Collider Constraints on the Dark Matter Interpretation of the CDMS II Results

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Abstract

The recent observation of three events by the CDMS II experiment can be interpreted as a 8.6 GeV dark matter scatters elastically with the nucleons inside the silicon detectors with a spin-independent cross section of $1.9 \times 10^{-41}$ cm$^2$. We employ the effective dark matter interaction approach to fit to the interpreted cross section, and make predictions for monojet and monophoton production at the LHC with the fitted parameters. We show that some of the operators are already ruled out by current data while the others can be further probed in the upcoming 14 TeV run of the LHC.
I. INTRODUCTION

Evidences for the omnipresence of dark matter in our present Universe have been well established through its gravitational effects spread over many different scales, ranging from the rotation curves of clusters and spiral galaxies, bullet clusters, weak lensing effects to the cosmic microwave background radiation. A number of recent observational experiments, especially the very precise measurement of the cosmic microwave background radiation in the Wilkinson Microwave Anisotropy Probe (WMAP) \cite{1} and Planck Mission experiments \cite{2} suggest that the dark matter (DM) relic density $\Omega_\text{c} h^2 = 0.1199 \pm 0.0027$, while the baryon density $\Omega_\text{b} h^2 = 0.02205 \pm 0.00028$ \cite{2}. However, its particle nature remains alluring to theorists and many particle dark matter models have been built over the years. In most of these popular models, dark matter is assumed to be nonbaryonic and electrically neutral. Detailed predictions of these models can now be further scrutinized by using data from various direct and indirect detection experiments as well as collider experiments like the Large Hadron Collider (LHC), and useful constraints can be deduced.

Many experiments are being performed or will be carried out in foreseeable future to investigate the particle nature of the DM. One category is the direct detection experiments with a large detector buried deeply underground or underneath a high mountain. In such background-free environments, one hopes to detect the rarely happened scattering of the DM particle with nuclei of the detector materials. A number of recent experiments detect some events, which cannot be accounted for by any known background sources, thus are interpreted as signals of DM. Coincidentally or not, they all fall into the light DM mass region, around 10 GeV. The first claimed DM signal was the seasonal variation in detection rate recorded by the DAMA \cite{3} experiment. Some positive results were also reported by CoGeNT \cite{4} and CRESST \cite{5}. More recently the CDMS II \cite{6} collaboration has seen three events, which correspond to a DM mass of 8.6 GeV and a spin-independent cross section of $\sigma_N^{SI} = 1.9 \times 10^{-41}$ cm$^2$. Such a large cross section of the DM particle with a nucleon could imply a large production cross section of DM particles at the LHC. The main purpose of this note is to investigate were the CDMS II events interpreted as signals of the DM, what would be the detectable signature at the LHC?

We adopt an effective interaction approach \cite{7,13} to describe the interactions of the dark matter particle with the standard model (SM) particles. The DM scattering off a nucleon
goes through the process $q\chi \rightarrow q\chi$ while one can interchange the quark in the final state with the $\chi$ in the initial and the process becomes $q\bar{q} \rightarrow \chi\bar{\chi}$. Since the DM particles in the final state would escape from detection in the particle detectors at the LHC, one has to attach either a gluon, photon, $Z$, or a $W$ boson in order to give a detectable signal. Thus, the most anticipated signals of dark matter at hadronic colliders are large missing energies in association with jets, photons, or leptons (from $W$ or $Z$ decays). For example, if we take one of the operators, $(\bar{\chi}\chi)(\bar{q}q)$, and attach a gluon or a photon to a quark leg, it will give rise to a monojet or a monophoton plus missing energy event. The LHC experiments have been actively searching for these signatures in some other context, such as large extra dimensions. We will use the most updated data on monojet and monophoton production from the LHC\cite{14,15} to constrain the effective dark matter interactions.

