Combining Supersymmetric Dark Matter with Recent Accelerator Data

A. B. Lahanas

University of Athens, Physics Department, Nuclear and Particle Physics Section,
GR–15771 Athens, Greece

D. V. Nanopoulos

Department of Physics, Texas A & M University, College Station, TX 77843-4242,
USA, Astroparticle Physics Group, Houston Advanced Research Center (HARC),
Mitchell Campus, Woodlands, TX 77381, USA, and
Academy of Athens, Chair of Theoretical Physics, Division of Natural Sciences,
28 Panepistimiou Avenue, Athens 10679, Greece

V. C. Spanos

Institut für Hochenergiephysik der Österreichischen Akademie der Wissenschaften,
A–1050 Vienna, Austria

In the framework of the Constrained Minimal Supersymmetric Standard Model we discuss the impact of the recent experimental information, especially from the E821 Brookhaven experiment on $g_\mu - 2$ along with the light Higgs boson mass bound from LEP, in delineating regions of the parameters which are consistent with cosmological data. The effect of these to the Dark Matter direct searches is also discussed.

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*PRESENTED by V. C. Spanos
1 Introduction

Supersymmetry (SUSY) is a landmark in our efforts to construct a unified theory of all fundamental interactions observed in nature. At very high energies, close to the Planck scale ($M_P$) it is indispensable in constructing consistent string theories, and at low energies ($\sim 1$ TeV) it seems unavoidable if the gauge hierarchy problem is to be resolved. Such a resolution provides a measure of the supersymmetry breaking scale $M_{SUSY} \approx \mathcal{O}(1$ TeV$)$. There is indirect evidence for such a low-energy supersymmetry breaking scale, from the unification of the gauge couplings [1] and from lightness of the Higgs boson as determined from precise electroweak measurements, mainly at LEP [2]. Furthermore, such a low energy SUSY breaking scale is also favored cosmologically. As is well known, $R$-parity conserving SUSY models, contain in the sparticle spectrum a stable, neutral particle, identifiable with the lightest neutralino ($\tilde{\chi}$), referred to as the LSP [3]. It is important [3] that such a LSP with mass, as low-energy SUSY entails, in the $100$ GeV – $1$ TeV region, may indeed provide the right form and amount of the highly desirable astrophysically and cosmologically Dark Matter (DM). The latest data about Cosmic Microwave Background (CMB) radiation anisotropies [4] not only favour a flat ($k = 0$ or $\Omega_0 = 1$), inflationary Universe, but they also determine a matter density $\Omega_M h^2_0 \approx 0.15 \pm 0.05$. Taking into account the simultaneously determined baryon density $\Omega_B h^2_0 \approx 0.02$, and the rather tiny neutrino density, they result to

$$\Omega_{DM} h^2_0 = 0.13 \pm 0.05$$

(1)

If we assume that all DM is supersymmetric due to LSP, i.e. $\Omega_{DM} \equiv \Omega_{\tilde{\chi}}$, it is tempting to combine the bound of Eq.1 with other presently available constraints from particle physics, such as the lower bound on the mass of the Higgs bosons ($m_h \geq 113.5$ GeV) provided by LEP [3] and the recent results from the BNL E821 experiment [5] on the anomalous magnetic moment of the muon ($\delta \alpha_\mu = 43(16) \times 10^{-10}$). Although the situation regarding the $g_\mu - 2$ has not been definitely settled, supersymmetry emerges as a prominent candidate in explaining the discrepancy between the Standard Model predictions and experimental measurements, and in the sequel we concede that this deviation accounted for SUSY. We find that this combination of the experimental information from high energy physics and cosmology puts austere bounds on the parameter space of the Constrained Minimal Supersymmetric Standard Model (CMSSM), enabling us to investigate the potential of discovering SUSY, if it is based on CMSSM, at future colliders and direct DM search experiments.

