Abstract

In these notes we review the proposal of Ref. 2) of a method to derive consistent and reinterpretable bounds from Dark Matter searches at colliders with the use of Effective Field Theories. The results are compared with the reach of Simplified Models, and it is shown that the improved exclusion power of Simplified Models is ultimately due to the resonant production of the mediator. This motivates the interpretation of monojet searches with the Effective Field Theory, to be complemented with dedicated searches of the mediators between Dark Matter and Standard Model.

1 Dark Matter searches at colliders

The search of Dark Matter (DM) is currently one of the main tasks of Particle Physics, and plays an important role in the scientific programme of the LHC.
At colliders, DM shows up as missing energy, and we need the associated production of another object in order to tag the event. This object can be a jet, or a photon, or an electroweak boson or the Higgs boson.

To describe the interaction between DM and the Standard Model we need an appropriate description in terms of a field theory. There is a plethora of microscopic models that include a DM candidate, so it is important to identify an approach that is as model independent as possible in order to interpret the results of these searches. Two possible approaches have been used up to now to interpret the (negative) results of DM searches at colliders.

The first and most obvious one is the use of Effective Field Theories (EFT), in which the Lagrangian is including only the degrees of freedom that are relevant below a given energy threshold, that we denote by $M_{\text{cut}}$. The advantages of EFTs are their ample generality, in the sense that they can parametrise potentially any model we can think of, and the limited number of parameters they contain, once we state the maximum mass dimension of the operators we want to consider. The downside is that their predictions are reliable only if the energy scale of the event is below the cut-off scale $M_{\text{cut}}$. When considering the energy scales involved at the LHC, this condition can be often violated\(^1\).

The second approach that was suggested to partially overcome this problem is the use of Simplified Models, that contain only the essential ingredients for the description of Dark Matter and its interactions: the DM candidate, and its mediator(s) with the Standard Model. Each Simplified Model can still reproduce a class of more complete theories, and has by construction an enlarged regime of validity with respect to EFTs, because we are including in the description another degree of freedom (the mediator). As a consequence, Simplified Models have an higher number of parameters or, generically speaking, of assumptions.

\section{Deriving consistent and general bounds using the EFT}

The goal of\(^2\) is using the EFT in order to derive, in a consistent way, bounds from DM searches at colliders that can be reinterpreted in any corresponding specific model.

In an EFT there are (at least) three free parameters: the mass $m_{\text{DM}}$ of the DM particle, the dimensionful coefficient $M_*$ appearing in the coefficient of the effective operator, and the cut-off scale $M_{\text{cut}}$ for the validity of the EFT. It is important to keep in mind that $M_*$ and $M_{\text{cut}}$ are two independent parameters.

\(^1\) Deriving consistent and general bounds using the EFT

\(^2\) 2 Deriving consistent and general bounds using the EFT
The meaning of the parameter $M_{\text{cut}}$ is illustrated by fig. 1, which sketches the differential cross section, as a function of the centre-of-mass energy $E_{\text{cm}}$, for a two-to-two process in two Simplified Models (red and blue lines) and in the corresponding EFT at low energies.

![Figure 1: Schematic representation of the differential cross section for a two-to-two process in two Simplified Models (red and blue lines) and in the corresponding EFT.](image)

The predictions of the two Simplified Models coincide, by definition, with the prediction of EFT for energies up to $E_{\text{cm}} = M_{\text{cut}}$. Once we fix a given EFT and we choose a value for the free parameter $M_{\text{cut}}$ we do not have a priori any guess of the behaviour of the cross-section in the underlying model at energies above $M_{\text{cut}}$. Hence, the only robust option, although conservative, to use the cross section predicted by the EFT is to restrict it to the energy range

$$E_{\text{cm}} < M_{\text{cut}}.$$  \hspace{1cm} (1)

This corresponds to selecting only the events falling into the grey shaded region in fig. 1. The centre-of-mass energy $E_{\text{cm}}$ should be defined, operatively, as the total invariant mass of the hard final states of the process: in the reaction $p p \rightarrow \text{DM}_1 \text{DM}_2 j$, where $p$ is a proton and $j$ is a jet, $E_{\text{cm}}$ is defined as

$$E_{\text{cm}} = \sqrt{(p^\mu(\text{DM}_1) + p^\mu(\text{DM}_2) + p^\mu(j))^2}. \hspace{1cm} (2)$$

The strategy we propose is the following: the simulated signal, which has to be compared with the observed exclusion limit on the cross section, should be restricted to the subset of events that satisfy eq. (1). In this way one systematically underestimates the signal, therefore obtains conservative bounds, but this is the best that can be achieved without making further assumption on
the underlying model.

