independent) part of the elastic neutralino-proton (neutron) cross section at zero momentum transfer $q=0$ is

$$\sigma_{\rm SI}^{p,n}(0)=4\frac{\mu^2}{\pi}[\mathcal{C}_{p,n}]^2,$$

where

$$\mathcal{C}_{p,n}=\sum_{q=u,d,s} f_{T_q}^{(p,n)}\mathcal{C}_q+\frac{2}{27}f_{TG}^{(p,n)}\sum_{c,b,t}\mathcal{C}_q .$$

The spin-dependent part of the elastic χ-nucleon cross section can be written as

$$\sigma_{\rm SD}^{p,n}(0)=4\frac{\mu^2}{\pi}3[\mathcal{A}_{p,n}]^2,$$

where

$$\mathcal{A}_{p,n}=\sum_{u,d,s}\mathcal{A}_q\Delta q^{(p,n)}$$

and

$$\mu=\frac{m_\chi M_{p,n}}{m_\chi+M_{p,n}}.$$

The effective couplings $\mathcal{A}_q$ and $\mathcal{C}_q$ of the neutralino-quark Lagrangian

$$L_{\rm eff}=\mathcal{A}_q\cdot\bar{\chi}\gamma_\mu\gamma_5\chi\cdot\bar{q}\gamma^\mu\gamma_5 q+\mathcal{C}_q\bar{\chi}\chi\cdot\bar{q}q+\mathcal{O}(1/m_{q}^{4})$$

which enter the cross sections one can find in Ref. [58]. The parameters $f_{Tq}^{(p,n)}$ and $f_{TG}^{(p,n)}$ are defined by

$$m_p f_{Tq}^{(p)}\equiv\langle p|m_q\bar{q}q|p\rangle,\quad f_{TG}^{(p,n)}=1-\sum_{q=u,d,s}f_{Tq}^{(p,n)} .$$

Following Ref. [4] we use the updated parameters

$$f_{Tu}^{(p)}=0.020\pm0.004,\quad f_{Td}^{(p)}=0.026\pm0.005,$$

$$f_{Ts}^{(p)}=0.118\pm0.062, \tag{2}$$

$$f_{Tu}^{(n)}=0.014\pm0.003,\quad f_{Td}^{(n)}=0.036\pm0.008,$$

$$f_{Ts}^{(n)}=0.118\pm0.062. \tag{3}$$

Our estimations of the effect of the inaccuracy in the determination of f_{Ts} on the total event rate agree with those obtained before in Ref. [58] and in Refs. [9], [31], [67], and [68]. For a different determination using an analytic analysis, see Ref. [7]. The two corridors do overlap. The inaccuracy maximally changes the proton-neutralino cross section (event rate) within about one order of magnitude. The value chosen in this work gives probably a more pessimistic view of the cross sections. The inaccuracy of other parameters has a smaller effect on the cross sections.

The factors $\Delta_i^{(p,n)}$ parametrize the quark spin content of the nucleon. A global QCD analysis for the g_1 structure functions [69], including $\mathcal{O}(\alpha_s^3)$ corrections, corresponds to the values [4]

$$\Delta_u^{(p)}=\Delta_d^{(n)}=0.78\pm0.02,\quad \Delta_d^{(p)}=\Delta_u^{(n)}=-0.48\pm0.02,$$

$$\Delta_s^{(p)} = \Delta_s^{(n)} = -0.15 \pm 0.02. \tag{4}$$

We calculate $\Omega_\chi h_0^2$ following the standard procedure on the basis of the approximate formula [70,71]. We take into account all channels of the $\chi-\chi$ annihilation. Since the neutralinos are mixtures of gauginos and higgsinos, the annihilation can occur both, via s-channel exchange of the Z^0 and Higgs bosons and t-channel exchange of a scalar particle. This constrains the parameter space [28,70]. As mentioned in the Introduction we require $0.1 < \Omega_\chi h_0^2 < 0.3$, for comparison we also present our results when $0.025 < \Omega_\chi h_0^2 < 1$.

Another stringent constraint is imposed by the branching ratio of $b \to s\gamma$ decay, measured by the CLEO Collaboration to be $1.0\times 10^{-4} < B(b\to s\gamma) < 4.2\times 10^{-4}$. In the MSSM this flavor-changing neutral current process receives contributions from $H^\pm - t$, $\tilde{\chi}^\pm - \tilde{t}$, and $\tilde{g} - \tilde{q}$ loops in addition to the standard model $W-t$ loop. This also restricts the SUSY parameter space [72].

