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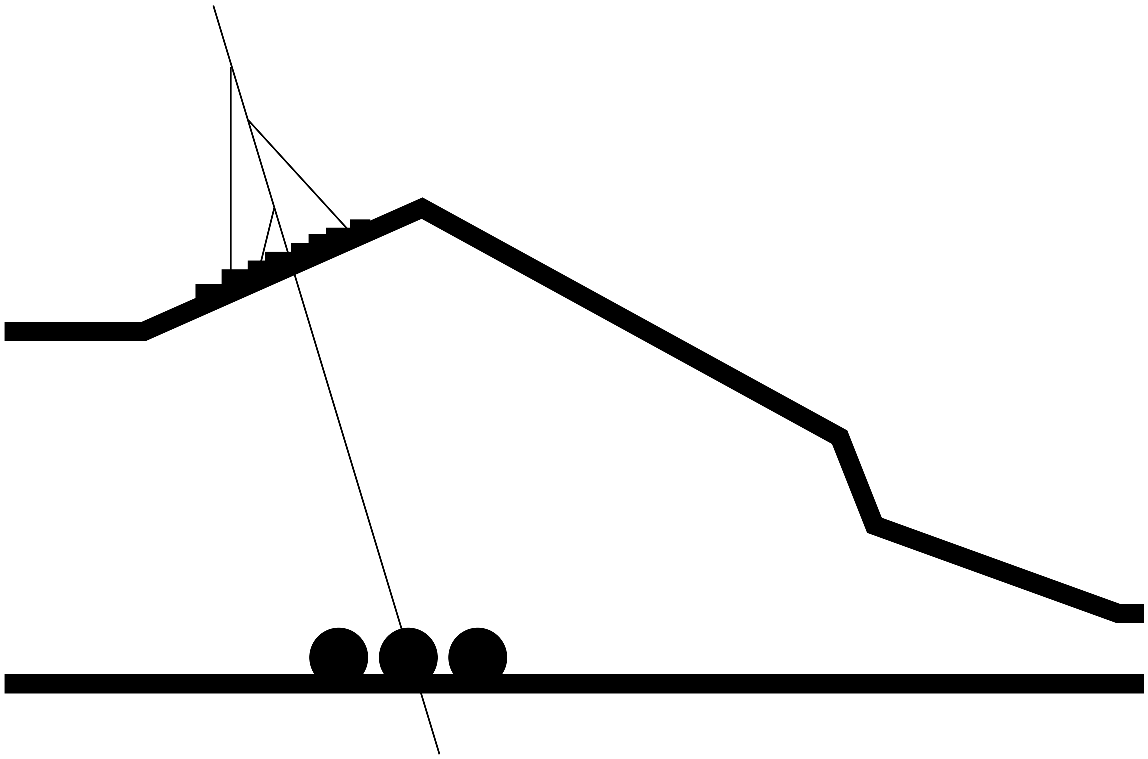

Investigating the DAMA annual modulation data in a mixed coupling framework

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Abstract

In this paper the data, collected by the $\simeq$ 100 kg NaI(Tl) DAMA set-up deep underground in the Gran Sasso National Laboratory of I.N.F.N. during four annual cycles (57986 $kg \cdot day$ statistics), are analysed in terms of WIMP annual modulation signature considering a candidate with mixed coupling to ordinary matter.

1 Introduction

WIMPs (Weakly Interacting Massive Particles) are expected to be a primary component of the dark matter halo in the Milky Way. The DAMA experiment is searching for WIMPs by investigating the so-called annual modulation signature [1, 2, 3, 4, 5, 6, 7] by means of the $\simeq$ 100 kg NaI(Tl) set-up [8] running deep underground in the Gran Sasso National Laboratory of the I.N.F.N.. The data collected during four annual cycles show, in a model independent way, an annual modulation of the low energy rate with peculiar features [6, 7]. As regards possible model dependent analysis, a purely spin-independent coupled candidate, which equally couples to proton and neutron, has been considered so far [2, 3, 4, 5, 6]. In this paper, instead, a candidate having not only a spin-independent, but also a spin-dependent coupling different from zero is investigated. This is possible for the neutralino in supersymmetric theories since both the squark and the Higgs bosons exchanges give contribution to the coherent (SI) part of the cross section, while the squark and the Z^0 exchanges give contribution to the spin dependent (SD) one. However, the results of the analyses presented here and in ref. [6] are not restricted to the neutralino case.

