IL NUOVO CIMENTO **38 C** (2015) 119
DOI 10.1393/ncc/i2015-15119-9

Colloquia: LaThuile15

Dark Matter: Collider *vs.* direct searches

T. Jacques

Section de Physique, Université de Genève - 24 quai E. Ansermet, CH-1211 Geneva, Switzerland

received 2 October 2015

Summary. — Effective Field Theories (EFTs) are a useful tool across a wide range of DM searches, including LHC searches and direct detection. Given the current lack of indications about the nature of the DM particle and its interactions, a model independent interpretation of the collider bounds appears mandatory, especially in complementarity with the reinterpretation of the exclusion limits within a choice of simplified models, which cannot exhaust the set of possible completions of an effective Lagrangian. However EFTs must be used with caution at LHC energies, where the energy scale of the interaction is at a scale where the EFT approximation can no longer be assumed to be valid. Here we introduce some tools that allow the validity of the EFT approximation to be quantified, and provide case studies for two operators. We also show a technique that allows EFT constraints from collider searches to be made substantially more robust, even at large center-of-mass energies. This allows EFT constraints from different classes of experiment to be compared in a much more robust manner.

PACS `95.35.+d` – Dark matter.

1. – Introduction

The LHC is searching for direct DM production at unprecedented energies, yet it has proven difficult to constrain the WIMP sector in a model-independent way. One potential solution is the use of Effective Field Theories (EFTs), where a DM-SM interaction is written as a single effective operator, integrating out the mediator. This has the satisfying feature of reducing the parameter space to a single mass ($m_{\rm DM}$) and an energy scale (Λ, also known as M_* in the literature), and reducing the number of WIMP models down to a small basis set.

Another advantage is that the EFT formalism makes it easy to compare the strength of constraints placed on DM by different experiments. Since each operator is described by just two parameters, it is easy to convert constraints on, say, the production cross section at the LHC into constraints on the DM-nucleon cross section, with conversion formulae given in, *e.g.*, refs. [1, 2]. However, it is important to remember that collider and direct searches for DM operate with completely different signals and energy scales, so that any comparison must be done carefully and bearing in mind the different range of applicability of the constraints.

One crucial difference is that the operators relevant to direct detection are the non-relativistic (NR) limits of the operators used for collider searches. There is not a one-to-one correspondence between the two sets of operators; several collider operators reduce to the same NR operator, and some collider operators correspond to a linear combination of NR operators. One consequence of this is that constraints on the usual spin-independent (SI) or spin-independent (SD) scattering cross sections apply to several collider operators, and that no single collider constraint on an operator covers the same model-space as a constraint on the SI or SD scattering rate. The translation between relativistic and non-relativistic operators has been studied in detail, *e.g.* [3, 4].

EFTs are inherently an approximation to a full UV-complete theory, and hence must be used with caution. Whilst the EFT approximation is clearly valid for the keV-scale energy transfers of direct detection experiments, the LHC is operating at a much larger energy scale where it is important to ensure that constraints on EFTs are internally consistent and fall in a region where the EFT approximation is valid. This issue has been known about since the early days of EFT studies. For example, refs. [5, 6] have compared constraints on some EFTs to those on simplified models, and found that constraints on Λ using UV complete models can either be substantially stronger or substantially weaker than those on EFTs, depending on the choice of parameters. This is especially important when comparing LHC EFT constraints with those from direct or indirect detection, as it can give a misleading impression of the relative strengths of the different classes of experiment if the LHC EFT constraints are not robust and presented with clear caveats on the range of validity.

References [7, 8] have proposed a method to quantify the validity of the EFT approximation, applying the approach to s-channel type operators. This has been extended to the t-channel in ref. [9] by considering a model where Dirac DM couples to SM quarks via t-channel exchange of a coloured scalar mediator.