The masses of the supersymmetric particles are constrained by the results from the high energy colliders. This imposes relevant constraints on the parameter space of the MSSM. In Ref. [6] we used the following lower bounds for the SUSY particles [73]: $M_{\tilde{\chi}_2^+} \geqslant 65$ GeV for the light chargino, $M_{\tilde{\chi}_1^+} \geqslant 99$ GeV for the heavy chargino, $M_{\tilde{\chi}^0_{1,2,3}} \geqslant 45, 76, 127$ GeV for non-LSP neutralinos, respectively; $M_{\tilde{\nu}} \geqslant 43$ GeV for sneutrinos, $M_{\tilde{e}_R} \geqslant 70$ GeV for selectrons, $M_{\tilde{q}} \geqslant 210$ GeV for squarks, $M_{\tilde{t}_1} \geqslant 85$ GeV for light top squarks, $M_{H^0} \geqslant 79$ GeV for neutral Higgs bosons, $M_{\mathrm{CH}} \geqslant 70$ GeV for the charged Higgs boson. On the basis of last LEP results [74] we use now new longer limits for charginos: $M_{\tilde{\chi}^\pm_{1,2}} \geqslant 100$ GeV, and neutral Higgs bosons: $m_{H^0} > 100$ GeV.

As previously [6], we explore the MSSM parameter space at the weak scale relaxing completely constraints following from any unification assumption. Nevertheless, we respect other available restrictions from cosmology, accelerator SUSY searches, rate flavor changing neutral current (FCNC) $b \to s\gamma$ decay, etc. [20,5,28].

The MSSM parameter space is determined by entries of the mass matrices of neutralinos, charginos, Higgs bosons, sleptons, and squarks. The relevant definitions one can find in Ref. [6]. The list of free parameters includes: $\tan\beta$ is the ratio of neutral Higgs boson vacuum expectation values, μ is the bilinear Higgs parameter of the superpotential, $M_{1,2}$ are soft gaugino masses, M_A is the CP-odd Higgs boson mass, $m^2_{\tilde{Q}}$, $m^2_{\tilde{U}}$, $m^2_{\tilde{D}}$ ($m^2_{\tilde{L}}$, $m^2_{\tilde{E}}$) are squared squark (slepton) mass parameters for the first and second generation, $m^2_{\tilde{Q}_3}$, $m^2_{\tilde{T}}$, $m^2_{\tilde{B}}$ ($m^2_{\tilde{L}_3}$, $m^2_{\tilde{\tau}}$) are squared squark (slepton) mass parameters for third generation and A_t, A_b, A_τ are soft trilinear couplings for the third generation. In our numerical analysis the parameters of the MSSM are randomly varied in the following intervals:

$$-1 < M_1 < 1 \ \ \text{TeV}, \quad -2 \ \ M_2, \mu, A_t < 2 \ \ \text{TeV},$$

$$1 < \tan\beta < 50, \quad 60 < M_A < 1000 \ \ \text{GeV}, \tag{5}$$

$$10 < m^2_Q, m^2_L, m^2_{Q_3}, m^2_{L_3} < 10^6 \ \ \text{GeV}^2.$$

Following Refs. [1], [9], and [67] we assume that squarks are basically degenerate. Bounds on flavor-changing neutral currents imply that squarks with equal gauge quantum numbers must be close in mass. With the possible exception of third generation squarks the assumed degeneracy therefore holds almost model independently [1]. Therefore for other sfermion mass parameters we used the relations $m^2_{\tilde{U}} = m^2_{\tilde{D}} = m^2_{\tilde{Q}}$, $m^2_{\tilde{E}} = m^2_L$, $m^2_{\tilde{T}} = m^2_{\tilde{B}} = m^2_{Q_3}$, $m^2_{\tilde{E}_3} = m^2_{L_3}$. The parameters A_b and A_τ are fixed to be zero. We consider the domain of the MSSM parameter space, in which we perform our scans, as quite spread and natural. Any extra expansion of it like, for example, using $-10 < M_2 < 10$ TeV, etc., of course, can be possible, but should be considered, contrary to Refs. [31], [40], and [41], as quite unnatural.

