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Majorana Dark Matter Cross Sections with Nucleons at High Energies

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Non-relativistic dark matter scattering with nucleons is constrained by direct detection experiments. We use the XENON constraints on the spin-independent and spin-dependent cross section for dark matter scattering with nucleons to constrain a hypothetical Majorana fermionic dark matter particle's couplings to the Higgs boson and Z boson. In the procedure we illustrate the change in the dark matter nucleon cross section as one goes from non-relativistic, coherent scattering to relativistic, incoherent scattering. While the Z invisible decay width excludes directly couplings of dark matter to ordinary matter, by introducing a light Z' portal to the dark sector, a relatively large dark matter nucleon cross section can be preserved even with accelerator experiment constraints for dark matter with a mass of ~ 10 GeV.

I. INTRODUCTION

The particle nature of dark matter (DM) is one of the biggest open questions at the intersection of particle physics and cosmology. There are many candidates for DM in a variety of models [1–4]. Cosmology and large scale structure constrain the DM density in the universe, relative to the critical density, to be $\Omega_{DM}h^2 = 0.112 \pm 0.006$ [4], in terms of the Hubble constant h in units of 100km/(s-Mpc), for cold, non-baryonic DM. This has implications for the annihilation cross section and mass of the DM [4–6]. Indirect constraints on the annihilation cross section and the DM cross section with nucleons come from, for example, the absence of neutrino signals from the solar core and Earth's core in neutrino telescopes [7–9]. Finally, there are constraints on the DM–nucleon cross section from direct detection experiments [10–20].

The direct detection limits on the DM–nucleon cross section at low energy come primarily from experiments which measure the nuclear recoil in elastic scattering of DM with nuclei [10]. The DM masses typically covered by these experiments [11–20] are on the order of a few GeV through on the order of 1 TeV. The momentum transfer is quite small, since the weakly interacting massive particles are non-relativistic, so the scattering off of nuclei is coherent. The energy dependence of the nuclear recoil depends on the sum of a term that is independent of the nuclear spin and another term that depends on the net spin of the nucleus. Depending on the particle type, the model of interactions and the nuclear target, the cross section may be dominated by spin-dependent (SD) scattering or spin-independent (SI) scattering.

Because of the coherence enhancement factor of A^2 for A nucleons in the nucleus, the SI cross section limits

are typically stronger than the SD cross section limits where there are cancellations between spins of nucleons. For example, the cross section limit per nucleon for SI couplings reaches a value of less than $\sigma_{SI} \sim 10^{-44}$ cm² for a DM mass ~ 30 GeV, while for SD couplings, the limit is closer to $\sigma_{SD} \sim 5 \times 10^{-39}$ cm² from direct detection experiments [4]. With cross section limits, one can then determine constraints on coupling constants and masses in a given particle physics model.

In the low mass region, on the order of 10 GeV, the direct detection limits are inconsistent between experiments, with DAMA/LIBRA [16] and CoGeNT [17] reporting detection, and other groups reporting exclusion regions for the same parameters [11, 12, 14]. Even with this uncertainty, it is interesting to explore how the non-relativistic t -channel scattering processes of direct detection experiments would translate to higher energy processes.

High energy DM may be produced in accelerator experiments and in cosmic ray interactions in the atmosphere, for example. In accelerator experiments, typically the process of interest is s -channel pair production of DM particles, here labeled by χ . In this letter, we consider the question of how direct detection constraints on the DM–nucleon cross section translate to the high energy, deep-inelastic scattering (DIS) cross section for DM particles with nucleons, a t -channel process. We use the constraints on the SI cross section [14] and the SD cross section [15] limited by the XENON Collaboration for the weakly interacting massive particle mass range of 10-1000 GeV.

The low energy cross section of direct detection experiments is non-relativistic and coherent while the high energy DIS cross section is relativistic and incoherent. As a result, it is possible that effective operators at low energy that are poorly constrained can be the dominant interactions at high energy. If the DM couplings are sufficiently large, then χN interactions, in principle, could mimic neutral current (NC) interactions of neutrinos with nucleons. The idea of DM interactions giving the same signal as neutrino NC interactions has been discussed in

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Refs. [21] and [22] for lower mass DM. Our goal here is to explore the possibility that while satisfying the direct detection constraints at low energies, the DM χN inelastic scattering cross section could be comparable to neutrino-nucleon cross sections at high energies for $m_\chi = 10 - 1000$ GeV.

