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Abstract

The EDELWEISS collaboration is searching for WIMP dark matter using natural Ge cryogenic detectors. The whole data set of the first phase of the experiment contains a fiducial exposure of 4.8 kg.day on ^{73}Ge, the naturally present (7.8%), high-spin Ge isotope. The sensitivity of the experiment to the spin-dependent WIMP-nucleon interactions is evaluated using the model-independent framework proposed by Tovey *et al.* [1]. It is shown that the EDELWEISS sensitivity for the WIMP-neutron coupling is competitive when compared with results of other spin-sensitive WIMP dark matter experiments. The current experimental limits lie however two orders of magnitude higher than the most optimistic SUSY models.

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Introduction

In direct searches for the Galactic cold dark matter in the form of Weakly Interacting Massive Particles (WIMPs), the experimental signature is the observation of nuclear recoils induced by WIMP scattering off nuclei in a terrestrial detector. If the WIMP is assumed to be the neutralino, the lightest supersymmetric particle, two types of couplings with matter have to be considered: scalar (spin-independent) and axial-vector (spin-dependent) [2].

For sufficiently heavy nuclei, the spin-independent interaction is expected to give the dominant contribution [2], due to the coherent enhancement approximately proportional to A^2, the square of the mass number. Experimental results are thus most often given as exclusion curves for the spin-independent WIMP-nucleon diffusion cross-section (see for instance [3, 4, 5, 6] and references therein).

For spin-dependent couplings, this enhancement is not present due to cancellation effects between paired nucleons within the nucleus. For example, in the single-particle shell model [7] the nuclear spin comes from the unpaired proton or neutron. Even with high-spin nuclei the sensitivity of direct detection experiments on the WIMP-nucleon cross-section is orders of magnitude lower than for the spin-independent case (see Refs. [8] and [9] for recent reviews). For axial-vector coupling, indirect detection experiments searching for high-energy neutrinos produced by WIMP annihilations in the Sun provide much higher sensitivity than direct detection ones [9]: the capture rate of WIMPs in the Sun core is governed by the scattering rate on protons (low mass, high specific spin).

For spin-dependent interactions, comparisons between WIMP-nucleon cross-section limits given by various experiments is problematic: the comparison of results obtained using targets with either an unpaired neutron or an unpaired proton relies on the assumptions concerning the ratio of the WIMP-neutron to the WIMP-proton cross-sections. This is particularly obvious in the framework of the simple single-particle model. Although it is expected that this ratio should be $\mathcal{O}(1)$ in minimal supersymmetric models [10], Tovey *et al.* [1] have proposed a method to extract limits on the spin-dependent interaction in the more general case where there is no constraint on this ratio. For a given WIMP mass, exclusion curves are obtained in the plane of the effective WIMP-neutron and WIMP-proton couplings. The same type of exclusion curves has been computed very recently [9] using a more rigorous formalism. Evaluations of current results of spin-dependent WIMP searches have been given using both techniques [8, 9].

The EDELWEISS collaboration searches for WIMP dark matter using natural Ge cryogenic detectors [11, 4, 12]. The whole data set of the first

phase of the experiment contains a fiducial exposure of 4.8 kg.day on ^{73}Ge, the naturally present (7.8%), high-spin Ge isotope. The aim of this paper is to compare, for the spin-dependent interaction and using the model-independent framework of Ref. [1], EDELWEISS limits with those of the most representative high spin target experiments. It will be shown that, despite the very low ^{73}Ge content of natural Ge, the EDELWEISS sensitivity for the WIMP-neutron coupling is competitive.

Experimental data

The EDELWEISS experiment is set in the Laboratoire Souterrain de Modane (LSM) in the Fréjus tunnel connecting France and Italy. Detectors used by the experiment are 320 g Ge phonon and ionization cryogenic detectors placed in a dilution cryostat at a regulated temperature of 17 mK. The experimental setup is described elsewhere [4, 11].