The goal here is to determine the regions of parameter space where the EFT approach is a valid description of a given model. To do this, first we need to consider what the EFT approximation physically means. The approximation is made by integrating out the mediator, and combining the remaining free parameters into a single energy scale. For a tree-level interaction between DM and the Standard Model (SM) via some mediator with mass M, this corresponds to expanding the propagator in powers of $Q_{\rm tr}^2/M^2$, truncating at lowest order, and combining the remaining parameters into a single parameter Λ. For an example scenario with a Z'-type mediator this corresponds to setting

$$\frac{g_{\rm eff}^2}{Q_{\rm tr}^2 - M^2} = -\frac{g_{\rm eff}^2}{M^2}\left(1 + \frac{Q_{\rm tr}^2}{M^2} + \mathcal{O}\left(\frac{Q_{\rm tr}^4}{M^4}\right)\right) \simeq -\frac{g_{\rm eff}^2}{M^2} \equiv -\frac{1}{\Lambda^2}, \tag{1}$$

where $Q_{\rm tr}$ is the momentum carried by the mediator, $g_{\rm eff}^2 \equiv g_{\rm DM}\, g_q$, and $g_{\rm DM}$, g_q are the DM-mediator and quark-mediator couplings respectively. Similar expressions exist for other operators.

There is a necessary kinematic condition for the validity of the EFT, derived in ref. [10], which has been used in the past as a guideline for the validity of the EFT approximation. In the s-channel, the mediator must carry at least enough energy to produce the DM at rest, $Q_{\rm tr} > 2m_{\rm DM}$. For the EFT to be valid, $M > Q_{\rm tr}$, and so we require $M > 2m_{\rm DM}$. Taking the couplings as large as possible while still remaining in the perturbative regime, $g_{\rm eff}^2 \simeq 4\pi$, the relationship $\frac{g_{\rm eff}^2}{M^2} \equiv \frac{1}{\Lambda^2}$ becomes $\Lambda > \frac{m_{\rm DM}}{2\pi}$.

Clearly this is not a *sufficient* condition for the approximation to be valid. Examining eq. (1), we see that instead we must satisfy the condition

$$Q_{\rm tr}^2 \ll M^2 = g_{\rm eff}^2 \Lambda^2. \tag{2}$$

Unfortunately this condition is impossible to test in the true EFT limit, since M has been combined with $g_{\rm eff}$ to form Λ. Instead, an assumption about $g_{\rm eff}$ or choice of M must be made. There is no lower limit to the coupling strength, so regardless of the scale of Λ, it is always possible that M is small enough that the EFT approximation does not apply.

Alternatively, the most optimistic choice is to assume that $g_{\rm eff} \simeq 4\pi$, the maximum possible coupling strength such that the model could still lie in the perturbative regime. As a middle ground, we test whether the EFT approximation is valid for values of $g_{\rm eff} > 1$, a natural scale for the coupling in the absence of any other information. In this case, the condition for the validity of the EFT approximation becomes $Q_{\rm tr}^2 < \Lambda^2$, which we will adopt in the following to assess the validity of the use of EFT at LHC for DM searches.

2. – Measuring the Validity of the EFT approximation

The validity of the EFT approximation has been studied for a broad, representative range of operators in refs. [7-9]. Here we will show results for two examples. First we consider the operator describing a vector coupling between Dirac DM χ and quarks q,

$$\mathcal{O}_V = \frac{1}{\Lambda^2} \left(\bar{\chi}\gamma_\mu\chi\right) \left(\bar{q}\gamma^\mu q\right). \tag{3}$$

This corresponds to the EFT limit of a simplified Z' model with pure vector (*i.e.* no axial-vector) couplings, described by the interaction Lagrangian

$$\mathcal{L}_{\rm int} = -\sum_q Z'_\mu g_q g_{\rm DM} [\bar{q}\gamma^\mu q] - Z'_\mu \; [\bar{\chi}\gamma^\mu \chi], \tag{4}$$

where the kinetic and gauge terms have been omitted, and the sum is over all quark flavours of choice. We also consider the following effective operator describing the interactions between Dirac dark matter and left-handed quarks,

$$\mathcal{O}_t = \frac{1}{\Lambda^2} \left(\bar{\chi}P_L q\right) \left(\bar{q}P_R\chi\right). \tag{5}$$

For this operator, only the coupling between dark matter and the first generation of quarks is considered. This operator can be viewed as the low-energy limit of a simplified model describing a quark doublet Q_L coupling to DM, via t-channel exchange of a scalar mediator S_Q,

$$\mathcal{L}_{\rm int} = g\, \bar{\chi} Q_L S_Q^* + \text{h.c.} \tag{6}$$

and integrating out the mediator. This model is popular as an example of a simple DM model with t-channel couplings and a coloured mediator, which exist also in well-motivated models such as supersymmetry where the mediator particle is identified as a squark, although the DM is a Majorana particle in this case.