We will consider various spin nature of the dark matter particle including Dirac and Majorana for fermionic dark matter, as well as real and complex scalar. Our strategy is as follows. For each operator that can contribute to the spin-independent (SI) cross section between the DM particle and the nucleon, we calculate the size of the effective scale $\Lambda$ that can account for the CDMS II cross section of $1.9 \times 10^{-41}$ cm$^2$ with dark matter mass of 8.6 GeV. With these parameter values we calculate the monojet and monophoton cross sections at the LHC and compare with the existing data. We shall then repeat the exercise for the operators that can contribute to the spin-dependent (SD) cross section if the CDMS II data is to be interpreted due to spin-dependent scattering between the DM particle and the nuclei\cite{16}.

The organization of this paper is as follows. In the next section, we describe the effective interaction approach and the operators that give rise to spin-independent and spin-dependent scattering between the DM particle and the nucleon. In Sec. III, we give the formulas for the DM-nucleon scattering cross sections. In Sec. IV, we determine the best fitted value of the effective scale of each operator from the CDMS II data and use these best fitted parameters to calculate the monojet/monophoton cross sections at the LHC. We summarize in Sec. V.

II. EFFECTIVE DARK MATTER INTERACTIONS

We assume that the dark matter particle, denoted by $\chi$, is a standard model singlet, and the $\chi$ can stand for a Dirac or Majorana fermion, real or complex scalar, depending on
the context. Also, $f$ stands for a SM fermion, including quarks and leptons. A thorough discussion of the operators can be found in Ref. [7]. Here we highlight those operators which are relevant to the spin-independent and spin-dependent scattering between the DM particle and the nucleon.

In the notation of Ref. [7], the operators that contribute to spin-independent cross sections are:

\begin{align}
O_1^D &= \sum_f \frac{C^f_1}{\Lambda_1^2} (\bar{\chi} \gamma^\mu \chi) \left( \bar{f} \gamma_\mu f \right), \\
O_7^{D,M} &= \sum_f \frac{C^f_7 m_f}{\Lambda_7^3} (\bar{\chi} \chi) \left( \bar{f} f \right), \\
O_{11}^{D,M} &= \frac{C_{11}}{\Lambda_{11}^3} (\bar{\chi} \chi) \left( -\frac{\alpha_s}{12\pi} G^{\mu\nu} G_{\mu\nu} \right), \\
O_{15}^C &= \sum_f iC^f_{15} \left( \chi^\dagger \leftrightarrow \partial_\mu \chi \right) \left( \bar{f} \gamma^\mu f \right), \\
O_{17}^{C,R} &= \sum_f \frac{C^f_{17} m_f}{\Lambda_{17}^2} (\bar{\chi}^\dagger \chi) \left( \bar{f} f \right), \\
O_{19}^{C,R} &= \frac{C_{19}}{\Lambda_{19}^2} (\bar{\chi}^\dagger \chi) \left( -\frac{\alpha_s}{12\pi} G^{\mu\nu} G_{\mu\nu} \right),
\end{align}

where $\Lambda_i$ is the heavy mass scale for the connector sector that has been integrated out and $C_i$ is an effective dimensionless coupling constant of order $O(1)$ that can be absorbed into $\Lambda_i$. Here $D$ and/or $M$ in the superscript of $O_1$, $O_7$, and $O_{11}$ denote that the DM $\chi$ can be a Dirac and/or Majorana fermion. Also, $C$ and/or $R$ in the superscript of $O_{15}$, $O_{17}$, and $O_{19}$ denote that the DM $\chi$ can be a complex and/or real scalar. The $m_f$ dependence in the coupling strength of some of the operators is included for scalar-type interactions because this factor appears naturally from dark matter models with scalar exchange diagrams. For operators involving gluons, the factor of strong coupling constant $\alpha_s(2m_\chi)$ is also included because these operators are induced at one loop level as a result of integrating the heavy quarks and evaluated at the scale $2m_\chi$ where $m_\chi$ is the dark matter mass.