2 Neutralino relic density

It has been argued that for large $\tan \beta$ the neutralino relic density ($\Omega_{\tilde{\chi}} h^2_0$) can be compatible with the recent cosmological data which favour small values for $\Omega_{\tilde{\chi}} h^2_0$. In this
The neutralino ($\tilde{\chi}$) pair annihilation through $s$-channel pseudo-scalar Higgs boson ($A$) exchange leads to an enhanced annihilation cross sections reducing significantly the relic density [7], while the heavy $CP$-even Higgs ($H$) exchange is $P$-wave suppressed and not that important. The importance of this mechanism, in conjunction with the recent cosmological data which favour small values of the DM relic density, has been stressed in [8,9]. The same mechanism has been also invoked [10] where it has been shown that it enlarges the cosmologically allowed regions. In fact cosmology does not put severe upper bounds on sparticle masses, and soft masses can be in the TeV region, pushing up the sparticle mass spectrum to regions that might escape detection in future planned accelerators. Such upper bounds are imposed, however, by the recent $g_{\mu} - 2$ E821 data [8,11] constraining the CMSSM in such a way that supersymmetry will be accessible to LHC or other planned $e^+e^-$ linear colliders if their center of mass energy is larger than about 1.2 TeV [12]. The bounds put by the $g_{\mu} - 2$ has been the subject of intense phenomenological study the last few months [12–17].

The $\tilde{\chi}\tilde{\chi}$ fusion to the pseudo-scalar Higgs boson, $A$, which subsequently decays to a $b\bar{b}$ or a $\tau\bar{\tau}$, becomes the dominant annihilation mechanism for large $\tan\beta$, when the pseudo-scalar mass $m_A$ approaches twice the neutralino mass, $m_A \simeq 2m_{\tilde{\chi}}$. In fact by increasing $\tan\beta$ the mass $m_A$ decreases, while the neutralino mass remains almost constant, if the other parameters are kept fixed. Thus $m_A$ is expected eventually to enter into the regime in which it is close to the pole value $m_A = 2m_{\tilde{\chi}}$, and the pseudo-scalar Higgs exchange dominates. It is interesting to point out that in a previous analysis of the direct DM searches [9], we had stressed that the contribution of the $CP$-even Higgs bosons exchange to the LSP-nucleon scattering cross sections increases with $\tan\beta$. Therefore in the large $\tan\beta$ regime one obtains the highest possible rates for the direct DM searches. Similar results are presented in Ref. [18]. In the framework of the CMSSM the chargino mass bound as well as the recent LEP Higgs mass bound [5] already exclude regions in which $\tilde{\chi}$ has a large Higgsino component, and thus in the regions of interest the $\tilde{\chi}$ is mainly a bino. A bino is characterized by a very small coupling to the pseudo-scalar Higgs $A$, however the largeness of $\tan\beta$ balances the smallness of its coupling giving a sizeable effect when $m_A \simeq 2m_{\tilde{\chi}}$, making the $s$-channel pseudo-scalar exchange mechanism important.

It becomes obvious from the previous discussion that an unambiguous and reliable determination of the $A$-mass, $m_A$, is necessary in order to to calculate the neutralino relic density especially in the large $\tan\beta$ region. The details of the procedure in calculating the spectrum of the CMSSM can be found elsewhere [15,16]. Here we shall only briefly discuss some points which turn out to be essential for a correct determination of $m_A$. In the constrained SUSY models, such as the CMSSM, $m_A$ is not a free parameter but is determined once $m_0, M_{1/2}, \mu$ as well as $\tan\beta$ and the sign of $\mu$ are given. $m_A$ depends sensitively on the Higgs mixing parameter, $m_3^2$, which is determined from minimizing the one-loop corrected effective potential. For large $\tan\beta$ the derivatives of the effective potential with respect the Higgs fields, which enter into the minimization conditions, are plagued by terms which are large and hence potentially dangerous, making the per-
turbative treatment untrustworthy. In order to minimize the large $\tan \beta$ corrections we had better calculate the effective potential using as reference scale the average stop scale $\bar{Q}_i \simeq \sqrt{m_{\tilde{t}1} m_{\tilde{t}2}}$ [19]. At this scale these terms are small and hence perturbatively valid. Also for the calculation of the pseudo-scalar Higgs boson mass all the one-loop corrections must be taken into account. In particular, the inclusion of those of the neutralinos and charginos yields a result for $m_A$ that is scale independent and approximates the pole mass to better than 2% [20]. A more significant correction, which drastically affects the pseudo-scalar mass arises from the gluino–sbottom and chargino–stop corrections to the bottom quark Yukawa coupling $h_b$ [21–24]. The proper resummation of these corrections is important for a correct determination of $h_b$ [25, 26], and accordingly of the $m_A$.