Specific particle physics models may predict either SI or SD dominated cross sections. General discussions of effective interactions relevant to DM–nucleon interactions appear in, for example, Refs. [23–25]. There are results on specific model assumptions, looking at the SI and SD constraints along with cosmological, collider physics and neutrino telescope constraints in, e.g., Refs. [24–30].

To avoid a multi-dimensional parameter space of a specific beyond-the-Standard Model, we consider here the simple case of DM, a stable Majorana fermion. One example of Majorana fermionic DM is discussed in Ref. [31]. For simplicity, we treat the couplings of the Majorana fermion to the Higgs boson and Z boson as the only unknown parameters. This example will be sufficient to illustrate the translation of low energy, non-relativistic but coherent scattering cross section limits from the XENON collaboration [4, 14, 15] to high energy, incoherent DIS of DM with nucleons. We show that these limits are such that the DM–nucleon cross section may be comparable to the neutrino-nucleon cross section for a range of energies and DM masses of order 10 GeV or 1 TeV. However, the addition of LEP constraints and cosmological constraints excludes the possibility of DM masquerading as neutrinos in the Standard Model (SM) NC interactions. We discuss a possible low mass axial vector exchange that would permit an evasion of these constraints, yet still allow neutrino-scale χN interactions.

In the next section, we review the constraints of DM couplings with the SM Higgs boson coming from the SI direct detection limit, and with the Z boson from the SD direct detection limit, for DM masses in the range of 10–1000 GeV. We show that Z exchange for $m_\chi = 10$ GeV, at the current upper limit for the $Z - \chi\chi$ coupling from $\sigma(\chi N)$ direct detection limits, gives NC cross section larger than the νN NC cross section. As long as the annihilation channel to a real or virtual Z is permitted ($\chi\chi \rightarrow Z$), the direct detection limits are not the most constraining. For $m_\chi < M_Z/2$, the invisible decay width of the Z provides the strongest constraint. For a range of masses, if χ is the DM responsible for the bulk of the DM in the universe, the DIS cross section for $\chi - N$ scattering will be considerably smaller than the neutrino-nucleon NC cross section. An alternative scheme for DM couplings to ordinary matter through a light Z' could allow DM DIS to be roughly comparable to neutrino DIS, as discussed in Sec. III.

II. MAJORANA FERMIONIC DM AND HIGH ENERGY DIS CROSS SECTIONS

Majorana fermions are a useful example of particles in which the low energy direct detection constraints nevertheless allow a fairly large weak interaction cross section for high energy DM DIS with nucleons. As discussed in Ref. [23], there are only two surviving terms in the effective interactions of Majorana DM with nucleons N in the non-relativistic limit:

$$\mathcal{L} \sim A \bar{\chi} \gamma^\mu \gamma_5 \chi \bar{N} \gamma_\mu \gamma_5 N + B \bar{\chi} \chi \bar{N} N. \quad (1)$$

We consider separately the couplings which contribute to the SI and SD non-relativistic DM–nucleon cross sections, then evaluate the consequences for deep inelastic DM–nucleon scattering. In Section III, we discuss other constraints on the DM couplings.

A. Spin-independent effective operators

If the DM is a Dirac fermion, a vector coupling with the Z is permitted. The limit on the Z vector coupling to DM comes from the SI cross section and is of order $\sim 10^{-3}$ times the SM coupling. If the Z vector and axial vector couplings to a Dirac fermionic DM particle are related, the SI low energy cross section constraint would mean that high energy χN scattering would be quite suppressed. It is primarily for this reason that we are considering the DM as Majorana fermions.