The main characteristic of the EDELWEISS detectors is the simultaneous measurement of the phonon and the ionization signals. The ionization signal is measured by Al electrodes sputtered on each side of the crystal and the phonon signal by a NTD heat sensor glued onto one electrode. The measurement of both signals provides a very good event-by-event discrimination between nuclear and electronic recoils, typically more than 99.9% above 15 keV. More details on the detectors and their performances can be found in Ref. [12]. Following the first published data [4, 11], a new set of three detectors was operated in the cryostat, all of them having either a Ge or Si amorphous layer for better charge collection.

Between 2000 and 2003, four physics runs have been performed with different detectors, trigger conditions and efficiencies. All these runs have been re-analysed with an uniform analysis threshold of 15 keV and using the efficiency versus recoil energy function of each run. A detailed presentation of the experimental data and a thorough discussion of their analysis is given in Ref. [13]. Only the most relevant features are summarized hereafter.

In 2000 and 2002, 13.6 kg.day (after the fiducial volume cut) were accumulated with two detectors [4, 11]. Two events compatible with nuclear recoils have been recorded in 2000 above the new analysis threshold of 15 keV, and two in 2002. In 2003 two other runs have been performed with new detectors but with two different triggers. In the first run, the trigger was the fast ionization signal (run 2003i, fiducial exposure 25.7 kg.day). In the second run, the trigger was the phonon signal (run 2003p, fiducial exposure 22.7 kg.day). This latter trigger condition improves the efficiency at low energy: the baseline resolution is better on the phonon channel and the full recoil energy deposition E_R is recorded, instead of the quenched frac-

tion $E_I = Q.E_R$ in the ionization channel. In the runs 2003i and 2003p, the numbers of observed events compatible with nuclear recoils above the analysis threshold are 17 and 19, respectively. This apparent increase of the raw nuclear recoil rates in the new 2003 runs is explained by the significant increase in efficiency at low energy in the new data set (see Ref. [13] for details). Only three events lie in the energy interval from 30 to 100 keV, a result consistent with the previous data sets [4, 11]. The entire set of data for the EDELWEISS-I experiment consists therefore of a fiducial exposure of 62.0 kg.day with a total of 40 events compatible with nuclear recoils above 15 keV. Conservatively considering all these events as WIMP interactions, a 90 % C.L. upper limit on the WIMP-nucleon cross-section as a function of the WIMP mass is derived with the Optimum Interval Method [14].

For the spin-dependent coupling, one must consider the exposure on ^{73}Ge (4.8 kg.day) and a specific form factor. Here, the form factor of Dimitrov *et al.* [15] is used, with the usual approximation that the isoscalar, isovector and interference form factors are identical in order to make the form factor independent of the WIMP-nucleon couplings [1]. The resulting uncertainty on the cross-section is within $\pm 15\%$ up to a WIMP mass of 1 TeV/c^2. Other calculations of spin-dependent scattering on ^{73}Ge are briefly presented hereafter. The resulting 90 % C.L. limits on the WIMP-nucleus cross-section σ_A for WIMP masses between 20 GeV/c^2 and 1 TeV/c^2 are listed in table 1. These limits are conservative as they neglect any contribution from the spin-independent coupling.

Model-independent Exclusion Limits

For spin-dependent interactions the WIMP-nucleus cross-section σ_A at zero momentum transfer can be approximated by the expression (see for instance [2]):

$$\sigma_A = \frac{32}{\pi} G_F^2 \mu_A^2 (a_p \langle S_p \rangle + a_n \langle S_n \rangle)^2 \frac{J+1}{J}, \qquad (1)$$

where G_F is the Fermi coupling constant, μ_A the WIMP-nucleus reduced mass, $a_{p,n}$ the effective WIMP-proton(neutron) couplings, $\langle S_{p,n} \rangle$ the expectation values of the proton(neutron) spins within the nucleus and J the total nuclear spin. WIMP-nucleon cross-sections $\sigma_{p,n}^{lim(A)}$ in the limit $a_{n,p} = 0$ respectively, are defined as [1]:

$$\sigma_{p,n}^{lim(A)} = \frac{3}{4} \frac{J}{J+1} \frac{\mu_{p,n}^2}{\mu_A^2} \frac{\sigma_A}{\langle S_{p,n} \rangle^2}, \qquad (2)$$

where $\mu_{p,n}$ is the WIMP-proton(neutron) reduced mass and σ_A the WIMP-nucleus cross-section limit (at 90% CL) deduced from the experiment.