In calculating the LSP relic abundance, we solve the Boltzmann equation numerically using the machinery outlined in Ref. [8]. In this calculation the coannihilation effects, in regions where $\tilde{\tau}_R$ approaches in mass the LSP, which is a high purity Bino, are properly taken into account.

In what follows only the $\mu > 0$ case is considered. The $\mu < 0$ case is not favored by the recent $b \to s\gamma$ data, as well as by the observed discrepancy of the $g_\mu - 2$, if the latter is attributed to supersymmetry, and therefore we shall discard it.

In the panels shown in figure 1 we display our results by drawing the cosmologically allowed region $0.08 < \Omega h^2 < 0.18$ (dark green) in the $m_0, M_{1/2}$ plane for values of $\tan \beta$ equal to 50 and 55 respectively. Also drawn (light green) is the region $0.18 < \Omega h^2 < 0.30$. The default values for the masses of massive quarks are $m_t = 175$ GeV, $m_\tau = 1.777$ GeV and $m_b(m_b) = 4.25$ GeV. The remaining inputs are shown on the top of each panel. The solid red mark the region within which the supersymmetric contribution to the anomalous magnetic moment of the muon falls within the E821 range $\alpha_{\mu}^{SUSY} = (43.0 \pm 16.0) \times 10^{-10}$. The dashed red line marks the boundary of the region when the more relaxed lower bound $11 \times 10^{-10} \leq \alpha_{\mu}^{SUSY}$ is used, corresponding to the $2\sigma$ lower bound of the E821 range. Along the blue dashed-dotted lines the light CP-even Higgs mass takes values 113.5 GeV (left) and 117.0 GeV (right) respectively. The line on the left marks therefore the recent LEP bound on the Higgs mass [3]. Also shown is the chargino mass bound 104 GeV [4]. The shaded area (in red) at the bottom of each figure, labelled by TH, is theoretically disallowed since the light stau is lighter than the lightest of the neutralinos. From the displayed figures we observe that for values of $\tan \beta$ up to 50 the cosmological data put an upper bound on the parameter $m_0$. However, there is practically no such upper bound for the parameter $M_{1/2}$, due to the coannihilation effects [14] which allow for $M_{1/2}$ as large as 1700 GeV within the narrow coannihilation band lying above the theoretically disallowed region.

For $\tan \beta = 55$ a large region opens up within which the relic density is cosmologically allowed. This is due to the pair annihilation of the neutralinos through the pseudo-
Figure 1: Cosmologically allowed regions of the relic density for two different values of \(\tan \beta\) in the \((M_{1/2}, m_0)\) plane. The remaining inputs are shown in each figure. The mass of the top is taken 175 GeV. In the dark green shaded area \(0.08 < \Omega_{\tilde{\chi}^0} < 0.18\). In the light green shaded area \(0.18 < \Omega_{\tilde{\chi}^0} < 0.30\). The solid red lines mark the region within which the supersymmetric contribution to the anomalous magnetic moment of the muon is \(\alpha_{\mu}^{\text{SUSY}} = (43.0 \pm 16.0) \times 10^{-10}\). The dashed red line is the boundary of the region for which the lower bound is moved to \(11 \times 10^{-10} < \alpha_{\mu}^{\text{SUSY}}\). The dashed-dotted blue lines are the boundaries of the region \(113.5 \text{ GeV} \leq m_{Higgs} \leq 117.0 \text{ GeV}\).

scalar Higgs exchange in the s-channel. As explained before, for such high \(\tan \beta\) the ratio \(m_A/2m_{\tilde{\chi}}\) approaches unity and the pseudo-scalar exchange dominates yielding large cross sections and hence small neutralino relic densities. In this case the lower bound put by the \(g_\mu - 2\) data cuts the cosmologically allowed region which would otherwise allow for very large values of \(m_0, M_{1/2}\). The importance of these corridors has been stressed in the analysis of [11]. However, in the analysis presented here these show up at higher values of the parameter \(\tan \beta\). We should remark at this point that in our analysis we use the value of \(\alpha_{\text{strong}}(M_Z)\) as input and relax unification of the \(\alpha_3\) gauge coupling with the others. In the constrained scenario it is almost impossible to reconcile gauge coupling unification with a value for \(\alpha_{\text{strong}}(M_Z)\) consistent with experiment due to the low energy threshold effects. This change affects drastically the values of other parameters and especially that of the Higgsino \((\mu)\) and Higgs \((m_2^2)\) mixing parameters that in turn affect the pseudo-scalar Higgs boson mass which plays a dominant role.