The standard search channel for these scenarios is missing energy plus one or more jets, although there are other promising complementary search channels. The dominant process contributing to the missing energy plus jet signal is $q\bar{q} \rightarrow \chi\bar{\chi}g$, for which the differential cross section has been calculated.

To test whether the EFT approximation is valid in jet searches, a ratio is defined of the cross section truncated so that all events pass the condition, to the total cross section:

$$R_\Lambda \equiv \frac{\sigma|_{Q_{\rm tr}<\Lambda}}{\sigma} = \frac{\int_{p_{\rm T}^{\rm min}}^{p_{\rm T}^{\rm max}} {\rm d}p_{\rm T} \int_{-2}^{2} {\rm d}\eta \left.\frac{{\rm d}^2\sigma}{{\rm d}p_{\rm T}{\rm d}\eta}\right|_{Q_{\rm tr}<\Lambda}}{\int_{p_{\rm T}^{\rm min}}^{p_{\rm T}^{\rm max}} {\rm d}p_{\rm T} \int_{-2}^{2} {\rm d}\eta \frac{{\rm d}^2\sigma}{{\rm d}p_{\rm T}{\rm d}\eta}}. \tag{7}$$

The integration limits on these quantities are chosen to be comparable to those used in standard searches for WIMP DM by the LHC Collaborations (see, for instance, refs. [11-13]).

Figures 1, 2 show isocontours of four fixed values of R_Λ as a function of both $m_{\rm DM}$ and Λ, for the $\mathcal{O}_V$ and $\mathcal{O}_t$ operators respectively. Contrasted with $\mathcal{O}_V$, the ratio for the t-channel operator has less DM mass dependence, being even smaller than in the s-channel case at low DM masses and larger at large DM masses, without becoming large enough to save EFTs.

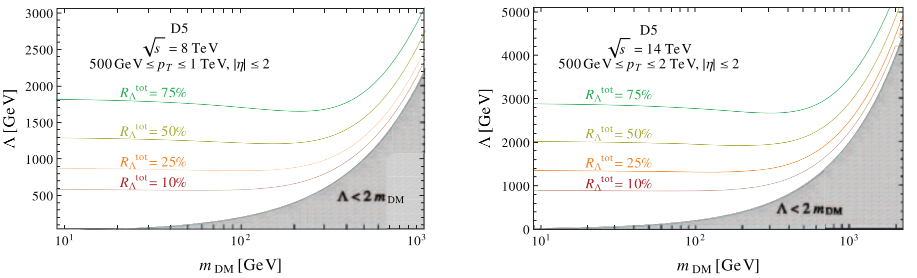

Fig. 1. – Contours of the fraction of events for which the EFT approximation is valid, for the effective operator with a vector-type coupling, at $\sqrt{s} = 8\,$TeV (left) and 14 TeV (right). The grey shaded region indicates where the EFT approximation has necessarily fully broken down for kinematic reasons. From ref. [8].

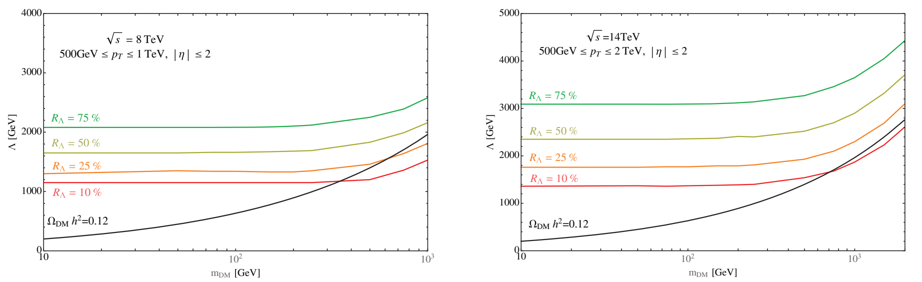

Fig. 2. – Contours of the fraction of events for which the EFT approximation is valid, for the $\mathcal{O}_t$ operator described in the text, at $\sqrt{s} = 8\,$TeV (left) and 14 TeV (right). The black solid curves indicates the correct relic abundance. From ref. [9].

