Letter of Interest: Effective Field Theory for Dark Matter Direct Detection

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Abstract: Dark matter (DM) scattering on nuclei in direct detection experiments is well suited to an Effective Field Theory (EFT) description. We review two parametrizations of DM interactions: the three flavor DM EFT where the degrees of freedom are the DM, quarks, gluons and, photons; and the NR EFT where the degrees are the DM, protons, and neutrons. In practice, the results of direct DM detection experiments are most conveniently compared using the partonic three flavor DM EFT, since in this case the Wilson coefficients can be taken constant (w.r.t. the momentum transfer), and can be rather straightforwardly compared to UV models. This, then, captures all DM UV models in which the mediators are heavier than a few hundred MeV. We also discuss the use of EFTs for connecting the low energy direct detection scattering rates with the UV DM theory. All the results of this program are available in the DirectDM computer code.

Introduction. For a large class of dark matter (DM) models, the physics of direct detection experiments can be described using Effective Field Theories (EFTs) [1–29]. The reason is that the momentum transfer q for DM scattering on a nucleus is small, typically less than 200 MeV, so that the effect of forces mediated by particles heavier than this scale can be described by an EFT. Furthermore, the interactions between the DM and the nucleus can be organized via a power counting parameter q/Λ_χ where q is the momentum transfer and Λ_χ is the chiral symmetry breaking scale. (That is, the interactions are organized by their chiral dimension [30, 31].)

The construction of DM EFTs has two goals. The first goal is to compare the results of direct detection experiments that use different target materials in a model-independent way. To achieve this, a DM EFT valid at a scale $\mu \simeq 2$ GeV can be constructed. The second goal is to connect the results of the direct detection experiments to the physics at much higher scales: indirect DM searches, DM production at the LHC, and ultimately to the full UV theory of DM. In this case one can construct a tower of EFTs, see Fig. 1.

DM EFT for comparing direct detection experiments. At low energies, the interactions of DM with the SM can be parametrized in two different ways. The first is in terms of an EFT where DM interacts with quarks, gluons, and photons (three-flavor DM EFT at $\mu \simeq 2$ GeV [21]). The second option is the Galilean invariant EFT, or NR-EFT, in which DM interacts with non-relativistic neutrons and protons [9, 10, 12]. NR-EFT is an EFT, in a strict sense, only in the limit where $q \ll m_\pi$ and $e \to 0$, where e is the electric charge – i.e. also neglecting QED effects. In this case, the NR-EFT is the pion-less (and photon-less) limit of chiral EFT for DM [18–20].

In the three-flavor DM EFT, the operators are organized in terms of operator dimensions so that the effective Lagrangian takes the form $\mathcal{L}_{\rm DMEFT} = \sum_{d,a} \mathcal{C}_a^{(d)} \mathcal{Q}_a^{(d)}/\Lambda^{d-4}$, where $\mathcal{C}_a^{(d)}$ are dimensionless Wilson coefficients, and Λ is the typical scale of the UV theory for DM. The sum is over different operators, $\mathcal{Q}_a$, of dimension d. An example of a $d = 6$ operator for fermionic DM is $(\bar\chi\gamma^\mu\chi)(\bar q\gamma_\mu q)$, for a vectorial interaction, or a $d = 7$ operator $(\bar\chi\chi)G^a_{\mu\nu}G^{a\mu\nu}$ for a scalar interaction. The full basis of up to and including dimension-7 operators can be found in [26] for the case $m_\chi \ll \Lambda$.

By contrast, in the NR-EFT, the degrees of freedom are the DM and the non-relativistic neutrons and protons. Usually the NR-EFT is truncated at leading chiral order so that the effective DM interactions take the form $\mathcal{L}_{\rm NR} = \sum_a c_a^N(q)\mathcal{O}_a^N$, where the interaction operators $\mathcal{O}_a^N$ involve the non-relativistic DM and nucleons, with the latter only entering in the form of single nucleon currents. For instance, both vector and scalar mediators give rise to an operator $\mathbb{1}_\chi \otimes \mathbb{1}_N$, where $\mathbb{1}_\chi(\mathbb{1}_N)$ are the number operators for DM (nucleons).