For a Majorana fermion, the vector coupling with the Z does not occur, so the SI cross section limit on Majorana DM χ comes from scalar couplings. There is an allowed effective interaction with quarks

$$\mathcal{O}_f^H = c_f \bar{\chi} \chi \bar{f} f. \quad (2)$$

If the scalar exchange is a Higgs boson, the quantity c_f depends on the Higgs boson mass, the nuclear matrix element of the $f = q$ operators and the coupling of the DM to the Higgs boson. We proceed in our discussion with the assumption that the scalar is a Higgs boson and write

$$\mathcal{L}^h = y_\chi \bar{\chi} \chi h. \quad (3)$$

The constraint on y_χ from the SI limit based on the Higgs contribution to the SI cross section per nucleon, following Ref. [26], is

$$\sigma(\chi N \rightarrow \chi N)^{SI} \simeq 5 \times 10^{-8} \text{pb} \left(\frac{y_\chi}{0.1} \right)^2 \left(\frac{115 \text{ GeV}}{m_H} \right)^4. \quad (4)$$

Using the XENON100 limits [4, 14] and Eq. (4), we set the upper values of y_χ to 0.25, 0.031, and 0.027 for $m_\chi = 10, 25$ and 100 GeV, respectively, for $m_H = 125$ GeV. These values are listed in Table 1.

m_χ [GeV]	m_H [GeV]	y_χ	c_χ^Z
10	115/125	0.21/0.25	1.77
25	125	0.031	0.40
100	125	0.027	0.56

TABLE I: Approximate limits on the Higgs boson and Z couplings to DM based on direct detection limits on the SI [4, 14] and SD cross section for scattering with neutrons[15].

Given the DM coupling to the Higgs boson, at high energies, one contribution to the $\chi - N$ DIS cross section comes from the effective operator

$$\mathcal{O}_f^H = \frac{y_\chi y_f}{Q^2 + m_H^2} \bar{\chi} \chi \bar{f} f, \quad (5)$$

for momentum transfer Q and $y_f = m_f/v$, where f represents the quarks and $v = 246$ GeV is the vacuum expectation value that characterizes the weak symmetry breaking scale. For the DIS cross section, we consider $E_\chi \geq 10$ GeV, so Q can be low, and the charm and b components of the nucleon are not large at low Q . There is an effective coupling of the Higgs boson to gluons through a top quark loop [32], however, the gluon contribution to χN scattering does not change our conclusions so we neglect it here.

B. Spin-dependent effective operators

The axial vector coupling of a Majorana particle to the Z is allowed, where the coupling can be written as

$$\mathcal{L}_M^Z = c_\chi^Z \frac{g}{2 \cos \theta_W} \bar{\chi} \gamma_\mu \gamma_5 \chi Z^\mu. \quad (6)$$

Through an effective operator $\mathcal{O} \sim (\bar{\chi} \gamma_\mu \gamma_5 \chi)(\bar{f} \gamma^\mu \gamma_5 f)$, the coupling c_χ^Z is constrained by the SD direct detection limits. Cohen et al. in Ref. [26] write, with the Z exchange effective operator, a low energy elastic cross section which can be revised to account for just $\chi -$ neutron (n) scattering:

$$\sigma_{SD}(\chi n \rightarrow \chi n) \sim 3.2 \times 10^{-4} \text{ pb} \left(\frac{c_\chi^Z}{0.1} \right)^2. \quad (7)$$

For $m_\chi = 10$ GeV, the SD direct detection cross section limit [15] is ~ 0.1 pb, while for $m_\chi = 25$ GeV, $\sigma_{SD} \lesssim 5 \times 10^{-3}$ pb and for $m_\chi = 100$ GeV, $\sigma_{SD} \lesssim 10^{-2}$ pb. These constraints yield the values of c_χ^Z shown in Table I. We remark that the SD direct detection cross section limits on $\sigma_{SD}(\chi p)$ from, for example, PICASSO [18] and COUPP [19], translated to limits on c_χ^Z are weaker than the XENON10 limits on $\sigma_{SD}(\chi n)$ for $m_\chi < 1000$ GeV. The KIMS limits on $\sigma_{SD}(\chi p)$ [20] are competitive with the XENON10 limits at high mass (above 100 GeV). For example, for $m_\chi = 10^3$ GeV, the KIMS limit reduces c_χ^Z from the XENON10 limit by 25%. We use the XENON10 limits here since the lower mass regime is of primary interest.