On the other hand, the following operators contribute to the spin-dependent scattering cross section

\begin{align}
O_4^{D,M} &= \sum_f \frac{C^f_4}{\Lambda_4^2} (\bar{\chi} \gamma^{\mu\nu} \gamma^5 \chi) \left( \bar{f} \gamma_\mu \gamma^5 f \right), \\
O_5^D &= \sum_f \frac{C^f_5}{\Lambda_5^2} (\bar{\chi} \sigma^{\mu\nu} \chi) \left( \bar{f} \sigma_{\mu\nu} f \right).
\end{align}
The relative importance to SI or SD scattering cross section from each of the above operators can be easily understood by nonrelativistic expansions, which had been fully analyzed in previous work \[^7\]. We will ignore the evolution effects of the above effective operators in our analysis.

The validity and pitfalls of using effective dark matter interaction approach for LHC studies have been examined by a number of authors in Refs.\[^17\] [\(^18\)].

### III. DIRECT DETECTION

The solar system moves around in the Galactic halo with a nonrelativistic velocity \(v \sim 10^{-3}c\). When the dark matter particles move through a detector, which is usually put under a deep mine or a mountain to reduce backgrounds, and create collisions with the detector, some signals may arise in phonon-type, scintillation-type, ionization-type, or some combinations of them, depending on the detector materials. The event rate is extremely low because of the weak-interaction nature of the dark matter. There are controversies among various direct detection experiments. Both DAMA \[^3\] and CoGeNT \[^4\] observed some positive signals of dark matter detection, which point to a light dark matter (\(\sim 5 - 10 \text{ GeV}\)) with the \(\sigma_{\chi N}^{\text{SI}} \sim 10^{-41} \text{ cm}^2\). The very recent CDMS \[^6\] has seen three events, which correspond to a DM mass of 8.6 GeV and a spin-independent cross section of \(\sigma_{\chi N}^{\text{SI}} = 1.9 \times 10^{-41} \text{ cm}^2\) between the DM particle and the nucleon or a spin-dependent cross section of \(\sigma_{\chi n}^{\text{SD}} = 10^{-35} \text{ cm}^2\) \[^16\] between the DM particle and the neutron. We shall use these cross sections and interpret it as a SI or SD scattering between the DM particle and the nucleon, and calculate the parameter of each operator that can give such cross sections.

In the following we will not concern about the exclusions by the XENON100 data \[^19\] for spin-independent cross sections (\(\sigma^{\text{SI}}\)), and XENON10 \[^20\], ZEPLIN \[^21\] and SIMPLE \[^22\] data for spin-dependent cross sections (\(\sigma^{\text{SD}}\)). As pointed out by a few recent analyses that there may be some inconsistency in the low DM mass region of the XENON data \[^23\].
A. Spin-Independent Cross Section

For a nuclei $N$ composed of $Z$ protons and $(A - Z)$ neutrons, the SI cross section contributed by the operator $O_D^1$ is given by

$$
\sigma_{\chi N}^{\text{SI}}(0) = \frac{\mu_{\chi N}^2}{\pi} |b_N|^2 ,
$$

where

$$
\mu_{\chi N} = \frac{m_\chi m_N}{m_\chi + m_N} ,
$$
is the reduced mass for the $\chi N$ system and

$$
b_N = Z b_p + (A - Z) b_n ,
$$

with

$$
b_p = \frac{1}{\Lambda_4} (2 C_1^u + C_1^d) ,
$$

$$
b_n = \frac{1}{\Lambda_4} (C_1^u + 2 C_1^d) .
$$

For $O_D^7$, we have

$$
\sigma_{\chi N}^{\text{SI}}(0) = \frac{\mu_{\chi N}^2}{\pi} |f_N|^2 ,
$$

where

$$
f_N = Z f_p + (A - Z) f_n ,
$$

with

$$
f_{p,n} = \frac{m_{p,n}}{\Lambda_7^2} \left\{ \sum_{q=u,d,s} C_q^f f_{Tq}^{(p,n)} + \frac{2}{27} f_{Tq}^{(p,n)} \sum_{Q=c,b,t} C_Q^{Tg} \right\} ,
$$

and

$$
f_{Tq}^{(p,n)} \equiv 1 - \sum_{q=u,d,s} f_{Tq}^{(p,n)} .
$$

For the Majorana case of $O_M^7$, one should multiply Eq.(14) by a factor of 4. For a recent re-evaluation of the hadronic matrix elements $f_{Tq}^{(p,n)}$ using the latest lattice calculation results of the strange quark $\sigma_s$ term and its contribution inside the nucleon, see Ref. [24].