There are two approaches to NR-EFT that are often taken in the literature. One can work in the strict EFT limit, which corresponds to the pion-less limit of chiral EFT, and the assumption that DM does not couple to photons, even not through higher dimension operators. In this case c_a^N can be taken to be constant (see, e.g., [32–38]). The other option is to allow $c_a^N(q)$ to depend on the momentum exchange, since at $\mu = 2$ GeV QCD and QED still have long-range degrees of freedom, e.g., pions or the photon. This SM dynamics can be incorporated in a non-perturbative matching from the three-flavor DM

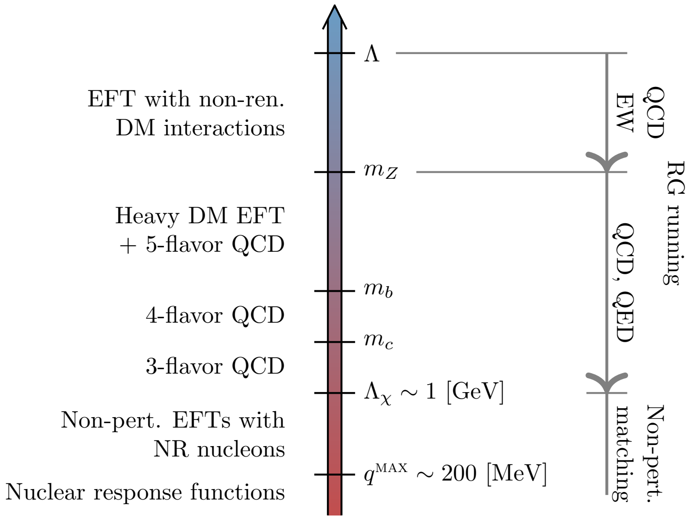

Figure 1. The tower of EFTs linking the UV scale Λ to the scale of interactions between the nucleons and the DM.

EFT onto NR-EFT (in this case NR-EFT is not an EFT in the strict sense, but is rather equivalent to the leading order of chiral EFT that includes photons as dynamical degrees of freedom). The $c_a^N(q)$ can then be viewed as functions of $\mathcal{C}_a^{(d)}$ with known dependence on the momentum transfer, q; the leading order expressions are given, e.g., in [21].

Taking $c_a^N(q)$ to be constant unnecessarily introduces model dependence into the NR-EFT. For instance, such a choice does not capture DM UV theories that give dominant contributions to either of the two dimension 5 operator in the three-flavor EFT (see Sec. 4 of [21]), or to one out of four dimension 6 operators, or to four out of ten dimension 7 operators (not counting flavor multiplicities). Furthermore, the limit of constant c_a^N does not appreciably reduce the number of unknown parameters: there would be 24 parameters that are to be varied in direct detection fits to NR-EFT assuming only $\mathcal{O}_1^N, \ldots, \mathcal{O}_{12}^N$ non-relativistic operators are generated vs. 25 independent combinations of Wilson coefficients $\mathcal{C}_a^{(d)}$ that would be varied in three flavor EFT fits staying at dimension 7 (excluding dimension 7 operators with derivatives) and at leading order in chiral expansion.

Therefore, we argue that the model-independent comparison of direct detection experiments is best done as follows: the Wilson coefficients $\mathcal{C}_a^{(d)}$ in three-flavor DM EFT can be taken to be constants that can be freely varied in a fit. Since the DM EFT has a clear counting by operator dimension, one can truncate the expansion, for instance at dimension 7, making the approach tractable in terms of the number of unknown parameters. Furthermore, the matching onto the NR-EFT, or more generally the chiral EFT [18, 20, 39], is organized via a power counting parameter (i.e. the chiral expansion). The leading-order expressions are given in [21], but sub-leading contributions, such as the effect of two-body currents, can also be included [29, 39, 40]. The nuclear responses can then be calculated using the NR-EFT/chiral EFT. This approach captures all UV models of DM where the mediators are heavier than a few hundred MeV.

Connecting with the UV. When connecting the results of direct detection experiments to the UV theory of DM several different scales enter: the DM mass, m_χ, the scale of the DM-SM mediators, Λ, and, finally, the standard model (SM) scales – the masses of the SM particles and the scale of strong interactions, $\Lambda_{\rm QCD}$. The hierarchy between these scales determines which EFTs constitute the tower that connects the direct detection and UV scales, see, e.g., Fig. 1. We are in the middle of a program of constructing the EFTs for each self consistent ordering of the EFT scales, as well as for various DM spins and electroweak quantum numbers. The ultimate goal is to provide leading-order predictions for direct detection rates for any choice of a UV theory. This also means that electroweak corrections need to be included since they mix operators with very different non-relativistic limits. The current and future results of this research are available in the form of the DirectDM computer code.