3

It is shown in [1] that the *allowed* values of a_p and a_n for a particular WIMP mass obey the inequality:

$$\left(\frac{a_p}{\sqrt{\sigma_p^{lim(A)}}} \pm \frac{a_n}{\sqrt{\sigma_n^{lim(A)}}} \right)^2 \leq \frac{\pi}{24 G_F^2 \mu_p^2}. \tag{3}$$

The sign between parentheses is that of $\frac{\langle S_p \rangle}{\langle S_n \rangle}$. Equation (3) defines two parallel straight lines in the (a_n, a_p) plane, the slope of which is $\frac{-\langle S_n \rangle}{\langle S_p \rangle}$. The allowed values of a_p and a_n are within the band defined by these two lines (while in [9] an extremely elongated ellipse is found). For experiments with two active nuclei with different $\frac{\langle S_p \rangle}{\langle S_n \rangle}$ ratios the combination of the two bands gives rise to a closed elliptical contour.

Nuclear spin structure calculations have been recently reviewed by Bednyakov and Šimkovic [16]: for ^{73}Ge the two most comprehensive spin structure analyses are from Ressel et al. [17] and from Dimitrov et al. [15] (see table 2). The corresponding form factors are very similar. In these calculations the neutron spin $\langle S_n \rangle$ varies by $\sim 20\%$ depending on the nuclear stucture model. The value of the ratio $\frac{\langle S_n \rangle}{\langle S_p \rangle}$ is model dependent, but is always much greater than unity. Thus the odd-N, even-Z nucleus ^{73}Ge nucleus is mainly sensitive to a_n only, and in that sense is complementary to other detectors made out of odd-Z material such as ^{23}Na, ^{127}I, ^{7}Li, ^{19}F or ^{27}Al.

Table 1 gives the values of the spin-dependent WIMP-nucleon cross-sections deduced from our experimental σ_A values using eq. (2) and the $\langle S_{p,n} \rangle$ taken from [15].

Plots of the WIMP-nucleon cross-sections $\sigma_{p,n}^{lim(A)}$ versus the WIMP mass are shown in Fig. 1 and 2. Figures 3 and 4 show the regions in the (a_n, a_p) plane allowed by EDELWEISS, using eq. (3) and the experimental values of table 1, for two illustrative WIMP masses $M_\chi = 50$ and 500 GeV/c^2. A comparison is made with other experiments representative of various techniques: NaI scintillators (NAIAD experiment [18]), fluored bolometers (Kamioka LiF [19]), sapphire bolometers (CRESST-I [20]), freon droplets (SIMPLE [21], PICASSO [22]) and the other natural Ge cryogenic experiment (CDMS-II [5]). A more exhaustive comparison can be found in the review of Giuliani [8]. All experiments use the same dark matter halo model to extract σ_A. Form factors, values of $\langle S_{p,n} \rangle$ specific to each nucleus and WIMP-nucleon cross-sections $\sigma_{p,n}^{lim(A)}$ are given in [18], [19], [21] and [22] .

For the CRESST-I (sapphire) experiment, relevant cross-sections can be deduced from the published data using $\langle S_{p,n} \rangle$ values from [23] for ^{27}Al (neglecting the ^{16}O spin sensitivity). For the CDMS experiment limits on spin-dependent nucleon cross-sections are derived in Ref. [9], including the cou-

pling dependency in the form factor rather than taking the isoscalar, isovector and interference terms to be identical. For consistency, $\sigma_{p,n}^{lim(A)}$ are recomputed from the CDMS data (no event in 52.6 kg.day raw exposure in Ge detectors over 10 to 100 keV recoil energy) using the experimental efficiency quoted in Ref. [9], form factor and $\langle S_{p,n} \rangle$ values from Ref. [15]. The differences in the a_n allowed regions defined by the two calculations are insignificant in the limit $a_p = 0$.