III. RESULTS AND DISCUSSION

A. Coannihilation

The effects of coannihilation may become important when the next to the lowest super-symmetric particle (NLSP) has a mass which lies close to the LSP mass [75]. The size of the effects is exponentially damped by the factor $e^{-\Delta_i x}$ where $\Delta_i = (m_i/m_\chi - 1)$, $x = m_\chi/kT$, and where m_χ is the LSP mass. Because of this damping the coannihilation effects are typically important only for regions of the parameter space where the constraint $\Delta_i < 0.1$ is satisfied. Some of the possible candidates for NLSP are the light stau $\tilde{\tau}_1$, $\tilde{e}_R$, the next to the lightest neutralino χ^0_2, and the light chargino χ^+_1. It was found that in MSUGRA the upper limit on the neutralino mass consistent with the current experimental constraints on the relic density is extended from 200 to 600 GeV [76] when the effects of $\chi - \tilde{\tau}$ coannihilation are included.

By means of excluding points which can give nonnegligible contribution to relic neutralino annihilation via coannihilations with other SUSY particles we simply have estimates of the influence of the coannihilation to our previous results. We used the constraint: $(m_i - m_{\mathrm{LSP}})/(m_{\mathrm{LSP}}) < 0.2$, where i runs over next-to-LSP neutralino, charginos, staus, stops, etc. In accordance with previous estimates of Refs. [35], [67], [32], and [21] we found that the coannihilation does not significantly change our main results. In fact, less than 20% of the models were denied by this coannihilation constraint, which in the case of $0.025 < \Omega_\chi h_0^2 < 1$ excludes points with simultaneously small $|\mu|$ ($|\mu| < 500$ GeV) and large $|M_1|$ ($|M_1| > 600$ GeV), allowing for a substantial nongaugino fraction of the LSP only in the region of relatively small $|\mu|$ If the relic abundance of neutralinos is located in the range $0.1 < \Omega_\chi h_0^2 < 0.3$, the coannihilation constraint appears less restrictive.

B. Cross sections

Our calculations with the updated nucleon structure [4] for the WIMP-nucleon cross section of both spin and scalar

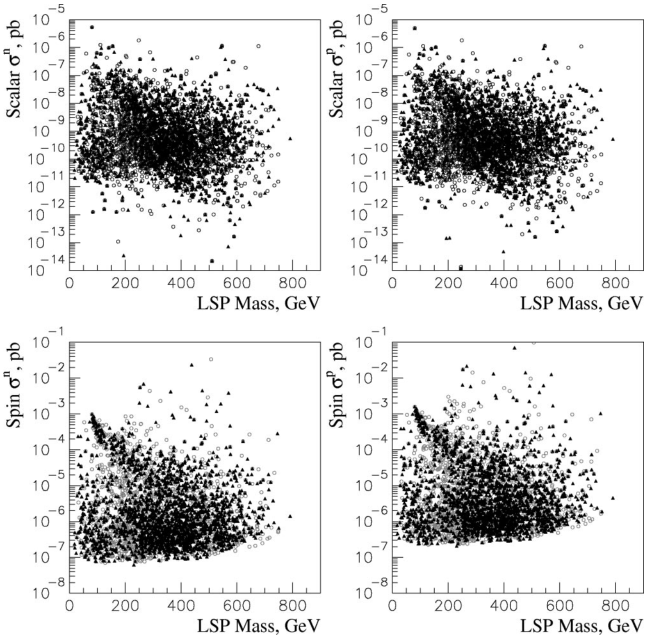

FIG. 1. Cross sections of spin-dependent and spin-independent interactions of WIMP's with proton and neutron. Filled triangles (light circles) correspond to relic neutralino density $0.1<\Omega_\chi h_0^2<0.3$ ($0.025<\Omega_\chi h_0^2<1$).

interactions as function of the WIMP mass are depicted below as scatter plots (Figs. 1–6).

The use of the updated parameters (2)–(4) does not change significantly the general distribution of points over the scatter plots as compared with calculations with earlier nucleon parameters [77–79] used in Refs. [6], [18], [19], and [58].

Scatter plots with individual cross sections of spin-dependent and spin-independent interactions of WIMP's with proton and neutron are given in Fig. 1 as function of the LSP mass. In the figure light circles correspond to cross sections calculated under the old assumption that $0.025<\Omega_\chi h_0^2<1$. Filled triangles give the same cross sections but the constraint on the flat and accelerating universe is imposed by $0.1<\Omega_\chi h_0^2<0.3$. One can see that the reduction of the allowed domain for the relic density does not significantly affect spin-dependent and the spin-independent WIMP-nucleon cross sections, i.e., restriction to a flat and accelerating universe weakly affects these cross sections.