References

[1] J. Bagnasco, M. Dine and S. D. Thomas, *Detecting technibaryon dark matter*, *Phys. Lett.* **B320** (1994) 99–104, [hep-ph/9310290].

[2] M. Pospelov and T. ter Veldhuis, *Direct and indirect limits on the electromagnetic form-factors of WIMPs*, *Phys. Lett.* **B480** (2000) 181–186, [hep-ph/0003010].

[3] A. Kurylov and M. Kamionkowski, *Generalized analysis of weakly interacting massive particle searches*, *Phys. Rev.* **D69** (2004) 063503, [hep-ph/0307185].

[4] J. Kopp, T. Schwetz and J. Zupan, *Global interpretation of direct Dark Matter searches after CDMS-II results*, *JCAP* **1002** (2010) 014, [0912.4264].

[5] J. Fan, M. Reece and L.-T. Wang, *Non-relativistic effective theory of dark matter direct detection*, *JCAP* **1011** (2010) 042, [1008.1591].

[6] V. Cirigliano, M. L. Graesser and G. Ovanesyan, *WIMP-nucleus scattering in chiral effective theory*, *JHEP* **10** (2012) 025, [1205.2695].

[7] R. J. Hill and M. P. Solon, *Universal behavior in the scattering of heavy, weakly interacting dark matter on nuclear targets*, *Phys.Lett.* **B707** (2012) 539–545, [1111.0016].

[8] R. J. Hill and M. P. Solon, *WIMP-nucleon scattering with heavy WIMP effective theory*, *Phys. Rev. Lett.* **112** (2014) 211602, [1309.4092].

[9] A. L. Fitzpatrick, W. Haxton, E. Katz, N. Lubbers and Y. Xu, *The Effective Field Theory of Dark Matter Direct Detection*, *JCAP* **1302** (2013) 004, [1203.3542].

[10] A. L. Fitzpatrick, W. Haxton, E. Katz, N. Lubbers and Y. Xu, *Model Independent Direct Detection Analyses*, 1211.2818.

[11] J. Menendez, D. Gazit and A. Schwenk, *Spin-dependent WIMP scattering off nuclei*, *Phys. Rev.* **D86** (2012) 103511, [1208.1094].

[12] N. Anand, A. L. Fitzpatrick and W. C. Haxton, *Weakly interacting massive particle-nucleus elastic scattering response*, *Phys. Rev.* **C89** (2014) 065501, [1308.6288].

[13] P. Klos, J. Menéndez, D. Gazit and A. Schwenk, *Large-scale nuclear structure calculations for spin-dependent WIMP scattering with chiral effective field theory currents*, *Phys. Rev.* **D88** (2013) 083516, [1304.7684].

[14] M. Cirelli, E. Del Nobile and P. Panci, *Tools for model-independent bounds in direct dark matter searches*, *JCAP* **1310** (2013) 019, [1307.5955].

[15] G. Barello, S. Chang and C. A. Newby, *A Model Independent Approach to Inelastic Dark Matter Scattering*, *Phys. Rev.* **D90** (2014) 094027, [1409.0536].

[16] R. J. Hill and M. P. Solon, *Standard Model anatomy of WIMP dark matter direct detection II: QCD analysis and hadronic matrix elements*, *Phys.Rev.* **D91** (2015) 043505, [1409.8290].

[17] R. Catena and P. Gondolo, *Global fits of the dark matter-nucleon effective interactions*, *JCAP* **1409** (2014) 045, [1405.2637].

[18] M. Hoferichter, P. Klos and A. Schwenk, *Chiral power counting of one- and two-body currents in direct detection of dark matter*, *Phys. Lett.* **B746** (2015) 410–416, [1503.04811].

[19] M. Hoferichter, P. Klos, J. Menendez and A. Schwenk, *Analysis strategies for general spin-independent WIMP-nucleus scattering*, *Phys. Rev. D* **94** (2016) 063505, [1605.08043].

