LHC Dark Matter Searches

Felix Kahlhoefer

Rudolf Peierls Centre for Theoretical Physics, University of Oxford,
1 Keble Road, Oxford OX1 3NP, United Kingdom

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We review the experimental and theoretical status of dark matter searches at the LHC and the interplay with direct detection experiments. A particular emphasis is placed on discussing the usefulness and validity of effective operators and possible ways to go beyond this simple approach. Moreover, we consider cases where loop contributions are important for the comparison of collider searches and direct detection experiments.

1 Introduction

It is a remarkable fact that one of the leading experiments for the detection of weakly interacting massive particles (WIMPs) is the CERN Large Hadron Collider (LHC). Although any WIMPs produced at the LHC will escape from the detector unnoticed, we may observe large amounts of missing transverse energy ($\not{E}_T$) if one or more Standard Model (SM) particles are produced in association with the WIMPs. In particular, the LHC has the potential to produce WIMPs via their direct couplings to SM particles [1], i.e. by inverting the annihilation of WIMPs that occurred in the early Universe. In this case, one can obtain an observable signal if additional SM particles are produced via SM interactions, for example a single jet from initial state radiation.

Experimental searches for mono-jet events have been performed at the LHC by both CMS [2] and ATLAS [3]. To reduce backgrounds, experimental collaborations typically require both $\not{E}_T$ and the transverse momentum (p_T) of the primary jet to be large, i.e. of order of a few hundred GeV. Secondary jets with high p_T are usually also permitted, provided the two jets are not back-to-back. The dominant remaining backgrounds arise from $Z + j$ with invisibly decaying Z and from leptonically decaying $W + j$ with unidentified charged lepton.

Unfortunately, these backgrounds are rather large and the p_T spectrum of the signal — although slightly harder than the background — is essentially featureless. Consequently, mono-jet searches typically cannot provide conclusive information concerning the mass of the WIMPs. Nevertheless, the resulting bounds on the production cross section allow to directly constrain the couplings of WIMPs to quarks, which also determine the WIMP scattering cross section in direct detection experiments [4, 5].

Although mono-jet searches typically give the strongest constraints on the interactions of WIMPs, a convincing discovery of WIMPs at the LHC would require the observation of an excess in more than one search channel. Promising alternatives are mono-photon searches, mono-W searches, mono-Z searches, and searches for two jets or two heavy quarks in association with $\not{E}_T$. Observing an excess in several of these search channels would enable us to disentangle the couplings of WIMPs to various SM particles.

In this article, we want to address two questions: How do we make predictions (such as signal distributions) in order to optimize experimental cuts? And how do we interpret LHC searches in order to compare them with other experiments (such as direct detection)? To answer these questions, we need to specify the Lorentz structure of the assumed WIMP-quark interactions. In many cases, however, it is not necessary to specify the details of the mediator of the interaction.

2 From effective operators to simplified models

For sufficiently large mediator mass, we can integrate out the heavy mediator to obtain effective four-fermion interactions. For example, the vector operator $\mathcal{O}_\text{V} \equiv \frac{1}{\Lambda_\text{V}^2} (\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)$ could arise from integrating out a vector mediator with mass M_R and couplings g_q and g_χ to quarks and WIMPs, so that the suppression scale Λ associated with the scale of new physics would be given by $\Lambda^2 = M_R^2/(g_q\, g_\chi)$.

If the mediator is sufficiently heavy ($m_R \gg 1$ TeV), the effective interaction introduced above remain valid even at LHC energies. Both mono-jet cross sections and direct detection cross sections will then be proportional to Λ^{-4}, so that we can directly translate bounds from one kind of search to the other. For the vector operator and light WIMPs, for example, current LHC searches find $\Lambda \gtrsim 800$–900 GeV, corresponding to $\sigma_N \lesssim 10^{-39}\,\text{cm}^2$ [2, 3]. This bound implies that LHC searches are superior to direct detection experiments for $m_\chi \lesssim 5$ GeV, since collider searches do not suffer from a limitation for light WIMPs in contrast to direct detection experiments. On the other hand, LHC constraints are inferior for heavier WIMPs, since for spin-independent (SI) interactions direct detection experiments benefit from a coherent enhancement proportional to the square of the target nucleus mass. A similar bound on Λ is found for the axialvector operator, which is stronger than the typical constraints on spin-dependent (SD) interactions from direct detection experiments up to WIMP masses of a TeV. For larger masses, present collider searches cease to be constraining because of kinematics.