The different behavior of these cross sections with mass of the LSP can be seen from the plots. There is a more stringent lower bound for the spin-dependent cross section. It is at a level of 10^{-7} pb, which is about an order of magnitude larger than the one presented in Ref. [68], where for small tan β (tan $\beta=3$, $\mu<0$, and small m_χ) the effect of a cancellation induced by the difference in signs between Δ_u and $\Delta_{d,s}$ [Eq. (4)] was reported. Aside from the cancellation, the spin-dependent cross section peaks at about 10^{-4} pb and drops rapidly as m_χ increases down to 10^{-7--8} pb at $m_\chi\approx 600$ GeV [68]. We have checked that special consideration of the low tan β regime supplies us also with smaller cross section values for spin-dependent interactions, which do not enter in contradictions with Ref. [68].

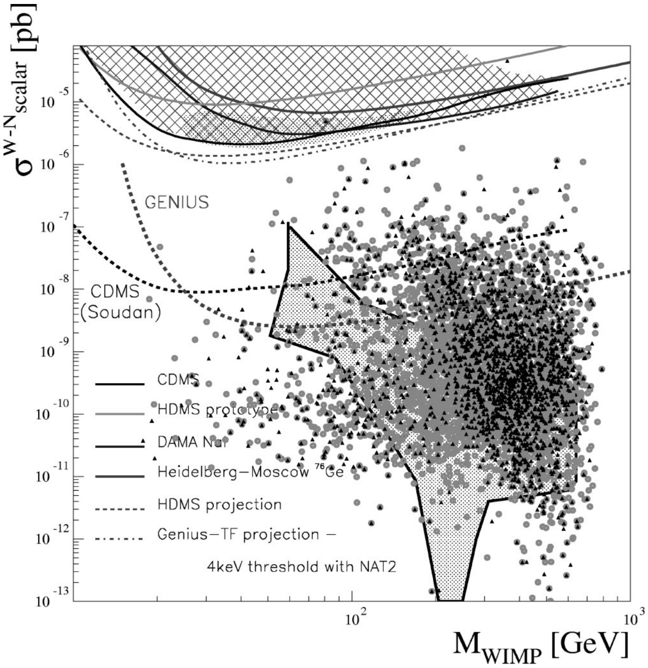

FIG. 2. WIMP-nucleon cross section limits in pb for scalar interactions as function of the WIMP mass in GeV. Filled circles present our calculations with updated nucleon structure (Ref. [4]) in ''nonaccelerating universe'' with $0.025<\Omega_\chi h_0^2<1$. Filled triangles give the same cross section but when $0.1<\Omega_\chi h_0^2<0.3$. The contours (shaded area enclosed with solid curve) for allowed scalar WIMP-proton cross sections from Refs. [4] and [68] are also given together with some current [DAMA (Ref. [2]), HEIDELBERG-MOSCOW (Ref. [80]), CDMS (Ref. [84]), and HDMS prototype (Ref. [81])] and future experimental exclusion curves [HDMS projection (Ref. [81]), GENIUS-TF (Ref. [82]), GENIUS (Ref. [83]), and CDMS (Ref. [84])].

Such a cancellation was found also in scalar cross sections for tan $\beta=10$ and $\mu<0$ [68]. In this case Higgs exchange is dominant. The cancellation in the MSUGRA is due to the cancellation between the up-type contribution (which is negative) and the down-type contribution, which is initially positive but decreasing, eventually becoming negative as we increase m_χ.

In Fig. 2 filled circles present our calculations when constraints due to an accelerating universe are not applied and as in Refs. [6] and [8] we hold $0.025<\Omega_\chi h_0^2<1$. Filled triangles give the same cross section, but using as [4,35,31,67,68,32,21,22] the boundary $0.1<\Omega_\chi h_0^2<0.3$. The contours for allowed scalar WIMP-proton cross sections from Refs. [4] and [68] are also given together with some current (DAMA [2], CDMS [84], HEIDELBERG-MOSCOW [80], HDMS prototype [81]) and future-expected experimental exclusion curves (HDMS [81], GENIUS-TF [82], GENIUS [83], and CDMS [84]). This figure allows one to see the influence of the flat and accelerating universe on the distribution of WIMP-proton scalar cross section. The reduction left only 25% of points but nevertheless the distribution of the remaining points differs only slightly from the one obtained with $0.025<\Omega_\chi h_0^2<1$. The models with very small cross sections as well as models with very large cross