[20] F. Bishara, J. Brod, B. Grinstein and J. Zupan, *Chiral Effective Theory of Dark Matter Direct Detection*, *JCAP* **1702** (2017) 009, [1611.00368].

[21] F. Bishara, J. Brod, B. Grinstein and J. Zupan, *From quarks to nucleons in dark matter direct detection*, *JHEP* **11** (2017) 059, [1707.06998].

[22] F. D'Eramo, B. J. Kavanagh and P. Panci, *You can hide but you have to run: direct detection with vector mediators*, *JHEP* **08** (2016) 111, [1605.04917].

[23] F. Bishara, J. Brod, B. Grinstein and J. Zupan, *DirectDM: a tool for dark matter direct detection*, 1708.02678.

[24] F. D'Eramo, B. J. Kavanagh and P. Panci, *Probing Leptophilic Dark Sectors with Hadronic Processes*, *Phys. Lett.* **B771** (2017) 339–348, [1702.00016].

[25] J. Brod, B. Grinstein, E. Stamou and J. Zupan, *Weak mixing below the weak scale in dark-matter direct detection*, *JHEP* **02** (2018) 174, [1801.04240].

[26] J. Brod, A. Gootjes-Dreesbach, M. Tammaro and J. Zupan, *Effective Field Theory for Dark Matter Direct Detection up to Dimension Seven*, 1710.10218.

[27] C.-Y. Chen, R. J. Hill, M. P. Solon and A. M. Wijangco, *Power Corrections to the Universal Heavy WIMP-Nucleon Cross Section*, *Phys. Lett.* **B781** (2018) 473–479, [1801.08551].

[28] M. Hoferichter, J. Menendez and A. Schwenk, *Coherent elastic neutrino-nucleus scattering: EFT analysis and nuclear responses*, 2007.08529.

[29] M. Hoferichter, P. Klos, J. Menendez and A. Schwenk, *Nuclear structure factors for general spin-independent WIMP-nucleus scattering*, *Phys. Rev. D* **99** (2019) 055031, [1812.05617].

[30] S. Weinberg, *Nuclear forces from chiral Lagrangians*, *Phys. Lett.* **B251** (1990) 288–292.

[31] S. Weinberg, *Effective chiral Lagrangians for nucleon - pion interactions and nuclear forces*, *Nucl. Phys.* **B363** (1991) 3–18.

[32] PandaX-II collaboration, J. Xia et al., *PandaX-II Constraints on Spin-Dependent WIMP-Nucleon Effective Interactions*, *Phys. Lett. B* **792** (2019) 193–198, [1807.01936].

[33] Z. Liu, Y. Su, Y.-L. Sming Tsai, B. Yu and Q. Yuan, *A combined analysis of PandaX, LUX, and XENON1T experiments within the framework of dark matter effective theory*, *JHEP* **11** (2017) 024, [1708.04630].

[34] SuperCDMS collaboration, K. Schneck et al., *Dark matter effective field theory scattering in direct detection experiments*, *Phys. Rev. D* **91** (2015) 092004, [1503.03379].

[35] COSINE-100, Sogang Phenomenology Group collaboration, G. Adhikari et al., *COSINE-100 and DAMA/LIBRA-phase2 in WIMP effective models*, *JCAP* **06** (2019) 048, [1904.00128].

[36] DarkSide-50 collaboration, P. Agnes et al., *Effective field theory interactions for liquid argon target in DarkSide-50 experiment*, *Phys. Rev. D* **101** (2020) 062002, [2002.07794].

[37] DEAP collaboration, P. Adhikari et al., *Constraints on dark matter-nucleon effective couplings in the presence of kinematically distinct halo substructures using the DEAP-3600 detector*, 2005.14667.

[38] CDEX collaboration, Y. Wang et al., *First Experimental Constraints on WIMP Couplings in Effective Field Theory Framework from the CDEX Experiment*, 2007.15555.

[39] V. Cirigliano, M. L. Graesser, G. Ovanesyan and I. M. Shoemaker, *Shining LUX on Isospin-Violating Dark Matter Beyond Leading Order*, *Phys. Lett. B* **739** (2014) 293–301, [1311.5886].

[40] M. Hoferichter, P. Klos, J. Menendez and A. Schwenk, *Dark-matter-nucleus scattering in chiral effective field theory*, *PoS* **CD2018** (2019) 095, [1903.11075].