2 Theoretical framework

The studied process is the WIMP-nucleus elastic scattering and the measured quantity in underground set-ups is the recoil energy.

The differential energy distribution of the recoil nuclei can be calculated [9, 10] by means of the differential cross section of the WIMP-nucleus elastic processes

$$\frac{d\sigma}{dE_R}(v,E_R) = \left(\frac{d\sigma}{dE_R}\right)_{SI} + \left(\frac{d\sigma}{dE_R}\right)_{SD} =$$
$$= \frac{2G_F^2 m_N}{\pi v^2}\{[Zg_p + (A-Z)g_n]^2 F_{SI}^2(E_R) + 8\Lambda^2 J(J+1)F_{SD}^2(E_R)\} \qquad (1)$$

where: G_F is the Fermi coupling constant; m_N is the nucleus mass; v is the WIMP velocity in the laboratory frame; $E_R = m_{WN}^2 v^2(1-cos\theta^*)/m_N$ (with m_{WN} WIMP-nucleus reduced mass and θ^* scattering angle in the WIMP-nucleus c.m. frame) is the recoil energy; Z is the nuclear charge and A is the atomic number; $g_{p,n}$ are the effective WIMP-nucleon couplings for SI interactions; $\Lambda^2 J(J+1)$ is a spin factor. Moreover, $F_{SI}^2(E_R) = 3\frac{j_1(q\cdot r_0)}{q\cdot r_0}e^{-\frac{1}{2}s^2q^2}$ is the SI form factor according to ref. [11]; $q^2 = 2m_N E_R$ is the squared three-momentum transfer, $j_1(q\cdot r_0)$ is the spherical Bessel function of index 1, $s \simeq 1fm$ is the thickness parameter of the nuclear surface, $r_0 = \sqrt{r^2 - 5s^2}$ and $r = 1.2A^{\frac{1}{3}}fm$. As regards the SD form factor $F_{SD}^2(E_R)$ an universal formulation is not possible; in fact, in this case the internal degrees of the WIMP particle model (e.g. supersymmetry in case of neutralino) cannot be completely separated from the nuclear ones. It is worth to notice that this adds significant uncertainty in the final results. In the calculations presented here we have adopted the SD form factors of ref. [12] estimated by considering the Nijmengen nucleon-nucleon potential. It can be demonstrated that $\Lambda = \frac{a_p<S_p>+a_n<S_n>}{J}$ with J nuclear spin, $a_{p,n}$ effective WIMP-nucleon couplings for SD interaction and $< S_{p,n} >$ mean value of the nucleon spin in the nucleus. Therefore, the differential cross section and, consequently, the expected energy distribution depends on the WIMP mass and on four unknown parameters of the theory: $g_{p,n}$ and $a_{p,n}$.

The total cross section for WIMP-nucleus elastic scattering can be obtained by integrating equation (1) over E_R up to $E_{R,max} = \frac{2m_{WN}^2 v^2}{m_N}$:

$$\sigma(v) = \int_0^{E_{R,max}} \frac{d\sigma}{dE_R}(v, E_R) dE_R = \frac{4}{\pi} G_F^2 m_{WN}^2 \{ [Zg_p + (A-Z)g_n]^2 G_{SI}(v) + \\ +8\frac{J+1}{J} [a_p < S_p > +a_n < S_n >]^2 G_{SD}(v) \}. \tag{2}$$

Here $G_{SI}(v) = \frac{1}{E_{R,max}} \int_0^{E_{R,max}} F_{SI}^2(E_R) dE_R$; $G_{SD}(v)$ can be derived straightforward.

The standard point-like cross section can be evaluated in the limit $v \to 0$ (that is in the limit $G_{SI}(v)$ and $G_{SD}(v) \to 1$). Knowing that $< S_{p,n} >= J = 1/2$ for single nucleon, the SI and SD point-like cross sections on proton and on neutron can be written as:

$$\sigma_{p,n}^{SI} = \frac{4}{\pi} G_F^2 m_{W(p,n)}^2 g_{p,n}^2 \\ \sigma_{p,n}^{SD} = \frac{32}{\pi}\frac{3}{4} G_F^2 m_{W(p,n)}^2 a_{p,n}^2, \tag{3}$$

where $m_{Wp} \simeq m_{Wn}$ are the WIMP-nucleon reduced masses.