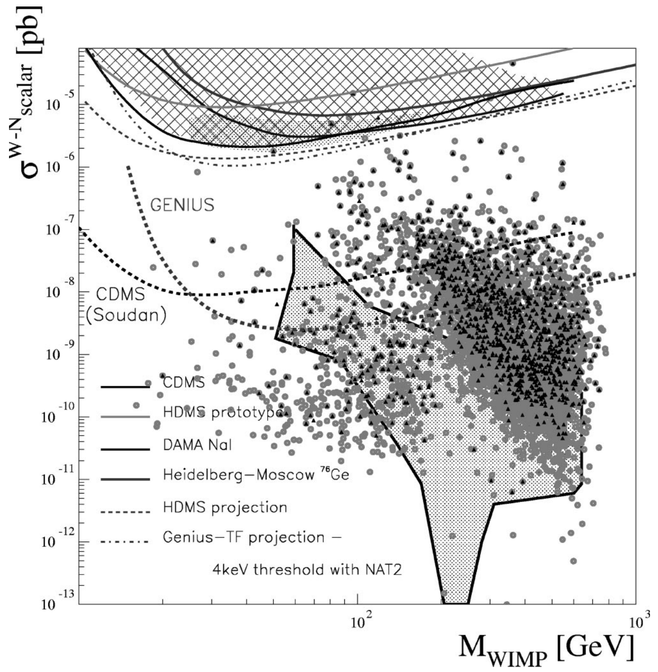

FIG. 3. The same as in Fig. 2, but filled circles give cross sections for $0.1<\Omega_{\chi}h_0^2<0.3$ and $\tan\beta>20$. Filled triangles give the same cross section, but when $\tan\beta>40$. The contour from (obtained from $\tan\beta<10$) [4,68] is also given.

sections (in fact, experimentally excluded) still persist.

One also can conclude that there is no contradiction between the result of Refs. [4] and [68] obtained in the MSUGRA with minimal number of free parameters and our phenomenological scan, which also allows models with very small cross sections.

While we have $1<\tan\beta<50$, the contour from Refs. [4] and [68] was obtained under the assumption that $\tan\beta\leqslant 10$ to avoid some uncertainties in the treatment of radiative corrections in the renormalization-group evolution of the MSSM parameters which affect the relic density calculations [68]. As noticed by many groups [58,24,6,35,32,21,22], the scalar cross section of elastic WIMP-nucleon scattering increases with $\tan\beta$. As can be seen from Fig. 1 of Ref. [6], $\tan\beta$ seems to be the only SUSY parameter with which the lower bound of the direct detection rate has the tendency to increase. The majority of the points at the scatter plots in Fig. 3 are shifted to the domain of larger cross section with increase of $\tan\beta$.

In general the increase of $\tan\beta$ effectively relaxes the μ constraint in MSUGRA (it allows μ to be smaller) and results in a non-negligible Higgsino component followed by significantly larger scalar cross section (see, for example, Ref. [6]).

We also report as before [58,19,6] nonuniversality of soft supersymmetry-breaking masses in the scalar and the gaugino sectors [see list of free parameters in Eq. (5)], resulting in larger cross sections, as noted in Refs. [67] and [68].

The spin-dependent and spin-independent WIMP-proton cross sections as functions of input parameters μ, m_Q^2, M_A, and $\tan\beta$ are depicted in Figs. 4 and 5.

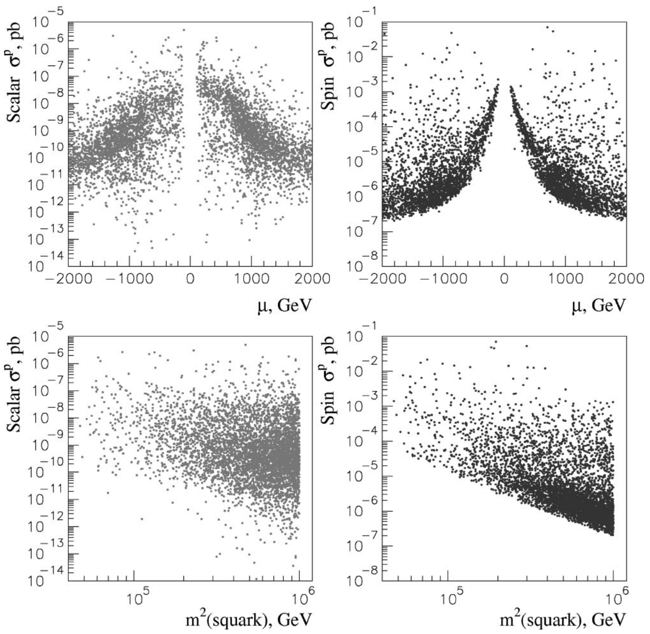

FIG. 4. Cross sections of WIMP-proton spin-dependent and spin-independent interactions as function of input parameters μ (upper panel) and m_Q^2 (lower panel) obtained with $0.1<\Omega_{\chi}h_0^2<0.3$.