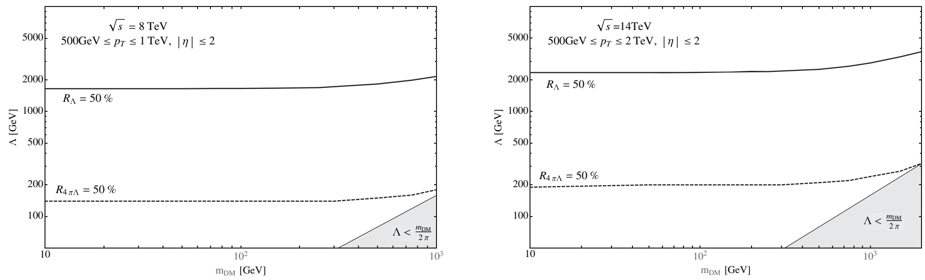

Fig. 3. – Contours for R_Λ for the $\mathcal{O}_t$ operator at $\sqrt{s} = 8\,\text{TeV}$ (left) and $14\,\text{TeV}$ (right), varying the cutoff $Q_{\text{tr}} < \Lambda$ and $Q_{\text{tr}} < 4\pi\Lambda$. The grey shaded area shows $\Lambda < m_{\text{DM}}/(2\pi)$, often used as a benchmark for the validity of the EFT. From ref. [9].

In fig. 2 we also see the curves corresponding to the correct DM relic density. For given m_{DM}, larger Λ leads to a smaller self-annihilation cross section and therefore to larger relic abundance. It is evident that the large-Λ region where the EFT is valid typically leads to an unacceptably large DM density.

In the most optimistic scenario for EFTs, the coupling strength g takes the maximum value (4π) such that the model remains in the perturbative regime. To demonstrate how these results depend on the coupling strength, fig. 3 shows isocontours for $R = 50\%$ for $\mathcal{O}_t$, for two cases: 1) the standard requirement that $Q^2_{\text{tr}} < \Lambda^2$, equivalent to requiring $g \simeq 1$, and 2) requiring $Q^2_{\text{tr}} < (4\pi\Lambda)^2$, equivalent to requiring $g \simeq 4\pi$.

The grey shaded area indicates the region where $\Lambda < m_{\text{DM}}/(2\pi)$. As discussed, this is sometimes used as a benchmark for the validity of the EFT approximation, since in the s-channel, Q_{tr} is kinematically forced to be greater than $2m_{\text{DM}}$.

3. – Rescaling EFT constraints

We have seen in the previous section that the EFT approximation is not generally valid at LHC energies. In this section we discuss a technique that can make EFT constraints *robust* at the cost of a weakened constraint. Recall that for a tree-level interaction between DM and the Standard Model (SM) via a Z'-type mediator, the EFT approximation corresponds to assuming eq. (1) holds. Similar expressions exist for other operators. Clearly the condition that must be satisfied for this approximation to be valid is eq. (2). The condition "$\ll$" is poorly defined, and so we instead use $Q^2_{\text{tr}} < g^2_{\text{eff}}\Lambda^2$ as a reasonable criteria with which to measure the validity of the EFT approximation for a given interaction.

We can use this condition to enforce the validity of the EFT approximation by restricting the signal (after the imposition of the cuts of the analysis) to events for which $Q^2_{\text{tr}} < M^2$. This truncated signal can then be used to derive the new, truncated limit on Λ as a function of $(m_{\text{DM}}, g_{\text{eff}})$.