The DAMA/Xe experiment [24] makes use of a ^{129}Xe target, an other example of odd-N, even-Z nucleus, as ^{73}Ge. The $\sigma_p^{lim(A)}$ can be calculated from the reported $\sigma_n^{lim(A)}$ cross-section. However this result deserves a special comment. The value of the quenching factor for liquid Xenon is taken in [24] as $Q = 0.44$, i.e. more than a factor of 2 greater than other measured values [25, 26]. Adopting these more recent and precise values shifts the nuclear recoil energy threshold of the DAMA/Xe experiment from 30 keV to at least 60 keV. For $M_\chi = 50$ GeV/c^2 the WIMP event rate at the threshold is then divided by a factor of 15 and even more if the fast decrease of the form factor with recoil energy is taken into account. The cross-section limit is underestimated by the same factor. This considerable uncertainty on the actual recoil energy scale does not allow any reliable comparison and the published results of DAMA/Xe are not shown on the figure.

Fig. 3 and 4 show that cryogenic natural Ge experiments such as EDELWEISS and CDMS give the most stringent limits on a_n, at roughly the same level as the a_p limits given by odd-Z detectors. The low ^{73}Ge content of natural Ge is balanced by the very low level of nuclear recoil backgrounds achieved in the cryogenic detectors and by the high neutron nuclear spin value of ^{73}Ge. The allowed region of minimal extension in the (a_n, a_p) plane is given by the combination of experiments with respectively high $\langle S_n \rangle$ and high $\langle S_p \rangle$ nuclei. The best limit on a_n is presently set by the CDMS experiment [5]. As shown in Ref. [9] the limit on a_p set by the neutrino observatories Super-K [27] and Baksan [28] is more than a factor of 10 better than current direct detection results.

Conclusions

For a WIMP mass between 50 and 500 Gev/c^2, current limits given by direct detection experiments are $|a_{n,p}| <$ few units, or equivalently $\sigma_{p,n}^{SD} <$ few pb. The maximal values given by SUSY models lie two orders of magnitude lower (see for instance [10, 29, 30]). Only a new generation of experiments designed to gain two orders of magnitude in sensitivity will be able to reach the SUSY predictions for $\sigma_{p,n}^{SD}$. EDELWEISS-II is one of these forthcoming

experiments [31].

In the experimentally constrained versions of Supersymmetry, the neutralino is not a pure gaugino and one expects $|a_p|/|a_n| \sim \mathcal{O}(1)$ (for example see Ref. [10]). To go beyond these constraints and fix limits on a_p by the direct detection technique, high sensitivity experiments, using efficient background rejection techniques and high $\langle S_p \rangle$ nuclear targets are needed. A multi nuclear target experiment, with powerful background discrimination capability and complementary proton vs neutron spin values would constitute an interesting new approach. Setting decisive constraints on the SUSY parameters for spin-dependent WIMP-nucleon interactions remains a considerable experimental challenge for direct detection experiments.

Acknowledgments

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$M_\chi(\text{GeV/c}^2)$	$\sigma_A(\text{pb})$	$\sigma_p^{lim(A)}(\text{pb})$	$\sigma_n^{lim(A)}(\text{pb})$
20	769.	1759.	11.1
30	304.	395.	2.50
40	201.	181.	1.14
50	192.	133.	0.845
60	199.	114.	0.721
80	238.	103.	0.651
100	291.	104.	0.661
200	648.	149.	0.945
400	1482.	262.	1.66
500	1917.	319.	2.02
600	2358.	377.	2.39
800	3247.	494.	3.13
1000	4140.	611.	3.87

Table 1: *Values of the WIMP-nucleus cross-section limit σ_A (at 90% CL) deduced from the experiment. The corresponding $\sigma_{p,n}^{lim(A)}$ cross-sections (eq. (2)) are calculated using $\langle S_{p,n} \rangle$ values from [15].*

	$\langle S_p \rangle$	$\langle S_n \rangle$
Ressel *et al.* [17] unquenched values	0.011	0.468
Ressel *et al.* [17] quenched values	0.009	0.372
Dimitrov *et al.* [15]	0.030	0.378