C. Deep inelastic scattering cross section

We now evaluate the deep inelastic cross section for Majorana fermion – isoscalar nucleon (N) scattering for $E_\chi = 10^3 - 10^6$ GeV. The high energy cross section, at the parton level for elastic DM – parton scattering in the $2 \rightarrow 2$ process is

$$\frac{d\hat{\sigma}}{dy} = \frac{1}{16\pi} \frac{\hat{s} - (m_\chi^2 + m_f^2)}{\hat{s}^2 - 2\hat{s}(m_\chi^2 + m_f^2) + (m_\chi^2 - m_f^2)^2} |\overline{\mathcal{M}}|^2, \quad (8)$$

where we label the parton mass with m_f . Here,

$$y = \frac{p_1 \cdot (k_1 - k_2)}{p_1 \cdot k_1} \quad (9)$$

for $2 \rightarrow 2$ scattering, e.g., $\chi(k_1) + q(p_1) \rightarrow \chi(k_2) + q(p_2)$.

The high energy matrix element is model and process dependent. For Higgs exchange with quarks with mass m_f , the spin-averaged matrix element squared is

$$|\overline{\mathcal{M}}|^2 = \left(\frac{y_\chi m_f}{v^2(t - m_H^2)} \right)^2 (t - 4m_\chi^2)(t - 4m_f^2). \quad (10)$$

Using the couplings y_χ in Table I, we find that $\sigma(\chi N)/E_\chi$ from Higgs exchange, using the couplings in Table 1, range between $2 \times 10^{-49} - 3 \times 10^{-45} \text{ cm}^2/\text{GeV}$ for $E_\chi = 10^3$ GeV, to $5 \times 10^{-47} - 4 \times 10^{-45} \text{ cm}^2/\text{GeV}$ for $E_\chi = 10^6$ GeV, where the larger cross sections correspond to $m_\chi = 10$ GeV. Variations of the Higgs mass, 115 – 127 GeV, have little effect.

For $E_\nu = 30 - 200$ GeV, the cross section with isoscalar nucleons for neutrinos is $(0.677 \pm 0.014) \times 10^{-38} \text{ cm}^2$ and for antineutrinos is $(0.334 \pm 0.008) \times 10^{-38} \text{ cm}^2$. At higher energies, the neutrino cross section falls with energy because of the effect of the propagator in the boson exchange [33, 34]. This same effect is seen in the DM – nucleon inelastic scattering cross section. Thus, Higgs scalar exchange is not an important process in which DM scattering with nucleons may mimic neutrino scattering at high energies.

The expression for Majorana fermion scattering with quarks via Z exchange from Eq. (6) is

$$\begin{aligned} |\overline{\mathcal{M}}|^2 = & 2(c_\chi^Z)^2 \left(\frac{g^2}{4 \cos^2 \theta_W (t - m_Z^2)} \right)^2 \\ & \times \left[(c_V^2 + c_A^2) ((s - m_\chi^2 - m_f^2)^2 \right. \\ & + (u - m_\chi^2 - m_f^2)^2 - 2tm_\chi^2) \\ & \left. + 2c_V^2 m_f^2 (t - 4m_\chi^2) - 2c_A^2 m_f^2 (t - 8m_\chi^2) \right] \end{aligned} \quad (11)$$

In Eq. (11), $c_V = T_3 - 2Q \sin^2 \theta_W$ and $c_A = T_3$, for $T_3 = \pm 1/2$ and electric charge Q for the Z couplings to ordinary fermions.