There is no noticeable dependence of these scatter plots on the other free parameters from Eq. (5), for which we therefore do not show scatter plots. One can see from Fig. 4 the similarity of the scatter plots for spin-dependent and scalar cross sections as functions of μ and m_Q^2. Decrease of both lower bounds of the cross sections with m_Q^2 occur due to increase of masses of squarks, which enter the *s*-channel in-

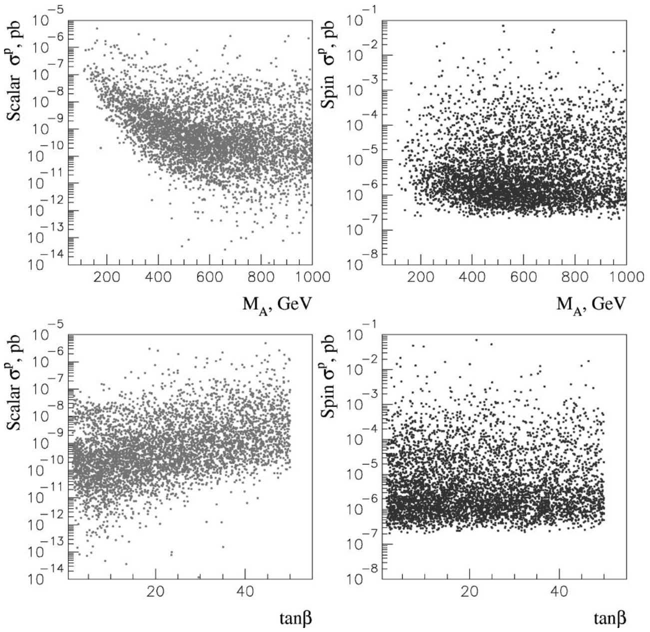

FIG. 5. Cross sections of WIMP-proton spin-dependent and spin-independent interactions as function of input parameters M_A (upper panel) and $\tan\beta$ (lower panel) obtained with $0.1<\Omega_{\chi}h_0^2<0.3$.

termediate states. The only visible difference concerns more sharp lower bounds for the spin-dependent cross section. Both spin-dependent and spin-independent cross sections increase when $|\mu|$ decreases, in agreement with Refs. [6], [31], [8], and [35]. It is not easy to trace the tendency in MSUGRA models because the parameter μ there is strongly constrained by the electroweak symmetry breaking condition (see, for example, Ref. [68]).

The increase of the scalar cross sections generally is connected with an increase of the Higgsino admixture of the LSP and increase of Higgsino-gaugino interference which enters this cross section [31,32,35]. The reason of the Higgsino growth can be nonuniversality of scalar soft masses [35], variation of intermediate unification scale [32], or new focus point regime of supersymmetry [31].

For example, as given in Ref. [32], the smaller the intermediate scale M_I is, the larger the Higgsino components become. In particular, for $M_I = 10^{16}$ GeV the LSP is mainly B-ino, the Higgs-neutralino-neutralino couplings are suppressed and therefore the cross sections are small. However for $M_I = 10^{11}$ GeV the Higgsino contributions become important and even dominant with the consequence of larger cross sections. It is also worth noting that, for any fixed value of M_I, the larger $\tan\beta$ is, the larger the Higgsino contributions become.

Also it is claimed [31] that in the specific context of minimal supergravity (focus point regime), a cosmologically stable mixed gaugino-Higgsino state emerges as an excellent, robust dark matter candidate. The claim relies on recent arguments, that all squark and slepton masses can be taken well above 1 TeV with no loss of naturalness on the basis of a seemingly reasonable objective definition of naturalness [40]. The mathematical basis of this result is the existence of focus points in renormalization group trajectories, which render the weak scale (i.e., the Higgs potential) largely insensitive to variations in unknown super-symmetry parameters.[1] While in these models the squark and slepton masses are unusually large, the electroweak gaugino and Higgsino particle masses are generically well below 1 TeV. The increase of the common soft scalar mass m_0 far beyond 1 TeV associated with decrease of $|\mu|$ below the gaugino masses, M_1, M_2, leads to significant mixing between Higgsino and gaugino states accompanied by Higgs boson diagrams enhancement. A net result is again large scalar cross sections.