For the operators we consider here, $\sigma \propto \Lambda^{-4}$, and so there is a simple rule for converting a rescaled cross section into a rescaled constraint on Λ if the original limit is based on a simple cut-and-count procedure. Defining $\sigma^{\text{cut}}_{\text{EFT}}$ as the cross section truncated such that all events pass the condition $g_{\text{eff}}\Lambda^{\text{rescaled}} > Q_{\text{tr}}$, we have

$$\Lambda^{\text{rescaled}} = \left(\frac{\sigma_{\text{EFT}}}{\sigma^{\text{cut}}_{\text{EFT}}}\right)^{1/4} \Lambda^{\text{original}}, \tag{8}$$

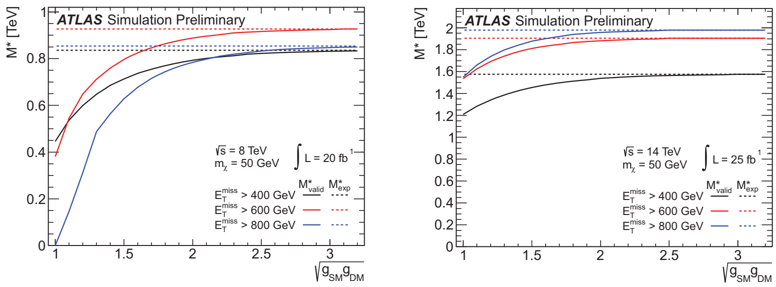

Fig. 4. – Rescaled simulated missing energy + jet limits on the $\mathcal{O}_V$ operator at 8 TeV (left) and 14 TeV (right), from ref. [13]. Note that M^* is equivalent to Λ.

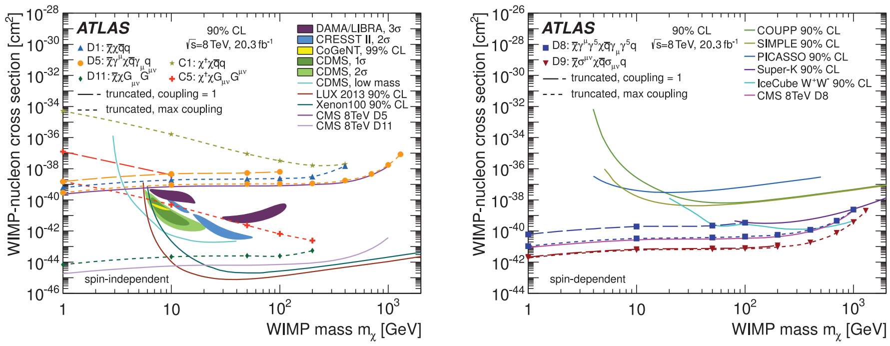

Fig. 5. – Comparison of direct detection constraints with rescaled ATLAS constraints, from ref. [12].

which can be solved for $\Lambda^{\text{rescaled}}$ via either iteration or a scan (note that $\Lambda^{\text{rescaled}}$ appears on both the LHS and RHS of the equation, via $\sigma_{\text{EFT}}^{\text{cut}}$). Similar relations exist for a given UV completion of each operator. The details and application of this procedure by ATLAS to their EFT constraints can be found in refs. [12, 13] for a range of operators. Since this method uses the physical couplings and energy scale Q_{tr}, it gives the strongest possible constraints in the EFT limit while remaining robust by ensuring the validity of the EFT approximation.

An example of this rescaling is shown in fig. 4, for the $\mathcal{O}_V$ operator, for simulated missing energy + jet constraints at 8 and 14 TeV. We see that the EFT constraint is substantially weaker than the "naive" constraint except for relatively large coupling strengths. One interesting feature is that the range of validity is larger at $\sqrt{s} = 14$ TeV than 8 TeV. This is slightly counter-intuitive, as we would expect the larger energy scale to lead to a larger Q_{tr}, and hence less validity. However, this is balanced by the fact that the baseline "naive" constraint is also much larger at 14 TeV, and hence the fraction of events passing the condition $Q_{\text{tr}} < g_{\text{eff}}\Lambda$ is greater at the larger energy scale for a given g_{eff}.