Because of their simplicity, effective operators can be very valuable tools to study the qualitative behaviour of different types of WIMP interactions and to develop an intuition for the relevant effects in mono-jet searches and direct detection experiments. For these reasons, there is an extensive literature on the interpretation of WIMP searches using effective operators (see e.g. [4, 6]). Nevertheless, there are reasons to be cautious when applying effective operators to LHC searches for WIMPs [5]. In particular, the UV completion should have perturbative couplings, meaning that $g_{q,\chi} \lesssim \sqrt{4\pi}$. Consequently, for $\Lambda = 900$ GeV, the mediator mass has to be smaller than about 3.2 TeV. Once the centre-of-mass energy $\sqrt{s}$ becomes comparable to this scale, we can no longer rely on an effective operator description, because the mediator may be produced on-shell (see e.g. [7, 8]).

Similarly, effective operators run into problems with unitarity [9]. For the vector operator and the process $q\bar{q} \to \chi\bar{\chi}$ one finds $\mathcal{M} = 2\sqrt{3}\, s/\Lambda^2$, so unitarity is violated for $\sqrt{s} > 1.9$ TeV, implying that new physics must appear below this scale. The conclusion is that effective operators may not be valid at the LHC, because the mediator may be accessible for LHC energies. Once the mediator can be produced on-shell, it becomes necessary to depart from an effective field theory description and specify the properties of the mediator (such as couplings, mass and decay width).

As a specific example we consider the case of a new massive gauge boson Z' arising from an additional broken $U(1)_X$ symmetry [10]. In particular, we consider an effective Lagrangian

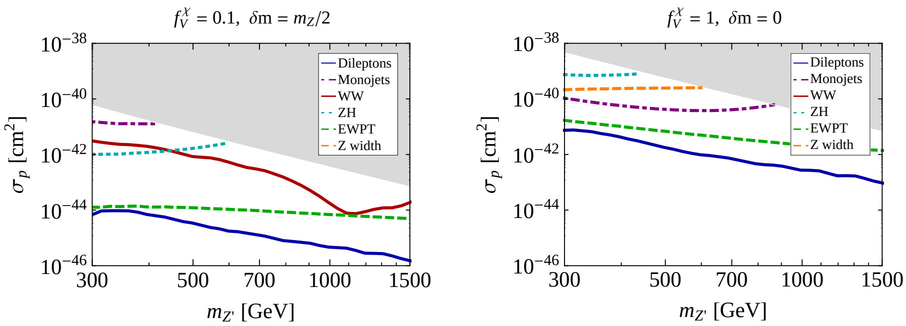

Figure 1: Bounds on the direct detection cross section for different choices of f_χ^V and δm. The grey shaded regions correspond to $\sin\epsilon > 0.8$.

that includes kinetic mixing and mass mixing [11]:

$$\mathcal{L} \supset -\frac{1}{2}\sin\epsilon\,\hat{B}_{\mu\nu}F'^{\mu\nu} + \delta m^2\,\hat{Z}_\mu Z'^\mu - f_\chi^{\mathrm{V}}\,Z'^\mu\,\bar{\chi}\gamma_\mu\chi\;.$$

There are 5 new parameters in this model: the mixing parameters $\sin\epsilon$ and δm^2, the direct coupling f_χ between the Z' and the WIMP, the Z' mass $m_{Z'}$ and the WIMP mass m_χ.