The arguments presented above do not work in SUGRA [68]. The LSP as Higgsino-like is almost excluded by LEP constraints [27] even if the assumptions of universal soft supersymmetry breaking are relaxed, and Higgsino dark matter is certainly excluded if universality is assumed, as is the case here. In addition to the LEP constraints, this is because the value of μ is predicted as a function of $m_{1/2}$ and m_0, placing the LSP firmly in the B-ino-like region. The same considerations exclude an LSP with mixed Higgsino/gaugino content.

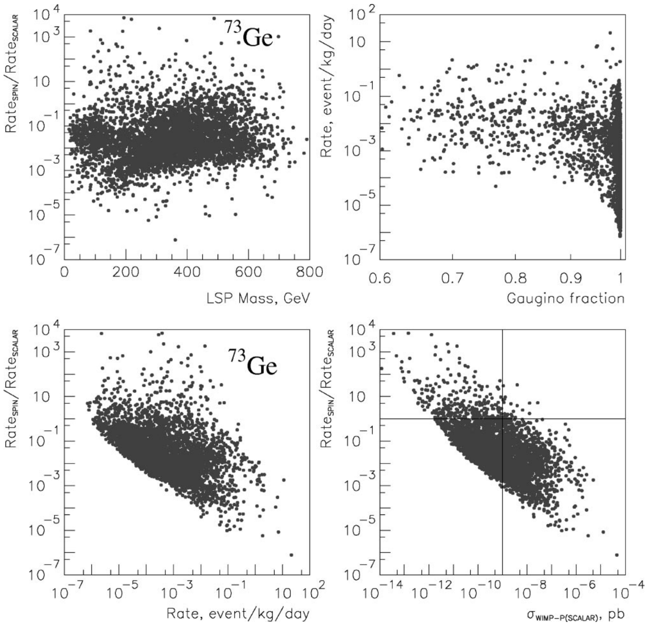

FIG. 6. Ratio of spin-dependent event rate to the spin-independent event rate in ^{73}Ge isotope as function of LSP mass (upper left), total (spin-dependent plus spin-independent) event rate (lower left), and scalar cross section of neutralino-proton interaction (lower right) obtained with $0.1 < \Omega_\chi h_0^2 < 0.3$. The vertical line gives the expected sensitivity of GENIUS (Ref. [83]). In the region above the horizontal line the spin contribution dominates. The total event rate versus gaugino fraction of LSP P also given (upper right).

In the SUGRA framework of Ref. [68] the elastic scattering cross sections, which are predicted for the LSP mass m_χ lie in a comparatively narrow band. This is essentially because the LSP is always mainly B-ino-like, so its couplings do not depend greatly on other MSSM parameters such as m_0. The principal causes of broadening are the uncertainties in the hadronic inputs and the possibilities of cancellations that may reduce the cross sections for some specific values of the unconstrained MSSM parameters [68].

Figure 5 shows that while the spin cross section displays almost full insensitivity to μ and M_A (Higgs bosons do not contribute) the scalar cross section possesses remarkable dependence on these parameters. The cross section rather quickly drops with growth of the CP-odd Higgs mass M_A and increases with $\tan\beta$ in accordance with results of Refs. [58], [24], [6], [35], [32], [21], and [22].

The different $\tan\beta$ and M_A dependence of spin-dependent and spin-independent cross section as well as general about-four-order-of-magnitude excess of spin-dependent cross section over spin-independent cross sections may be important for observations [87,88].

C. Role of the spin

To be more definite with the statement claimed above, in Fig. 6 we present a comparison of total spin-dependent versus total spin-independent event rates in ^{72}Ge (spin$=\frac{9}{2}$)—as

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[1] The background of the approach can be questioned (Ref. [85]) due to a possibility to shift the focus point for the Higgs mass parameter right to the GUT scale by means of the appropriate choice of the initial condition for the top Yukawa coupling (Ref. [86]). Anyway, from a phenomenological point of view the approach is interesting.

representative and one of the most promising isotopes for future construction of high-sensitivity detectors.