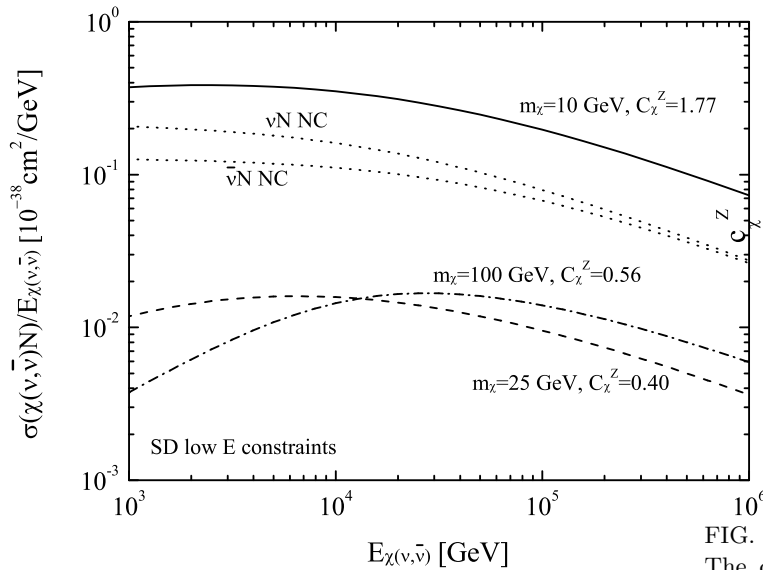


FIG. 1: The inelastic cross section for χ scattering with nucleons including only Z boson exchange from the SD limit on the coupling c_χ^Z . In this figure, the DM mass is set to 10, 25 and 100 GeV, and using c_χ^Z from Table I. $\sigma(\nu N, \bar{\nu} N)$ NC cross sections as a function of $E_{\nu, \bar{\nu}}$ are also shown.

In contrast to Higgs exchange, based just on the low energy direct detection constraints on c_χ^Z for Z boson exchange in χN interactions, the χN NC cross section can be comparable to νN NC interactions for low mass $m_\chi \lesssim 10$ GeV DM. Fig. 1 shows the NC cross section scaled by energy in units of 10^{-38} cm^2 for three DM masses and $m_\chi = 10, 25$ and 100 GeV. We use the CTEQ6.6 parton distribution functions [35] to evaluate the cross section. This figure shows that from $E \sim 10^5$ GeV, the $\sigma(\chi N) \sim 2.5 \times \sigma(\nu N)$. For higher masses, where the low energy XENON SD cross section constraints are weaker, the χN cross sections may be comparable to the neutrino – nucleon NC cross section. At low energy, one sees kinematic effects due to the larger mass.

In the next section, we review other constraints on the $\chi\chi Z$ coupling which exclude this mass regime for Majorana DM which couples directly to the Z . We discuss an alternative approach with a light Z' exchange.

III. DISCUSSION

Based on just the direct detection limits on the $\chi\chi Z$ coupling, one finds a mass region where, given high energy Majorana DM, the χN cross section with Z exchange is comparable to the neutrino – nucleon NC cross section. In Fig. 2, the dotted lines show the value of c_χ^Z such that the χN NC cross section equals $(\sigma(\nu N) + \sigma(\bar{\nu} N))_{NC}/2$ for $E = 10^4$ GeV and $E = 10^6$ GeV, as a function of m_χ . The solid curve in Fig. 2 corresponds to the XENON10 limit on the SD low en-

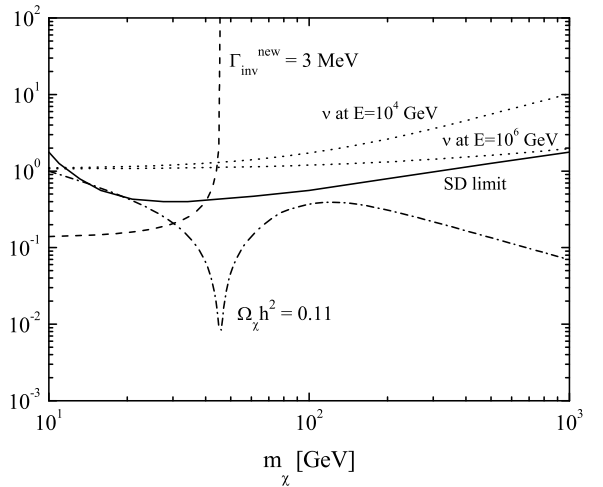


FIG. 2: The coupling of DM to the Z boson c_χ^Z versus m_χ . The dotted lines show the value of c_χ^Z such that the χN NC cross section equals $(\sigma(\nu N) + \sigma(\bar{\nu} N))_{NC}/2$ for $E = 10^4$ and 10^6 GeV, respectively. The dashed line shows the upper bound on the coupling versus mass to be consistent with the limit on new physics contributions to the invisible Z decay width. The solid curve shows the the upper bound on the coupling translated from the XENON10 limit on the SD cross section with neutrons. The dot-dashed line is the value of c_χ^Z such that the relic density of the DM $\Omega_{DM} h^2 = 0.11$ [31].

ergy cross section with neutrons, translated to an upper bound on c_χ^Z , as a function of m_χ .