In addition to the mono-jet searches discussed above, there are three further interesting search channels at the LHC: dilepton resonances, WW resonances and ZH production [12]. The resulting bounds directly constrain the mixing parameters ϵ and δm^2. For fixed mass mixing and fixed direct couplings, these constraints can thus be interpreted as bounds on $\sin\epsilon$ as a function of $m_{Z'}$, which in turn can be translated into bounds on the WIMP direct detection cross section. The resulting constraints are presented in Figure 1 (taken from [12]).

We observe that for $f_\chi^V = 0.1$ the LHC gives strong constraints on the direct detection cross section, comparable to the best bounds from current direct detection experiments. Increasing f_χ^V relaxes all bounds from the LHC since now smaller quark couplings — and therefore smaller mixing parameters — are sufficient to obtain similar direct detection cross section. At the same time the invisible partial width of Z' is increased so that decays of Z' into SM particles are additionally suppressed. Monojet searches, on the other hand, become significantly more constraining. Thus, even for $f_\chi^V = 1$, direct detection cross section above $10^{-41}\,\mathrm{cm}^2$ are excluded by dilepton and mono-jet searches as well as electroweak precision tests (EWPT).

This example illustrates that once we move away from effective operators there may be additional experimental signatures apart from mono-jet signals that may give strong bounds on the interactions of the dark mediator. There has been a lot of recent activity in constructing sets of simplified models in order to investigate these effects more systematically [7, 8]. In addition to s-channel mediators like a Z', there has also been much interest in models with t-channel mediators, which give rise to a somewhat different phenomenology [13, 14].

3 The importance of heavy-quark loops

So far, we have neglected an important complication, which is important for both effective operators and simplified models. While the LHC produces WIMPs with energies of up to

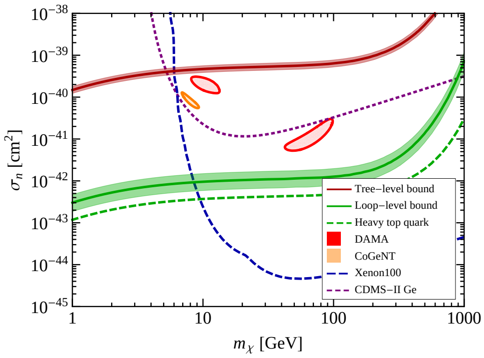

Figure 2: LHC mono-jet bounds on the WIMP-proton cross section for Yukawa-like couplings at tree-level (red) and loop-level (green) compared to various results from direct detection experiments.

several TeV, the WIMPs in the Galactic halo are non-relativistic with $v/c \sim 10^{-3}$ and the typical momentum transfer in direct detection experiments is of the order of a few MeV. To calculate direct detection cross sections, we must therefore evolve all operators from the TeV scale down to the hadronic scale. In the process, new interactions may be induced at loop level, leading to additional operators, which are assumed to be absent (or small) at the TeV scale.

As an example, we consider the exchange of a new heavy scalar or pseudoscalar mediator with Yukawa-like couplings to quarks [15]. Using tree-level diagrams alone, the suppression scale Λ is very difficult to constrain with LHC mono-jet searches [4, 5, 6] since the initial state contains (apart from gluons) only light quarks, which by assumption have small couplings to WIMPs. The situation changes dramatically beyond tree level, since now loop graphs involving virtual top quarks give rise to a $j + \not{E}_T$ signal [15]. The inclusion of these heavy-quark loops leads to a dramatic increase in the predicted mono-jet cross section and therefore a significant improvement of the bounds from LHC searches.

This observation is illustrated in Figure 2 (taken from [15]). We find that including the loop-level processes in the calculation increases the predicted mono-jet cross sections by a factor of about 500. Consequently, the inclusion of loop-level processes gives a pertinent improvement of the mono-jet bounds on the WIMP scattering cross section, in particular because it independently excludes the possibility that the CoGeNT excess or the DAMA modulation arise from the interactions of a heavy scalar mediator with Yukawa-like couplings.