As far as regards the SI case, the first term within squared brackets in eq. (2) can be re-written in the form

$$[Zg_p + (A-Z)g_n]^2 = \left(\frac{g_p + g_n}{2}\right)^2 \left[1 - \frac{g_p - g_n}{g_p + g_n}\left(1 - \frac{2Z}{A}\right)\right]^2 A^2 = g^2 \cdot A^2. \tag{4}$$

Since $\frac{Z}{A}$ is nearly constant for the nuclei typically used in direct searches for Dark Matter particles, the coupling g can be assumed – in a first approximation – as independent on the used target nucleus. Therefore, it is convenient to introduce a generalized SI WIMP-nucleon cross section $\sigma_{SI} = \frac{4}{\pi} G_F^2 m_{Wp}^2 g^2$.

Let us now introduce the useful notations

$$\bar{a} = \sqrt{a_p^2 + a_n^2}, \\ tg\theta = \frac{a_n}{a_p}, \\ \sigma_{SD} = \frac{32}{\pi}\frac{3}{4} G_F^2 m_{Wp}^2 \bar{a}^2, \tag{5}$$

where σ_{SD} is a suitable SD WIMP-nucleon cross section. The SD cross sections on proton and neutron can be, then, written as:

$$\sigma_p^{SD} = \sigma_{SD} \cdot cos^2\theta \\ \sigma_n^{SD} = \sigma_{SD} \cdot sin^2\theta. \tag{6}$$

In conclusion, equation (1) can be re-written in terms of σ_{SI}, σ_{SD} and θ as:

$$\frac{d\sigma}{dE_R}(v, E_R) = \frac{m_N}{2m_{Wp}^2 v^2} \cdot \Sigma(E_R) \tag{7}$$

with

$$\Sigma(E_R) = \{A^2\sigma_{SI}F_{SI}^2(E_R) + \frac{4}{3}\frac{(J+1)}{J}\sigma_{SD}\left[< S_p > \cos\theta + < S_n > \sin\theta\right]^2 F_{SD}^2(E_R)\}. \tag{8}$$

The mixing angle θ is defined in the $[0, \pi)$ interval; in particular, θ values in the second sector account for a_p and a_n with different signs. As it can be noted from its definition [10], $F_{SD}^2(E_R)$ depends on a_p and a_n only through their ratio and, consequently, depends on θ, but it does not depend on $\bar{a}$.

Finally, setting the local WIMP density, ρ_W, and the WIMP mass, m_W, one can write the energy distribution of the recoil rate (R) in the form

$$\frac{dR}{dE_R} = N_T \frac{\rho_W}{m_W} \int_{v_{min}(E_R)}^{v_{max}} \frac{d\sigma}{dE_R}(v, E_R) v f(v) dv = N_T \frac{\rho_W \cdot m_N}{2m_W \cdot m_{Wp}^2} \Sigma(E_R) I(E_R), \tag{9}$$

where: N_T is the number of target nuclei and $I(E_R) = \int_{v_{min}(E_R)}^{v_{max}} dv \frac{f(v)}{v}$ with $f(v)$ WIMP velocity distribution in the Earth frame [10]; $v_{min} = \sqrt{\frac{m_N \cdot E_R}{2m_{WN}^2}}$ is the minimal WIMP velocity providing E_R recoil energy; v_{max} is the maximal WIMP velocity in the halo evaluated in the Earth frame. The extension of formula (9) e.g. to multiple nuclei detectors can be easily derived.

3 Data analysis and results

According to sect. 2, we extend here the data analysis of ref. [6, 7] to the case of a WIMP having also a SD component different from zero. In addition, we account for the uncertainties on some of the used astrophysical, nuclear and particle physics parameters. Following the procedure already described in ref. [2, 3, 4, 5, 6], we build the y log-likelihood function which depends on the experimental data and on the theoretical expectations in the given model framework[1]. Then, y is minimized searching for parameters' regions allowed at given confidence level. Obviously, different model frameworks vary the expectations and, therefore, the values of the four free parameters: $\xi\sigma_{SI}$, $\xi\sigma_{SD}$, θ and m_W (where ξ is the WIMP local density in 0.3 GeVcm^{-3} unit), corresponding to the y minimum as discussed e.g. in ref. [5] for v_0 in the purely spin independent case [2]. For simplicity the effect of

[1]A model framework is identified not only by the general astrophysical, nuclear and particle physics assumptions, but also by the set of the used parameters values (such as WIMP local velocity, v_0, form factors parameters, etc.).