For $O_D^{11}$, the cross section is the same as $O_D^7$ with the following couplings

$$
f_{p,n} = \frac{m_{p,n}}{\Lambda_{11}^2} \frac{2}{27} f_{Tq}^{(p,n)} C_{11} ,
$$

For the Majorana case of $O_M^{11}$, multiply the cross section from $O_D^{11}$ by a factor of 4.
For $O_{15}^C$, the cross section is the same as $O_1^D$ with the following replacements

$$C_{1}^{u,d} \rightarrow C_{15}^{u,d},$$
$$\Lambda_{1} \rightarrow \Lambda_{15},$$

for the couplings in Eqs.(12) and (13). For $O_{17}^C$, the cross section is same as $O_7^D$ with the following replacement

$$C_{7}^{u,d} \rightarrow C_{17}^{u,d},$$
$$\Lambda_{7} \rightarrow \Lambda_{17},$$

for the coupling in Eq.(16). For $O_{19}^C$, the cross section is same as $O_{11}^D$ with the following replacement

$$C_{11} \rightarrow C_{19},$$
$$\Lambda_{11} \rightarrow \Lambda_{19},$$

in Eq.(18). The results for $O_{17,19}^R$ can by obtained by multiplying a factor of 4 to the corresponding cross sections from $O_{17,19}^C$, respectively.

**B. Spin-Dependent Cross Section**

For $O_4^D$, its contribution to the SD cross section is given by

$$\sigma_{\chi N}(0) = \frac{8\mu_N^2}{\pi} G_F^2 \bar{\Lambda}^2 J(J+1),$$

where $J$ is the total spin of the nuclei $N$, $G_F$ is the Fermi constant and

$$\bar{\Lambda} = \frac{1}{J}(a_p\langle S_p \rangle + a_n\langle S_n \rangle),$$

with $\langle S_p \rangle$ and $\langle S_n \rangle$ the average of the proton and neutron spins inside the nuclei respectively, and

$$a_{p,n} = \sum_{q=u,d,s} \frac{1}{\sqrt{2} G_F^2 \Lambda_4^q} \Delta q_{(p,n)}^{(p,n)},$$

with $\Delta q_{(p,n)}^{(p,n)}$ being the fraction of the spin carried by the quark $q$ inside the nucleon $p$ and $n$. For an updated analysis of $\Delta q_{(p,n)}$, see Ref.[24]. For $O_4^M$, one should multiply the cross section Eq.(25) by a factor of 4.
For $O_{5}^{P}$, its cross section is the same as $O_{4}^{P}$ with the following replacements in Eq.(27)

\[ C_{4}^{q} \rightarrow 2 C_{5}^{q} , \]  \hspace{1cm} (28)

\[ \Lambda_{4} \rightarrow \Lambda_{5} . \]  \hspace{1cm} (29)

IV. MONOJET AND MONOPHOTON PRODUCTION AT COLLIDERS

Dark matter particles can be produced in hadronic collisions simply by crossing the Feynman diagrams responsible for the SI or SD scattering between DM particles and nucleons. However, it would only give rise to something entirely missing in the detection. We therefore need some additional visible particles for trigger. One of the cleanest signatures is monojet or monophoton production, which has only a high $p_{T}$ jet or photon balanced by a large missing transverse momentum. The most precise measurements come from the CMS [14] and the ATLAS [15] experiments at the LHC.