It is also possible that the converse situation occurs, namely that LHC mono-jet searches give very strong bounds at tree level, because direct detection cross sections are SD. However, loop contributions can significantly boost direct detection bounds whenever they induce SI interactions. In fact, a rigorous classification of WIMP-nucleon interactions into SI and SD (or momentum suppressed) is not possible in general, as such a distinction is unstable under radiative corrections. This effect is most striking for tensor interactions, which induce magnetic dipole moments at loop level [16]. These loop-induced interactions lead to an SI part in the differential cross section that is additionally enhanced in the infrared due to the photon pole.

Bounds on the differential event rate from direct detection experiments can be used to infer strong bounds on the WIMP magnetic dipole moment. We can then convert these bounds into limits on the new-physics scale Λ entering the definition of the tensor operator and compare

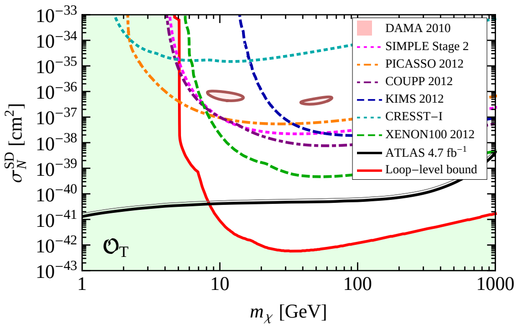

Figure 3: Bounds on the SD WIMP-nucleon cross section from direct detection experiments compared to the constraints resulting from loop-induced dark dipole moments and LHC searches for $j + \not{E}_T$.

these 'indirect' bounds on $\sigma_N^{\rm SD}$ with the conventional constraints on SD interactions from direct detection experiments with an odd number of protons or neutrons in the target atoms.

The resulting bounds and best-fit regions are shown in Figure 3 (from [16]). The solid red curve indicates the combined bound from loop-induced SI interactions. As expected, if WIMP interactions proceed via the tensor operator, experiments sensitive for SD interactions cannot currently probe the parameter region allowed by LHC mono-jet searches. Our central observation is, however, that even if we neglect the bounds from the LHC, the accessible parameter region is already excluded by constraints on the WIMP magnetic dipole moment unless $m_\chi < 5$ GeV. In other words, for $m_\chi \geq 5$ GeV there is no need for target nuclei with spin in order to constrain the tensor operator.

A related question concerns the magnitude of QCD corrections for mono-jet searches. These effects have been systematically investigated in [17] using MCFM and POWHEG. For most operators, next-to-leading order (NLO) corrections are small once parton showering (PS) is included. Nevertheless, these corrections are important, because they reduce scale dependencies and hence the theoretical uncertainty of the signal prediction.

4 Outlook

The LHC is in good shape to continue its search for WIMPs in the next few years. A recent ATLAS study concluded that with a centre-of-mass energy of 14 TeV the vector operator can be probed up to new physics scales of 2.3 TeV (corresponding to $\sigma_p \approx 3 \times 10^{-41}$ cm^2), provided even tighter cuts on $\not{E}_T$ will be applied to reduce systematic uncertainties [18]. Similarly, a 5σ discovery of vector interactions should be possible for $\sigma_p \approx 2 \times 10^{-40}$ cm^2.

In conclusion, the LHC is very well suited for constraining the WIMP production cross section and therefore probing the same interactions as direct and indirect detection experiments. A wide range of possible search channels has been investigated both by the theory community and the experimental collaborations. Although effective operators provide a convenient framework to interpret these searches, the description becomes inaccurate whenever the intermediate particles can be on-shell. As a first step to go beyond effective operators, there have been recent efforts to analyse LHC searches using simplified models (for example a Z' vector mediator).

At the same time, there has been important progress in our understanding of the importance of heavy-quark loops and NLO corrections and there are now public codes that are capable of including the resulting effects in future analyses.

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