[2]For example, in ref. [6] $m_W = (72^{+18}_{-15})$ GeV and $\xi\sigma_{SI} = (5.7 \pm 1.1) \cdot 10^{-6}$ pb correspond to the position of y minimum when $\mathrm{v}_0 = 170$ km/s, while $m_W = (43^{+12}_{-9})$ GeV and $\xi\sigma_{SI} = (5.4 \pm 1.0) \cdot 10^{-6}$ pb are found when $\mathrm{v}_0 = 220$ km/s.

the inclusion of known uncertainties on the parameters is generally expressed by making a superimposition of all the allowed regions [5, 6].

As regards the WIMP velocity distribution the same assumptions as in ref. [6] have been adopted here; in particular, v_0 can range between 170 km/s and 270 km/s [5, 6]. Moreover, to clearly point out the possible increase of sensitivity associated with the uncertainties on some other parameters we have varied: i) the measured ^{23}Na and ^{127}I quenching factors [9] from their mean values up to +2 times the errors [3]; ii) the nuclear radius, r, and the nuclear surface thickness parameter, s, in the SI form factor [11] from the values quoted in sect. 2 down to -20%; iii) the b parameter in the considered SD form factor from the given value [12] down to -20%. In addition, as in ref. [6] masses above 30 GeV and the physical constraint of the limit on the recoil rate measured in ref. [9] have been taken into account.

When the SD component is different from zero, a very large number of possible configurations are available; here for simplicity we show the results obtained only for 4 particular couplings, which correspond to the following values of the mixing angle θ: i) $\theta = 0$ (a_n =0 and $a_p \neq 0$ or $|a_p| >> |a_n|$); ii) $\theta = \pi/4$ ($a_p = a_n$); iii) $\theta = \pi/2$ ($a_n \neq 0$ and $a_p = 0$ or $|a_n| >> |a_p|$); iv) $\theta = 2.435$ rad ($\frac{a_n}{a_p}$ = -0.85, pure Z^0 coupling). The case $a_p = -a_n$ is nearly similar to the case iv).

In fig. 1 the regions, allowed by the data of ref. [6, 7], at 3 σ C.L. (colored areas) in the ($\xi\sigma_{SI}$, $\xi\sigma_{SD}$) plane are shown for given θ values and for some WIMP masses. Note that the calculation has been performed by minimizing the y function with the respect to the $\xi\sigma_{SI}$, $\xi\sigma_{SD}$ and m_W parameters for each given θ value; fig. 1 shows slices for given masses. In the same fig. 1 the dashed lines marked when $m_W = 50$ GeV represent the limit curves calculated for $v_0 = 220$ km/s from the data of the DAMA liquid Xenon experiment [13]; regions above these dashed lines could be considered excluded at 90% C.L. Since the ^{129}Xe nucleus – on the contrary of the ^{23}Na and of the ^{127}I – has the neutron as odd nucleon, a reduction of the allowed region is obtained only for the case $\theta \simeq \pi/2$; similar results are obtained for all the other WIMP masses. However, we further remark that the comparison of results achieved by different experiments – even more when different target nuclei and/or different techniques have been used – is affected by intrinsic uncertainties.

We take this occasion to comment that no quantitative comparison can be directly performed between the results obtained in direct and indirect searches because it strongly depends on assumptions and on the considered model framework. In addition, very large uncertainties are present in the evaluation of the results of the indirect searches themselves. In particular, a comparison would always require the calculation and the consideration of all the possible WIMP configurations in the given particle model (e.g. for neutralino: in the allowed parameters space), since it does not exist a biunivocal correspondence between the observables in the two kinds of experiments: WIMP-nucleus elastic scattering cross section (direct detection case) and flux of muons from neutrinos (indirect detection case)[4].

[3]Note that the usual notation to omit the uncertainty when equal to one unity on the less significant digit was used in ref. [9].