Figure 6 shows the weak dependence of the ratio on mass of the LSP with the mean value being approximately 0.01–0.1. There are very large and very small values for the ratio practically for any given mass of the LSP. The spin-independent (scalar) contribution obviously dominates in the domain of large expected rates in the Germanium detector ($R > 0.1$ events/day/kg) as was obtained before (see, for example, Ref. [58]). But as soon as the total rate drops down to $R < 0.01$ events/day/kg or, equivalently, the scalar neutralino-proton cross section becomes smaller than $10^{-9}-10^{-10}$ pb, the spin-dependent interaction may produce a rather non-negligible contribution to the total event rate. Moreover, if the scalar cross section decreases further ($\sigma < 10^{-12}$ pb), it becomes obvious that the spin contribution alone saturates the total rate and protects it (see lower bounds in Figs. 4 and 5) from decreasing below $R \approx 10^{-6}-10^{-7}$ events/day/kg [6].

This observation could be quite important for experiments actually looking for direct *detection* of dark matter, but not only for exclusion plots. Indeed, while scalar cross sections governed mostly by Higgs exchange can be rather small (when Higgs boson masses remain large enough, for example, in the next-to-minimal supersymmetric standard model [55]) the spin cross section cannot be arbitrarily small, because the mass of the Z boson, which gives the dominant contribution, is well defined, provided one ignores any possible fine-tuning cancellations [68].

Therefore if an experiment with sensitivity $10^{-5}-10^{-6}$ events/day/kg fails to detect a dark matter signal, an experiment with higher sensitivity (and nonzero spin target) will be able to detect dark matter particles only due to the spin neutralino-quark interaction.

IV. CONCLUSION

Recent measurements in modern cosmology have changed the expected fraction of the cold dark matter in the universe, new results for the nucleon structure were obtained, a new generation of high-sensitivity experimental detectors are under consideration. All these changes stimulated us to recalculate our previous analysis concerning detection of cold dark matter.

To this end we explored the MSSM parameter space at the weak scale where new accelerator and cosmological constraints are respected. We restrict the relic neutralino density to be in the range $0.1 \leqslant \Omega_\chi h^2 \leqslant 0.3$. We considered the variation of the spin-independent and spin-dependent WIMP-nucleon cross sections and of the expected event rate in ^{73}Ge, with parameters of the MSSM, uncertainties of the nucleon structure and other theoretical assumptions like universality and coannihilation.

The main results of the exploration can be summarized as follows.

(1) The results of our updated calculations fall in general agreement with calculations performed in MSUGRA as well as with other less restrictive approaches, which allowed larger variation of the cross sections and detection rates.

(2) The use of the updated parameters of the nucleon structure does not change significantly the general distribution of points over the scatter plots as compared with calculations with earlier nucleon parameters.

(3) In accordance with previous estimations we found that the coannihilation does not significantly change our main conclusions. We understand that our estimation of the coannihilation effect is somewhat indirect, but in the effMSSM approach there is no stringent correlation between parameters, which sometimes makes the coannihilation channels inexcitable.

(4) The new cosmological constraint on the relic neutralino density (due to flat and accelerating universe) which is numerically used in the form $0.1 < \Omega_\chi h_0^2 < 0.3$ in our approach does not significantly affect the resulting scatter plots for neutralino-nucleon elastic cross sections.

(5) To single out (mostly in the MSUGRA) theoretically a dominant contribution to the cross section or event rate one usually relies on the knowledge of the LSP composition. For example, as discussed through this paper, if the B-ino fraction is large, then the cross section is small. Nevertheless the situation is less transparent. As seen from Fig. 6 (upper right), the overwhelming majority of points (the region of highest point density) has $P \approx 1$, or very small Higgsino admixture and one should expect negligible event rate. Nevertheless this is not the case. There are a lot of points with sizable event rate for $P \approx 1$. Therefore qualitative estimations of the dominance of the given contribution on the basis, for example, of large gaugino fraction of the LSP ($P > 0.9$) can be quantitatively not always correct.

(6) We notice that for targets with spin-nonzero nuclei it would be the *spin-dependent interaction* that determines the lower bound for the direct detection rate when the cross section of the scalar interaction drops below about 10^{-12} pb. If this occurs the spin nuclear detectors would have notable advantage comparing with spinless detectors, or may become the only way to observe SUSY via direct dark matter detection.

Finally we would like to stress again the fact, clearly seen from Figs. 2 and 3, that to reliably investigate the SUSY parameter space and therefore to have a chance to beat accelerator experiments in searching for (or discovery of) the new physics (supersymmetry) one needs a GENIUS-like detector.

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