In our approach of effective DM interactions, we can attach either a gluon or a photon to one of the quark legs of the relevant operators. For example, in $O_{1,7}$ we can attach a gluon or a photon line to the fermion line. For gluonic operators we can either attach a gluon line to the gluon leg or attach the whole 4-point diagram to a quark line such that it becomes a $qg$-initiated process. The final state consists of a pair of DM particles and a gluon or a photon. We require the jet or photon to have a large transverse momentum according to the $p_{T}$ requirement of each experiment.

For each effective operator $O_{i}$ we calculate the value of $\Lambda_{i}$ such that the SI cross section is about $1.9 - 2.0 \times 10^{-41}$ cm$^{2}$. The results are shown in Table I. Under the assumption that the dark matter interacts universally with the quarks, the DM-nucleon cross section is about the same for proton and neutron (see Table I). We use a dark matter mass $m_{\chi} = 10$ GeV, and the results are not sensitive for $m_{\chi} \sim 8 - 12$ GeV.

The most recent monojet search was performed by the CMS collaboration [14] with an integrated luminosity of 19.5 fb$^{-1}$. It is almost the full data set before the shutdown. The search for monojet events was using the following selection cuts:

\[ p_{Tj} > 110 \text{ GeV}, \; |\eta_{j}| < 2.4, \; \not{E}_{T} > 250 - 550 \text{ GeV} , \]  \hspace{1cm} (30)

among which the

\[ \not{E}_{T} > 400 \text{ GeV} \]  \hspace{1cm} (31)
TABLE I. The fitted values $\Lambda_i$ for the operators $O_{1,7,11,15,17,19}$, which contribute to the spin-independent scattering between DM and nucleon. The corresponding predictions for the number of monojet events for each operator at LHC-8 for an integrated luminosity of $19.5 \text{ fb}^{-1}$ are also shown.

| Operators | $\Lambda_i$ (GeV) | $\sigma_{\chi N}^{\text{SI}}$ ($\times 10^{-41} \text{ cm}^2$) | Number of Monojet events with $19.5 \text{ fb}^{-1}$ LHC-8 Allowed/Ruled out |
|-----------|------------------|-----------------------------|--------------------------------------------------|
| $O_{11}^D$ | 2500             | 2.10                        | 7.2 allowed                                       |
| $O_{7}^D$  | 85               | 2.00                        | 2.3 allowed                                       |
| $O_{7}^M$  | 106.4            | 2.12                        | 1.3 allowed                                       |
| $O_{11}^D$ | 50.7             | 1.88                        | $8.6 \times 10^5$ ruled out                       |
| $O_{11}^M$ | 63.8             | 1.88                        | $4.4 \times 10^5$ ruled out                       |
| $O_{15}^C$ | 2500             | 2.10                        | 1.7 allowed                                       |
| $O_{17}^C$ | 175              | 2.00                        | $1.8 \times 10^{-3}$ allowed                     |
| $O_{17}^R$ | 250              | 1.84                        | $8.7 \times 10^{-4}$ allowed                     |
| $O_{19}^C$ | 117              | 1.89                        | 332 allowed                                       |
| $O_{19}^R$ | 147.3            | 1.89                        | 166 allowed                                       |

was used specifically for the context of dark matter. In Ref. [14], it was claimed that the best expected limit was obtained with $E_T > 400 \text{ GeV}$. We therefore follow their claim and use $E_T > 400 \text{ GeV}$. The observed upper limit on the number of events of the hypothetical signal of dark matter is

$$N_{\text{obs}}^{\text{SI}} < 434.$$  \hfill (32)

We simply compare this observed upper limit of number of events to the predictions implied by the CDMS II result. The numbers of monojet events for all SI operators are shown in the second last column of Table II while in the last column we say “allowed” or “ruled out” as compared with Eq. (32).

We note that our parton-level calculation gives similar numbers of events as the dark matter model in the experimental paper [14].