This truncation procedure allows a much fairer comparison with other experimental constraints. For a given g_{eff}, the collider EFT constraints are now robust and self-consistent, allowing comparison with direct detection results using the usual translation formulae [1, 2]. An example of this is given in fig. 5, from ref. [12], which compares

ATLAS and CMS constraints on a range of operators with direct constraints on the SI (left) and SD (right) scattering cross section from a variety of experiments. The ATLAS constraints are shown for two values of the coupling strength: $g_{\text{eff}} = 1$ as a standard benchmark, and the maximum coupling that remains in the perturbative regime as a best-case-scenario for the ATLAS constraints.

4. – Conclusions

Effective operators are a useful tool to constrain dark matter with as few free parameters as possible, however care must be taken with the assumptions involved, especially when comparing with other experiments. In this article we have introduced some measurements of the validity of the EFT approach for DM searches at colliders, by examining two reference operators, $\mathcal{O}_V$ and $\mathcal{O}_t$. It is clear that even for relatively modest coupling strengths and mediator masses, the validity of the EFT approximation at LHC energies can not be assumed, reinforcing the need to go beyond the EFT at the LHC when looking for DM signals.

However, it is not necessary to abandon the EFT approach entirely. We have reviewed a technique that allows constraints on Λ to be rescaled such that only events for which the EFT approximation is valid are utilised. This allows for a more robust comparison with other experimental constraints, for example direct detection, reinforcing the complementarity of the two approaches to DM searches.

* * *

This article is primarily based on ref. [9], by Giorgio Busoni, Andrea De Simone, TDJ, Enrico Morgante and Antonio Riotto, and ref. [12], by the ATLAS Collaboration with Andrea De Simone, TDJ and Antonio Riotto. I thank the organisers of the conference for the invitation and their generous support, and congratulate them on an excellent meeting.

REFERENCES

[1] Bai Y., Fox P. J. and Harnik R., *JHEP*, **12** (2010) 048 (arXiv:1005.3797 [hep-ph]).
[2] Goodman J., Ibe M., Rajaraman A., Shepherd W., Tait T. M. P. and Yu H. B., *Phys. Rev. D*, **82** (2010) 116010 (arXiv:1008.1783 [hep-ph]).
[3] Fitzpatrick A. L., Haxton W., Katz E., Lubbers N. and Xu Y., *JCAP*, **02** (2013) 004 (arXiv:1203.3542 [hep-ph]).
[4] Cirelli M., Del Nobile E. and Panci P., *JCAP*, **10** (2013) 019 (arXiv:1307.5955 [hep-ph]).
[5] Fox P. J., Harnik R., Kopp J. and Tsai Y., *Phys. Rev. D*, **85** (2012) 056011 (arXiv:1109.4398 [hep-ph]).
[6] Buchmueller O., Dolan M. J. and McCabe C., *JHEP*, **01** (2014) 025 (arXiv:1308.6799 [hep-ph]).
[7] Busoni G., De Simone A., Morgante E. and Riotto A., *Phys. Lett. B*, **728** (2014) 412 (arXiv:1307.2253 [hep-ph]).
[8] Busoni G., De Simone A., Gramling J., Morgante E. and Riotto A., *JCAP*, **06** (2014) 060 (arXiv:1402.1275 [hep-ph]).
[9] Busoni G., De Simone A., Jacques T., Morgante E. and Riotto A., *JCAP*, **09** (2014) 022 (arXiv:1405.3101 [hep-ph]).

[10] Goodman J., Ibe M., Rajaraman A., Shepherd W., Tait T. M. P. and Yu H. B., *Phys. Lett. B*, **695** (2011) 185 (arXiv:1005.1286 [hep-ph]).
[11] ATLAS Collaboration (Aad G. *et al.*), *Phys. Lett. B*, **705** (2011) 294 (arXiv:1106.5327 [hep-ex]).
[12] ATLAS Collaboration (Aad G. *et al.*), *Eur. Phys. J. C*, **75** (2015) 299; 408 (arXiv:1502.01518 [hep-ex]).
[13] ATLAS Collaboration (Aad G. *et al.*), ATL-PHYS-PUB-2014-007 (2014).