The SD direct detection limit is not the only constraint on Z couplings to Majorana DM. One indirect limit comes from assuming that χ makes up most of the DM in the universe, shown in Fig. 2 with the dot-dashed line. This is the value of c_χ^Z such that χ is the DM for which $\Omega_{DM} h^2 = 0.11$ [31]. Particularly for $m_\chi \simeq 10$ GeV, the Majorana DM χ may satisfy both this cosmological constraint, the SD limit on coupling, yet have a neutrino-like NC cross section at high energy.

The more stringent constraint on direct $\chi\chi Z$ couplings comes from Z decays. In Fig. 2, the dashed line labeled $\Gamma_{inv}^{new} = 3 \text{ MeV}$ shows the values of c_χ^Z versus m_χ such that the effective contribution to the invisible decay width of the Z is equivalent to an additional number of neutrinos $\Delta N_\nu = 0.02$ [36]. The mass range $m_\chi < M_Z/2$ is essentially excluded. This excludes light mass (~ 10 GeV) DM that could mimic neutrino signals if its primary coupling to the SM particles is directly via Z exchange.

For the parameter space where $m_\chi > M_Z/2$ with χ the DM in the universe (the dot-dashed line), c_χ^Z lies below the SD limit, and well below the region of parameter space where the χN cross section is comparable to the νN cross section. For example, $c_\chi^Z = 0.37$ for $m_\chi = 100$ GeV if χ annihilation through the Z is the process responsible for the DM density of the universe. For this parameter choice, $\sigma(\chi N)$ is about 1% of the average neutrino plus antineutrino NC cross section at $E = 10^3$ GeV, growing to about 9% of the average NC cross section

at $E = 10^6$ GeV. For $m_\chi = 1$ TeV, the allowed coupling to the Z from SD direct detection experiments is large enough that χN scattering could be comparable to νN scattering for high energies, however, χ could not be the principle DM in the universe because its annihilation cross section would be too large. Such large values of c_χ^Z for $m_\chi \gtrsim 50$ GeV is further constrained by neutrino induced muon events in IceCube [9].

With hints of a signal of a ~ 10 GeV DM particle coinciding with a prediction of the correct DM abundance in the universe, we revisit the case of $m_\chi = 10$ GeV. The invisible Z decay width is the major constraint for the simple extension of the SM with a low mass DM particle considered thus far. A further extension of the SM that could yield neutrino-like χN cross sections, and still be accommodated by current experiments, is a light portal model. Portal models, first introduced in Ref. [37], have a dark sector connected to the SM particles through mixing of a new scalar or gauge boson with the SM Higgs boson or the SM gauge bosons. While a Higgs portal model or vector boson portal model is more theoretically economical, we will assume here an axial vector portal, where a gauge boson Z' with axial vector couplings with χ mixes with the SM Z with a small mixing angle denoted by ξ .

The Z' couplings to the SM particles are suppressed by a factor of ξ in the amplitude, so Z' contributions to $SM \rightarrow SM$ processes are suppressed by ξ^4 . Processes with $SM \rightarrow \chi\chi$ are suppressed by ξ^2 . With a sufficiently small ξ , even a relatively low mass Z' is permitted.

As an example, we consider $m_\chi = 10$ GeV with an axial vector portal connection to the SM particles. We assume that the Z' couplings to the SM particles are the same as Z couplings, multiplied by ξ . From Fig. 2, approximate scaling shows that if $c_\chi^Z = 1.77$ from direct detection constraints, in the portal case,

$$c_\chi^{Z'} \xi M_{Z'}^2 / M_Z^2 = 1.77. \quad (12)$$

To look at a specific example, we take $M_{Z'} = 15$ GeV to discuss experimental constraints. With this mass, $c_\chi^{Z'} \xi \simeq 0.048$.