[4]In fact, the counting rate in direct search is proportional to the $\xi\sigma_{SD}$ and $\xi\sigma_{SI}$, while the muon flux is connected not only to $\xi\sigma_{SD}$ and $\xi\sigma_{SI}$, but also to the WIMP annihilation cross section. In principle,

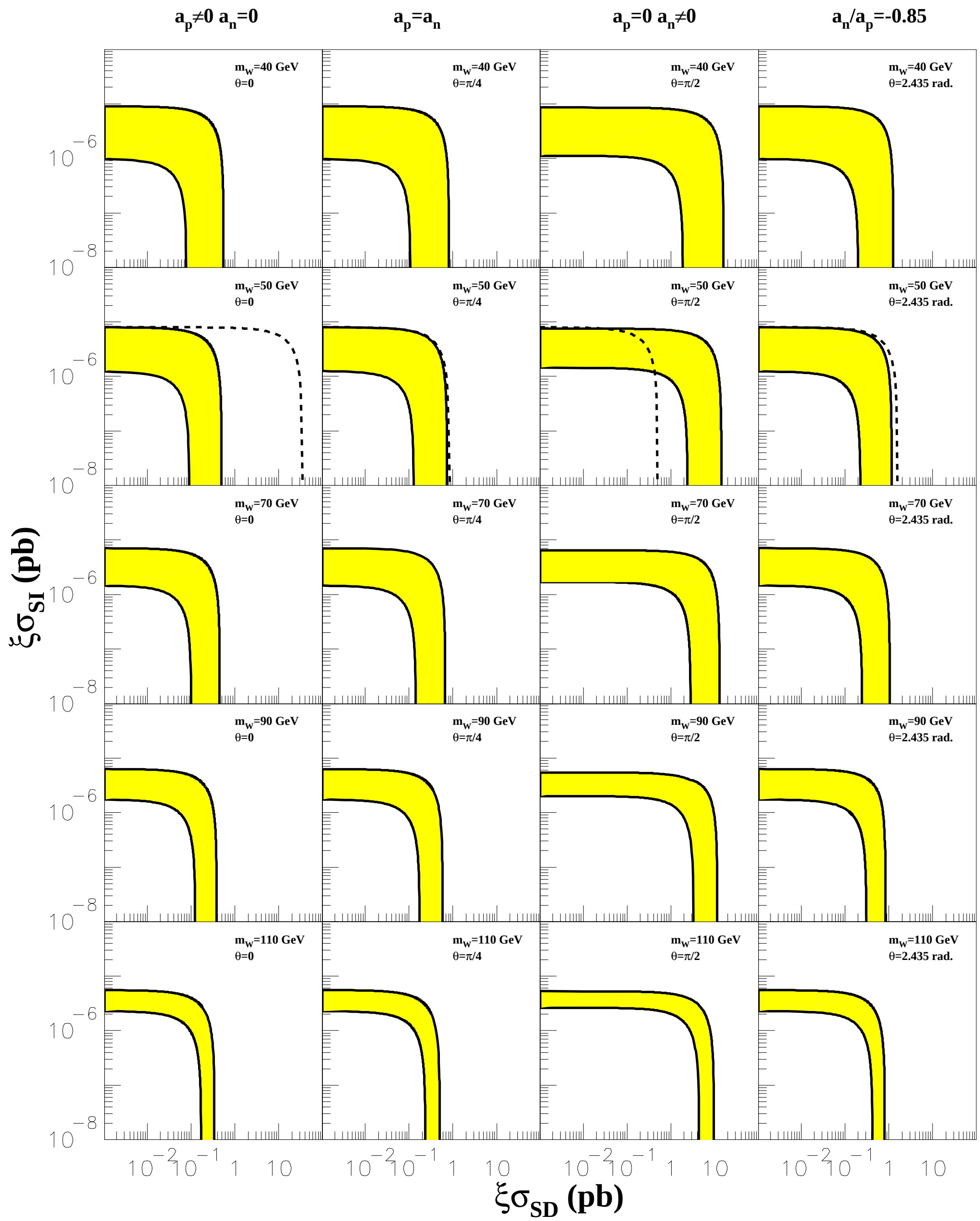

Figure 1: Regions allowed at 3 σ C.L. for WIMP configurations corresponding to: i) $\theta = 0$; ii) $\theta = \pi/4$ iii) $\theta = \pi/2$; iv) $\theta = 2.435$ rad. These regions have been calculated taking into account the uncertainties on v_0, on the quenching factors and on the SI and SD nuclear form factors parameters as mentioned in the text. The dashed lines given for the case $m_W = 50$ GeV represent the limit curves calculated for $v_0 = 220$ km/s from the data of the DAMA liquid Xenon experiment [13]. See text.