Table 2: *Spin values for ^{73}Ge ($J = 9/2$). See [16] for a critical evaluation of the various calculations.*
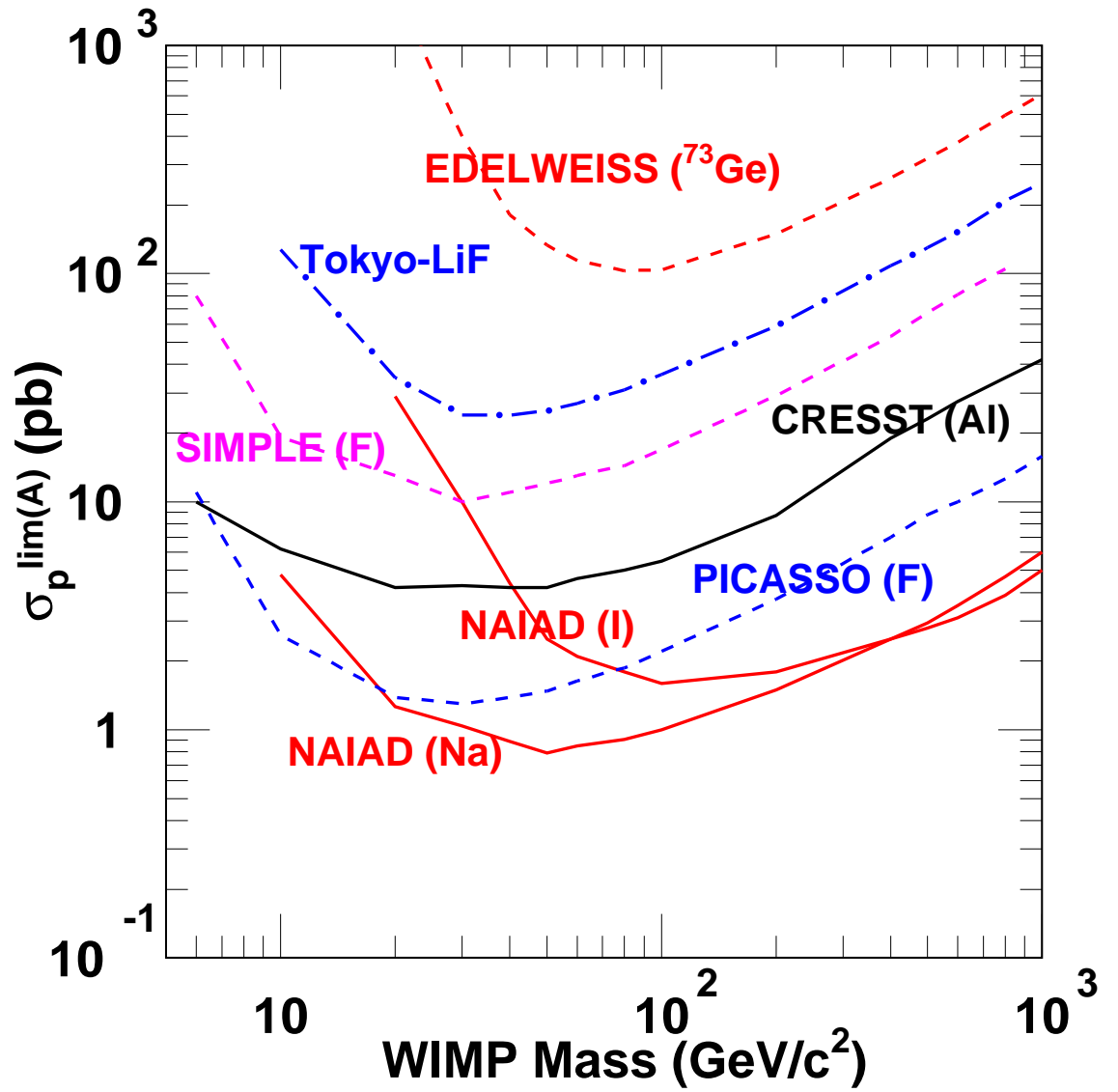