Fig. 3 shows with a dashed line the χN inelastic cross section for $c_\chi^{Z'} \xi = 0.048$, $m_\chi = 10$ GeV and $m_{Z'} = 15$ GeV. The inelastic cross section is not as large as the inelastic cross section rescaled for Z exchange because the typical Q is of order $Q \sim m_{Z'}$ at high energy. At a given value of Bjorken x , the parton distribution functions are smaller for $Q \sim m_{Z'}$ than they are for $Q \sim m_Z$. As the figure shows, the DIS cross section for χN scattering is comparable to the νN and $\bar{\nu} N$ cross section only for $E_\chi \sim 10^3 - 10^4$ GeV.

Even with this fairly large DIS cross section, the other constraints for $m_\chi = 10$ GeV are satisfied. The effective coupling for low energy $\chi\chi$ annihilation relevant to $\Omega_\chi h^2$ are unchanged. If we further assume that $c_\chi^{Z'} = 1$, the boson mixing angle is $\xi = 0.048$. This small mixing of $Z - Z'$ means that $Z \rightarrow \chi\chi$ is suppressed by $\xi^2 \sim 2 \cdot 10^{-3}$, so $\Gamma_{\text{inv}}^{\text{new}}$ limits are satisfied. The factor of ξ^4 in $SM \rightarrow SM$

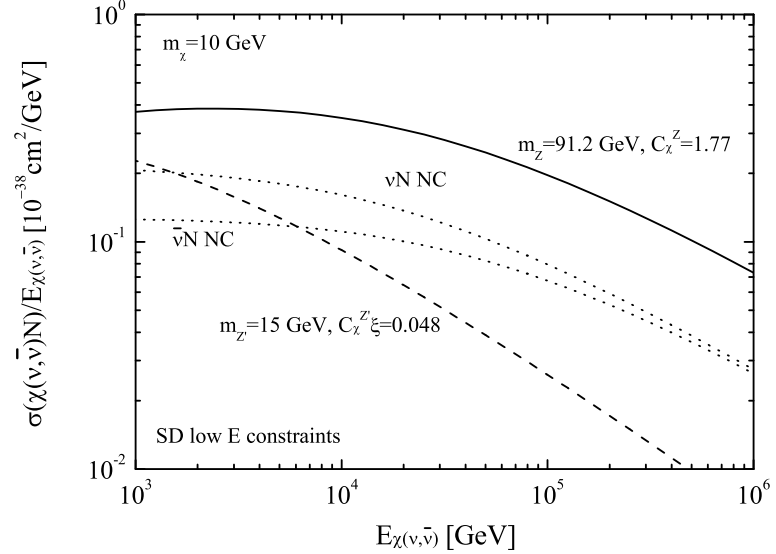


FIG. 3: The inelastic cross section for χ scattering with nucleons including only Z' boson exchange ($m_{Z'} = 15$ GeV), represented by the dashed line, from the SD limit on the coupling $c_\chi^{Z'} \xi = 0.048$. In this figure, the DM mass is set to 10 GeV. The solid and dotted curves, from Fig. 1, are shown for comparison.

processes ensures that even a low mass Z' has suppressed contributions.

Finally, one should consider collider limits on production of $\chi\chi$. As discussed experimentally [38–43] and theoretically (e.g., in Refs. [28–30]), DM signatures at colliders may appear as mono-jets plus missing energy or mono-photons plus missing energy. For s -channel production of a heavy boson, an effective four-fermion theory with partons and $\chi\chi$ can lead to strong constraints on the scale of the boson mass. For the scenario presented here, with a light mediator with $m_{Z'} < 2m_\chi$, resonant production of $\chi\chi$ is not possible and high energies give cross sections suppressed by $1/\hat{s}$, as noted in Ref. [28].

In conclusion, while we have not presented a specific model for Majorana DM coupling to ordinary matter through an axial vector portal, we have shown that there is the potential for neutrino-like couplings of the DM to nucleons. We have focused on Majorana DM because the spin-dependent couplings dominate the direct detection cross section. Scalar dark matter would have spin-independent Higgs exchange at low energy that have strong SI constraints from direct detection [25]. For high energy Majorana DM, this may lead to events that are indistinguishable from neutrino-nucleon NC events. Should a ratio of neutrino NC to charged current DIS rates be measured in experiments, the possibility of a high energy Majorana DM flux mixed with the neutrino flux should be explored in the context of specific models.

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