We repeat the whole exercise for the SD cross section. It was shown in Ref. [16] that a SD scattering between the DM and the neutron can explain the data with a SD cross section of $10^{-35} \text{ cm}^2$, which is six orders of magnitude above the SI one. We obtain the
TABLE II. The fitted values $\Lambda_i$ for the operators $O_{4,5}$, which contribute to the spin-dependent scattering between DM and nucleon. The corresponding predictions for numbers of monojet events are also shown.

| Operators | $\Lambda_i$ (GeV) | $\sigma_{\chi n}^{SD}$ (neutron) ($\times 10^{-36}$ cm$^2$) | Number of Monojet events with 19.5 fb$^{-1}$ | LHC-8 | Allowed/Ruled out |
|-----------|------------------|-------------------------------------------------|---------------------------------|-------|-----------------|
| $O_D^4$   | 28               | 8.93                                            | $4.5 \times 10^8$               |       | ruled out       |
| $O_M^4$   | 39.6             | 8.93                                            | $2.3 \times 10^8$               |       | ruled out       |
| $O_D^5$   | 28               | 8.93                                            | $3.6 \times 10^9$               |       | ruled out       |

fitted parameters $\Lambda_i$ for $O_D^{4,M}$ and $O_D^5$ in Table II. The corresponding predictions for the number of monojet events at the LHC-8 for these three operators are also shown in the second last column. It turns out the predicted numbers for monojet events are way too large compared with the experimental upper limit in Eq.(32). All these SD operators are ruled out.

In principle, one can also make use the monophoton event rates to get bound on the DM interactions. Nevertheless, the results obtained with monophoton are not as good as monojet at this stage.

In Table III, the monojet and monophoton cross sections for the SI operators allowed by the current LHC-8 data are predicted for LHC-14. The selection cuts on the monophoton events at the LHC-14 are

$$p_{T\gamma} > 125 \text{ GeV}, \quad |\eta\gamma| < 1.5, \quad E_T > 125 \text{ GeV}, \quad (33)$$

while the selection cuts for the monojet events are the same as those for LHC-8.

V. CONCLUSIONS

If the recent observation of three events by the CDMS II experiment is interpreted as a 8.6 GeV dark matter signal, it would give corresponding monojet/monophoton signals at the LHC. We employed the effective DM interaction approach and calculated the parameter that can account for the observed cross section of the CDMS II events. We found that the current LHC-8 monojet data has already ruled out the SD operators $O_D^{4,M}$ and $O_D^5$ that can be used to interpret the recent three events from CDMS II by SD scattering. One of
TABLE III. Predicted monojet and monophoton cross sections for operators $O_{1,7,15,17,19}$ at the LHC-14, which are still allowed by current data at the LHC-8. Here "-" means that the gluonic operators do not give rise to monophoton events in the first approximation.

| Operators | $\Lambda_i$ (GeV) | Monojet cross section (fb) | Monophoton cross section (fb) |
|-----------|-------------------|---------------------------|-----------------------------|
| $O_{D1}^D$ | 2500 | 4.9 | 0.43 |
| $O_{D7}^D$ | 85 | 14.3 | 2.25 |
| $O_{M17}^M$ | 106.4 | 7.5 | 1.17 |
| $O_{15}^C$ | 2500 | 1.1 | 0.096 |
| $O_{17}^C$ | 175 | $1.2 \times 10^{-3}$ | $3.85 \times 10^{-4}$ |
| $O_{17}^R$ | 250 | $5.6 \times 10^{-4}$ | $1.85 \times 10^{-4}$ |
| $O_{19}^C$ | 117 | 186 | - |
| $O_{19}^R$ | 147.3 | 92.7 | - |

the SI operators, $O_{11}^{D,M}$, is also ruled by the LHC-8 monojet data. However, one must take these results with caution since for those operators that were ruled out by the current LHC data, their best fitted effective scales are all less than 100 GeV. For such low scale, using the effective dark matter interaction may not be reliable at the LHC [17, 18]. Nevertheless, the surviving SI operators $O_{1,7,15,17,19}$ from the current LHC-8 data can be further probed in the LHC-14 run using the monojet as well as the monophoton events.

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