Figure 1: $\sigma_p^{lim(A)}$ versus WIMP mass for the various experiments quoted in the text (90% CL limits).
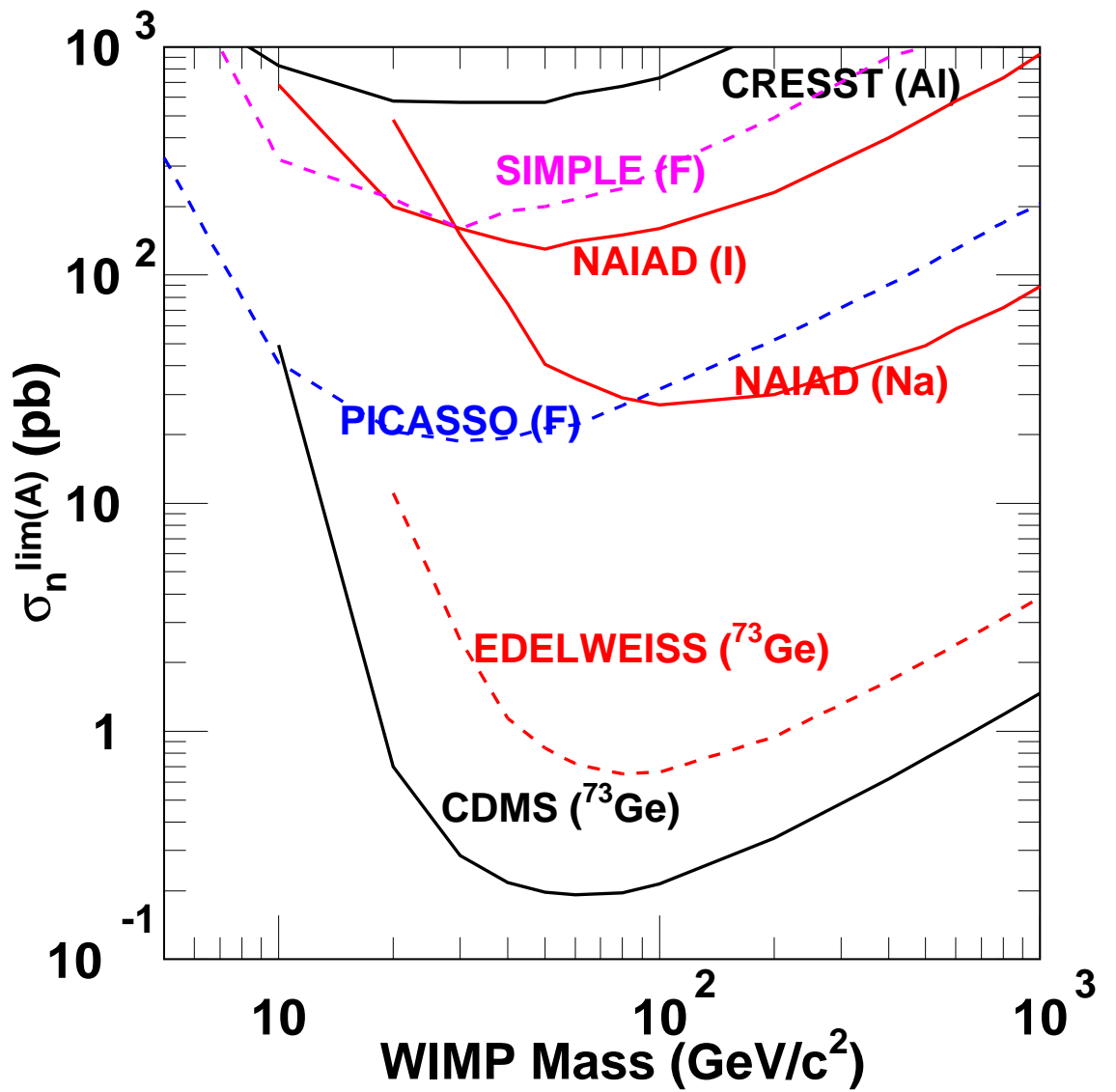
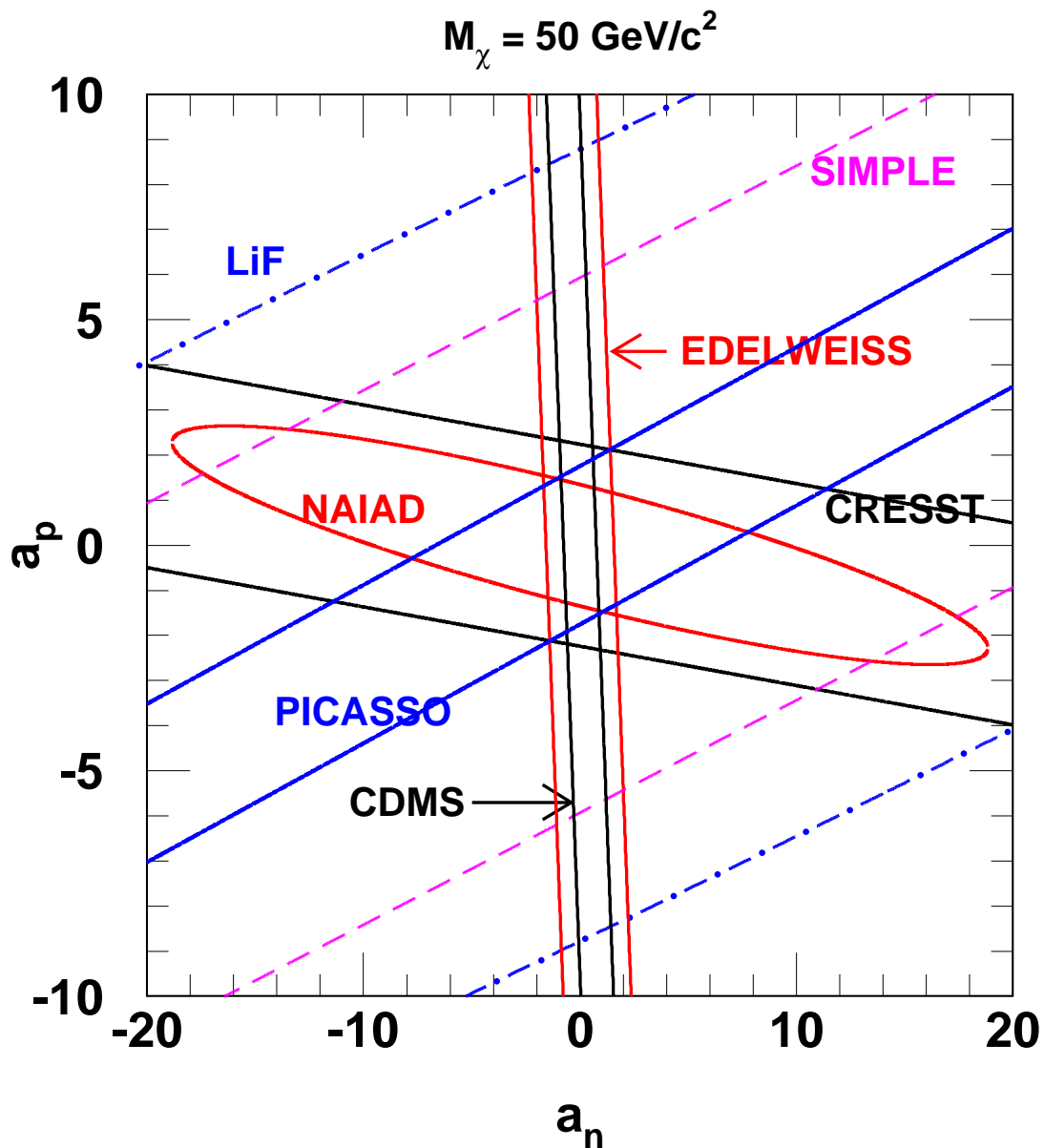Figure 2: The same as Fig. 1 for $\sigma_n^{lim(A)}$.