For the \(\tan \beta = 55\) case, close the highest possible value, and considering the conservative lower bound on the muon’s anomalous magnetic moment \(\alpha_{\mu}^{\text{SUSY}} \geq 11 \times 10^{-10}\) and values of \(\Omega_{\tilde{\chi}^0} h_0^2\) in the range \(0.13 \pm 0.05\), we find that the point with the highest
Table 1: Upper bounds, in GeV, on the masses of the lightest of the neutralinos, charginos, staus, stops and Higgs bosons for various values of $\tan \beta$ if the the E821 bounds are imposed. The values within brackets represent the same situation when the weaker bounds $11 \times 10^{-10} < \alpha_{\mu}^{SUSY} < 75 \times 10^{-10}$ are used (see main text).

| $\tan \beta$ | $\tilde{\chi}^0$ | $\tilde{\chi}^+$ | $\tilde{\tau}$ | $t$ | $h$ |
|-----------|-----------------|-----------------|----------------|-----|-----|
| 10        | 108 (174)       | 184 (306)       | 132 (197)      | 376 (686) | 115 (116) |
| 20        | 154 (255)       | 268 (457)       | 175 (274)      | 603 (990) | 116 (118) |
| 30        | 191 (310)       | 338 (560)       | 212 (312)      | 740 (1200) | 117 (118) |
| 40        | 201 (340)       | 357 (617)       | 274 (353)      | 785 (1314) | 117 (119) |
| 50        | 208 (357)       | 371 (646)       | 440 (427)      | 822 (1357) | 117 (119) |
| 55        | 146 (311)       | 260 (563)       | 424 (676)      | 606 (1237) | 115 (117) |

value of $m_0$ is (in GeV) at $(m_0, M_{1/2}) = (950, 300)$ and that with the highest value of $M_{1/2}$ is at $(m_0, M_{1/2}) = (600, 750)$. The latter marks the lower end of the line segment of the boundary $\alpha_{\mu}^{SUSY} = 11 \times 10^{-10}$ which amputates the cosmologically allowed stripe. For the case displayed in the bottom right panel of the figure the upper mass limits put on the LSP, and the lightest of the charginos, stops and the staus are $m_{\tilde{\chi}} < 287, m_{\tilde{\chi}^+} < 539, m_{\tilde{\tau}} < 1161, m_{\tilde{t}} < 621$ (in GeV). Allowing for $A_0 \neq 0$ values, the upper bounds put on $m_0, M_{1/2}$ increase a little and so do the aforementioned bounds on the sparticle masses. Thus it appears that the prospects of discovering CMSSM at a $e^+e^-$ collider with center of mass energy $\sqrt{s} = 800$ GeV, such as TESLA, are not guaranteed. However in the allowed regions the next to the lightest neutralino, $\tilde{\chi}'$, has a mass very close to the lightest of the charginos and hence the process $e^+e^- \rightarrow \tilde{\chi}' \tilde{\chi}'$, with $\tilde{\chi}'$ subsequently decaying to $\tilde{\chi} + l^+l^-$ or $\tilde{\chi} + 2$ jets, is kinematically allowed for such large $\tan \beta$, provided the energy is increased to at least $\sqrt{s} = 900$ GeV. It should be noted however that this channel proceeds via the $t$-channel exchange of a selectron is suppressed due to the heaviness of the exchanged sfermion.