As already pointed out in ref. [6], when the SD contribution goes to zero (y axis), an interval not compatible with zero is obtained for $\xi\sigma_{SI}$ (see fig. 1). Similarly, when the SI contribution goes to zero (x axis), finite values for the SD cross section are obtained. Large regions are allowed for mixed configurations also for $\xi\sigma_{SI} \lesssim 10^{-5}$ pb and $\xi\sigma_{SD} \lesssim 1$ pb; only in the particular case of $\theta = \frac{\pi}{2}$ (that is $a_p = 0$ and $a_n \neq 0$) $\xi\sigma_{SD}$ can increase up to $\simeq 10$ pb, since the ^{23}Na and ^{127}I nuclei have the proton as odd nucleon.

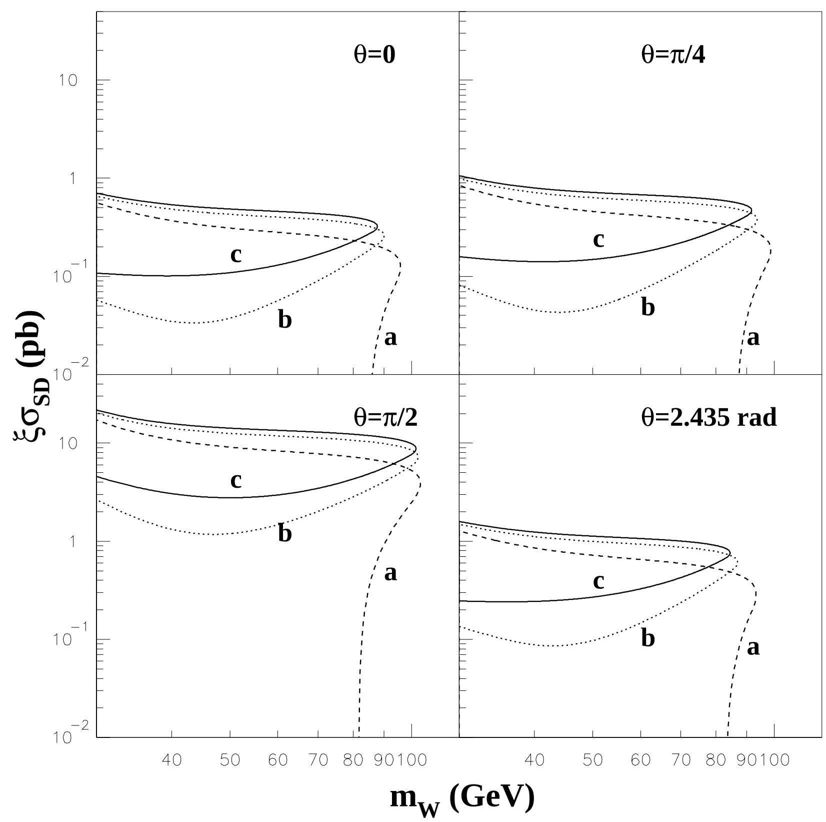

Figure 2: 3 σ C.L. allowed region for a mixed coupled candidate: a) $\xi\sigma_{SI} = 3 \cdot 10^{-6}$ pb; b) $\xi\sigma_{SI} = 1 \cdot 10^{-6}$ pb; c) $\xi\sigma_{SI} = 5 \cdot 10^{-8}$ pb. For simplicity, the calculations have been performed here by fixing $v_0 = 220$ km/s and the quenching factors and the parameters of the SI and SD nuclear form factors at their mean values. See text.

At this point, we give in fig. 2 a simple verification of the following items: i) finite values can be allowed for $\xi\sigma_{SD}$ even when $\xi\sigma_{SI} \simeq 3 \cdot 10^{-6}$ pb as in the region allowed in the pure SI scenario of ref. [6] (contour a); ii) regions not compatible with zero in the $\xi\sigma_{SD}$ versus m$_W$ plane are allowed even when $\xi\sigma_{SI}$ values much lower than those allowed

the three cross sections can be correlated, but only when a specific model is adopted and by non directly proportional relations.

in the pure SI scenario of ref. [6] are considered (contours b and c). For simplicity, in this case the calculations have been performed by using $v_0 = 220$ km/s and the quenching factors and the parameters of the SI and SD nuclear form factors at their mean values. The general trend for other $\xi\sigma_{SI}$ and θ values can be easily inferred. Fig. 2 clearly shows the existence of allowed mixed configurations up to masses of $\simeq$ 85 GeV in this model framework; moreover, it has been calculated that the inclusion of known uncertainties in the parameters as well as of possible dark halo rotation will further extend the allowed regions up to $\simeq$ 140 GeV mass (1 σ C.L.).