Figure 3: Allowed regions in the (a_n, a_p) plane for $M_\chi = 50$ GeV/c^2, for the experiments quoted in the text. The region allowed by each experiment is within the corresponding parallel straight lines or ellipse.
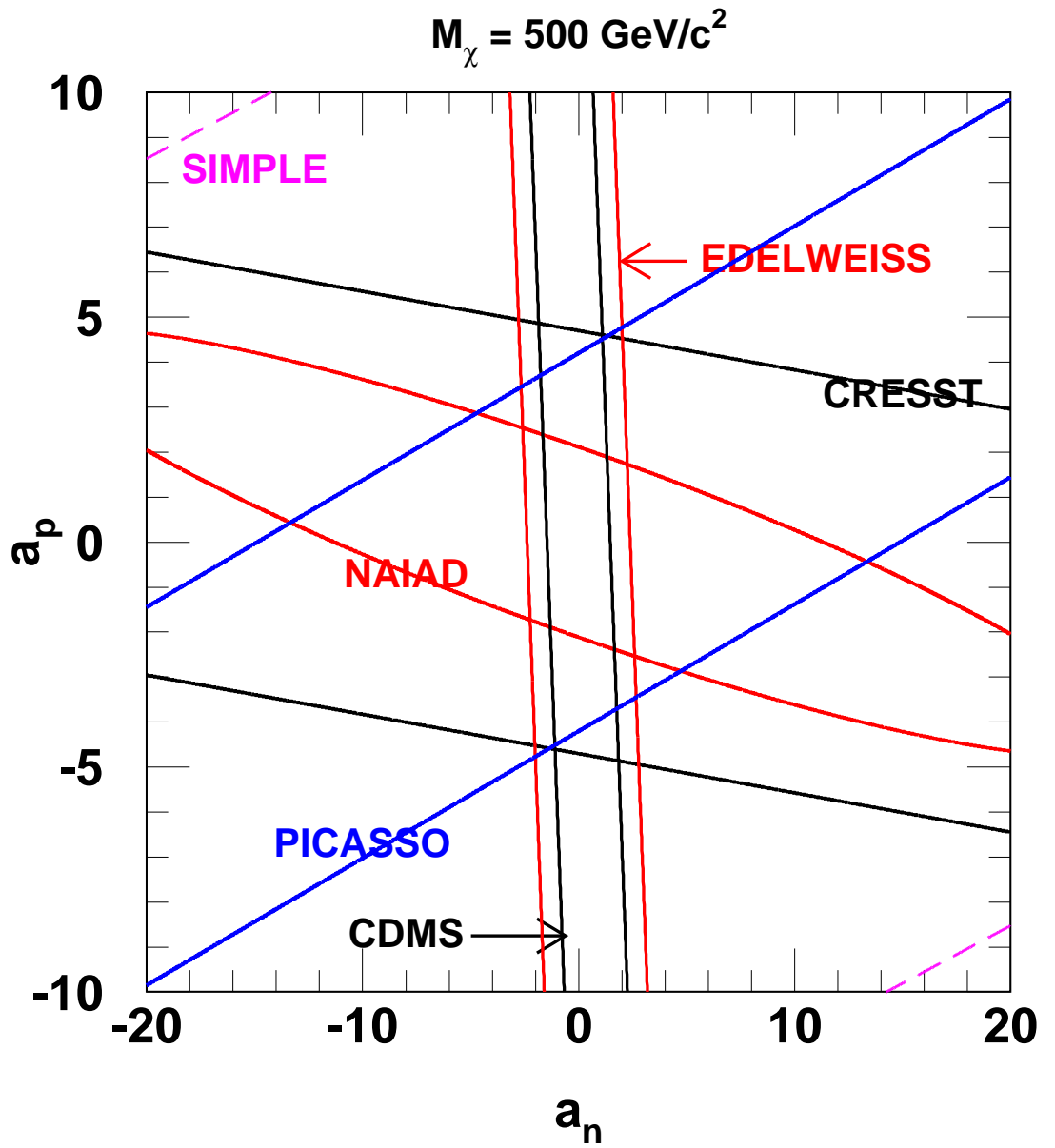
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Figure 4: The same as Fig. 3 for $M_\chi = 500$ GeV/c^2.