The situation changes, however, when the strict E821 limits are imposed $\alpha_{\mu}^{SUSY} = (43.0 \pm 16.0) \times 10^{-10}$. For instance in the $\tan \beta = 55$ case displayed in figure there is no cosmologically allowed region which obeys this bound. For the other cases, $\tan \beta < 50$, the maximum allowed $M_{1/2}$ is about 475 GeV, occurring at $m_0 \simeq 375$ GeV, and the maximum $m_0$ is 600 GeV when $M_{1/2} \simeq 300$ GeV. The upper limits on the masses of the sparticles quoted previously reduce to $m_{\tilde{\chi}} < 192, m_{\tilde{\chi}^+} < 353, m_{\tilde{\tau}} < 775, m_{\tilde{t}} < 436$ all in GeV. However, these values refer to the limiting case $A_0 = 0$. Scanning the parameter space allowing also for $A_0 \neq 0$ we obtain the upper limits displayed in the table. In this the unbracketed values correspond to the E821 limits on the $g_{\mu} - 2$. For completeness we also display, within brackets, the bounds obtained when the weaker lower bound $\alpha_{\mu}^{SUSY} \geq 11 \times 10^{-10}$ is imposed. We see that even at TESLA with center of mass energy
Figure 2: In the \((M_{1/2}, m_0)\) plane, we display all points compatible with \(\alpha_{\mu}^{SUSY} = (43.0 \pm 16.0) \times 10^{-10} (+)\) and \(11 \times 10^{-10} < \alpha_{\mu}^{SUSY} < 75 \times 10^{-10} (\diamond)\). All the points are consistent with the cosmological bound \(\Omega_\chi h^2_0 = 0.13 \pm 0.05\) and they are grouped in regions, separated by dashed contours each of which is the boundary of \(\tan \beta\) with the value shown beneath. In the top region, designated by \(\tan \beta = 55\), the parameter \(\tan \beta\) takes values between 50 and 55.

\(\sqrt{s} = 800\) GeV, the prospects of discovering CMSSM are guaranteed in the \(e^+e^- \to \tilde{\chi}^+\tilde{\chi}^-\) if the E821 bounds are imposed.

In the figure we display in the \((M_{1/2}, m_0)\) plane the points which are consistent both with the muon’s anomalous magnetic moment bounds mentioned before and cosmology, as well as with the other accelerators data. Each of the points is taken from a sample of 45,000 random points in the part of the parameter space defined by \(m_0 < 1.5 \text{ TeV}, M_{1/2} < 1.5 \text{ TeV}, |A_0| < 1 \text{ TeV}\) and \(2 < \tan \beta < 55\). All the points are consistent with the cosmological bound \(\Omega_\chi h^2_0 = 0.13 \pm 0.05\). The plus points (colored in blue) are those consistent with the E821 bound \(27 \times 10^{-10} < \alpha_{\mu}^{SUSY} < 59 \times 10^{-10}\), while the diamonds (colored in green) are consistent with the more relaxed bound \(11 \times 10^{-10} < \alpha_{\mu}^{SUSY} < 75 \times 10^{-10}\). The points are grouped in regions, separated by dashed contours, each of which constitutes the boundary of \(\tan \beta\) with the value shown beneath. In the region designated as \(\tan \beta = 55\) all points have \(55 > \tan \beta > 50\). It is seen clearly that only a few points in the \(\tan \beta > 50\) case can survive the E821 bound. For \(\tan \beta < 50\) the parameter \(M_{1/2}\) cannot be larger than about 500 GeV, attaining its maximum value at \(m_0 \approx 400\) GeV, and the maximum \(m_0\) is 725 GeV occurring at \(M_{1/2} \simeq 275\) GeV. The upper limits put on \(m_0, M_{1/2}\) result to the sparticle mass bounds displayed in the table.
Figure 3: Scatter plot of the scalar neutralino-nucleon cross section versus $m_{\tilde{\chi}}$, from a random sample of 45,000 points. On the top of the figure the CDMS excluded region and the DAMA sensitivity region are illustrated. Pluses (+) (in blue colour) are points within the E821 experimental region $\alpha_{\mu}^{SUSY} = (43.0 \pm 16.0) \times 10^{-10}$ and also cosmologically acceptable $\Omega_{\tilde{\chi}} h_0^2 = 0.13 \pm 0.05$. Diamonds (○) (in green colour) are also cosmologically acceptable points, but with $\alpha_{\mu}^{SUSY}$ within the region $11 \times 10^{-10} < \alpha_{\mu}^{SUSY} < 75 \times 10^{-10}$. Crosses (×) (in red colour) represent the rest of the points of our random sample. Here the Higgs boson mass bound $m_h > 113.5$ GeV has been properly taken into account.