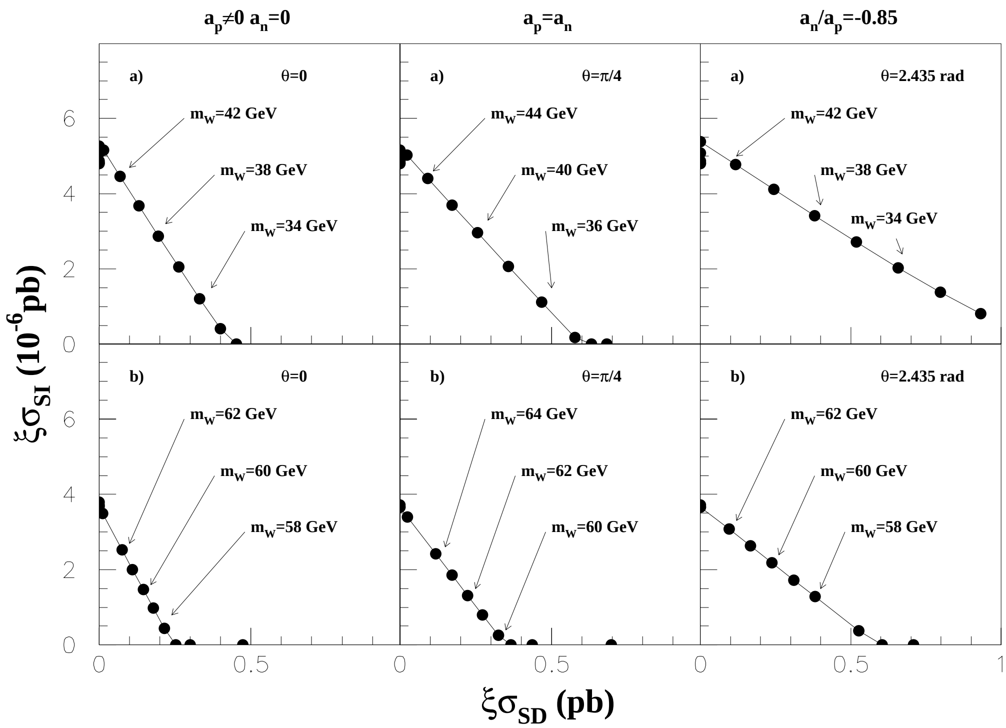

Figure 3: Minimum of the y function in the plane ($\xi\sigma_{SI}$, $\xi\sigma_{SD}$) when fixing m_W and θ at the quoted values. Two cases are represented: a) when fixing $v_0 = 220$ km/s and the quenching factors and the SI and SD nuclear form factors parameters at their mean values; b) when considering $v_0 = 170$ km/s and taking into account the uncertainties on the quenching factors and on the SI and SD nuclear form factors parameters as mentioned in the text. We do not report here the cases with $\theta = \pi/2$ and $v_0 = 270$ km/s because they do not provide any minimum having both $\xi\sigma_{SI}$ and $\xi\sigma_{SD}$ different from zero. See text.

Finally, to further point out the existence of minimum with both SI and SD couplings we have minimized – at variance of the previous approach – the y function with the respect to $\xi\sigma_{SI}$ and $\xi\sigma_{SD}$ for fixed m_W and θ values. The obtained minima in the ($\xi\sigma_{SI}$, $\xi\sigma_{SD}$) plane for some m_W and θ pairs are shown in fig. 3 where two particular different model frameworks (see figure caption) have been considered as examples. The associated C.L. ranges roughly between $\simeq 3$ and $\simeq 4\ \sigma$.

4 Conclusion

In conclusion the analysis discussed in this paper has shown that the DAMA data of the four annual cycles, analysed in terms of WIMP annual modulation signature, can also be compatible with a mixed scenario where both $\xi\sigma_{SI}$ and $\xi\sigma_{SD}$ are different from zero. The pure SD and pure SI cases have been implicitly given.

Further investigations are in progress. Moreover, the data of the 5^{th} annual cycle are already at hand, while – after a full upgrading of the electronics and of the data acquisition system – the set-up is running to collect the data of a 6^{th} annual cycle. Finally, the exposed mass will be increased in near future up to $\simeq 250$ kg to achieve higher experimental sensitivity.

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