3 Direct Dark Matter searches

We shall discuss now the impact of the $g_{\mu} - 2$ measurements and of the Higgs mass bound $m_h > 113.5$ GeV on the direct DM searches. We are using the same random sample as in figure 2 in order to calculate the spin-independent, $\tilde{\chi}$-nucleon cross section ($\sigma_{\text{scalar}}$). In figure 3 we plot the scalar $\tilde{\chi}$-nucleon cross section as function of the LSP mass, $m_{\tilde{\chi}}$. On the top of the figure the shaded region (in cyan colour) is excluded by the CDMS experiment [28]. The DAMA sensitivity region (coloured in yellow) is also plotted [29]. Pluses (+) (in blue colour) represent points which are both compatible with the E821 data $\alpha_{\mu}^{SUSY} = (43.0 \pm 16.0) \times 10^{-10}$ and the cosmological bounds for the neutralino relic density $\Omega_{\tilde{\chi}} h_0^2 = 0.13 \pm 0.05$. Diamonds (○) (in green colour) are points which are cosmologically acceptable with respect to the aforesaid bounds, but the bound to the $\alpha_{\mu}^{SUSY}$ has been relaxed to its 2σ region, namely $11 < \alpha_{\mu}^{SUSY} \times 10^{10} < 75$. The crosses (×) (in red colour) represent the rest of the points of our random sample. Here the Higgs boson mass bound, $m_h > 113.5$ GeV has been properly taken into account. From this figure it is seen that
Figure 4: Scatter plot of the scalar neutralino-nucleon cross section versus $m_{\tilde{\chi}}$, from a random sample of Fig. 3. Diamonds (⋄) (in green colour) are cosmologically acceptable points, without putting an restriction from the $\alpha^\text{SUSY}_\mu$. Crosses (×) (in red colour) represent points with unacceptable $\Omega_{\tilde{\chi}} h^2_0$.

the points which are compatible both the $g_\mu - 2$ E821 and the cosmological data (crosses) yield cross sections of the order of $10^{-8} - 10^{-9}$ pb and the maximum value of the $m_{\tilde{\chi}}$ is about 200 GeV. If one allows the 2σ region of the $g_\mu - 2$ bound the lower bound of preferred cross sections is $10^{-10}$ pb and correspondingly the upper bound of $m_{\tilde{\chi}}$ is drifted up to 350 GeV.

Comparing figure 3 and 4 one can realise how $g_\mu - 2$ data constrain $m_{\tilde{\chi}}$ mass to be up to 200 GeV or 350 GeV for the 1σ or 2σ case respectively. In figure 3 we don’t impose the constraints stemming from $g_\mu - 2$ data, therefore due to the coannihilation processes the cosmologically acceptable LSP mass can be heavier than 500 GeV. What is also important to be noticed about the direct searches of DM is that imposing the $g_\mu - 2$ data the lowest allowed $\tilde{\chi}$-nucleon cross section increased by about 1 order of magnitude, from $10^{-11}$ pb to $10^{-10}$ pb. Similar results are presented in Ref. [30]. This fact is very encouraging for the future DM direct detection experiments, with sensitivities extending up to $10^{-9}$ pb [31].

4 Conclusions

Concluding, we combined recent high energy physics experimental information, like the anomalous magnetic moment of the muon measured at E821 Brookhaven experiment and
the light Higgs boson mass bound from LEP, with the cosmological data for DM. By doing so we studied the imposed constraints on the parameter space of the CMSSM and hence we assessed the potential of discovering SUSY, if it is based on CMSSM, at future colliders and DM direct searches experiments. The bounds put on the sparticle spectrum can guarantee that in LHC but also in a $e^+e^-$ linear collider with center of mass energy $\sqrt{s} = 800$ GeV, such as TESLA, CMSSM can be discovered. The guarantee for a linear collider with this energy is lost in a charged sparticle final state channel, if the lower bound on the value of $g_\mu - 2$ is lowered to its $\approx 2\sigma$ value, but not for the LHC. In this case only by increasing the center of mass energy to be $\approx 1.2$ TeV, a $e^+e^-$ linear collider can find CMSSM in $\tilde{\tau}\tilde{\tau}^*$ or $\tilde{\chi}^\pm\tilde{\chi}^-$ channels. The impact of the E821 experiment’s result along with the bound on Higgs mass is also significant for the direct DM searches. We found that the maximum value of the spin-independent $\tilde{\chi}$-nucleon cross section attained is of the order of $10^{-8}$ pb. Moreover this cross section can not be lower than $10^{-10}$ pb, which is very promising for the forthcoming direct DM experiments.

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