In 2) we illustrate our procedure with the exclusion limits obtained in the monojet search performed by ATLAS 3) with 10 fb$^{-1}$ at a collision energy $\sqrt{s} = 8$ TeV at the LHC. We choose a model including a Majorana fermion $X$ as DM particle, with an effective interaction with the quarks given by

\[ L_{\text{EFT}} = -\frac{1}{M_*^2} (X\gamma^\mu\gamma^5 X) \left( \sum_{\text{flavours}} \bar{q}\gamma^\mu\gamma^5 q \right). \] (3)

Further details about the experimental search and the analysis we have performed can be found in 3, 2). For present purposes, it is sufficient to say that the experimental search defines 4 signal regions (SR), each with a different cut on the transverse momentum $p_T^{\text{jet}}$ of the leading jet and on the missing transverse energy. The results of the analysis performed by using the restriction (1) are shown in fig. 2.

![Figure 2: Lower exclusion bounds on $M_*$ as a function of $m_{\text{DM}}$ for different values of $M_{\text{cut}}$, reported in the plots with the same colour of the corresponding lines. The four plots correspond to the four signal regions of 3).](image-url)

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It is worth noting in fig. 2 that, for values of $M_{\text{cut}}$ below $\sim 1$ TeV, the stronger limit comes from the softer signal region (SR1, at the top left). Indeed, the higher is the cut on $p_{T}^\text{jet}$, the higher is the centre-of-mass energy required to produce signal, and the less likely it is for a signal event to pass the requirement (1). This shows that, in order to improve the sensitivity for low values of $M_{\text{cut}}$, it is important to improve the sensitivity in the softer signal regions.

By looking at fig. 2, we could ask ourselves what is a plausible value for $M_{\text{cut}}$. One can relate two dimensionful parameters of the EFT, $M_*$ and $M_{\text{cut}}$, through a relation of proportionality

$$M_{\text{cut}} = g_* M_*,$$

where $g_*$, which we call effective coupling strength of the effective theory, must be regarded again as a free parameter. This amounts to trading the free parameter $M_{\text{cut}}$ for another free parameter $g_*$. A possible approach is then deriving the exclusion limits for a fixed value of $g_*$, rather than for a fixed $M_{\text{cut}}$. The corresponding results are shown in fig. 3.

**Figure 3: Combined exclusion limits on $M_*$ as function of $m_{\text{DM}}$ for different values of $g_*$, reported in the plots with the same colour of the corresponding lines. The areas below the dashed lines correspond to the regions where $M_* < 2m_{\text{DM}}/g_*$, where the value of $g_*$ is the one corresponding to the colour of the dashed line. Within those regions, the condition (1) for the validity of the EFT is automatically violated.**
The consequence that can be drawn from fig. 3 is that current monojet searches do not set a bound on EFTs with a coupling strength $g_\star \lesssim 1$.

3 Comparison with the exclusion reach of Simplified Models

In order to assess the difference between the reach of the exclusion limit obtained within the EFT, restrained as we propose, and within Simplified Models, we identify two Simplified Models leading to the effective operator (3). The first one is a Simplified Model with a $Z'$ vector boson that mediates the process $qq \rightarrow XX$ in the $s$-channel at tree level, while in the second model (inspired by supersymmetric models) there are coloured scalar mediators exchanged in the $t$-channel at tree level. For more details about these models, see 2).

The bound obtained in the EFT can be immediately recast once we specify the relation between the expression of the parameters of the EFT in terms of the parameters of the Simplified Model: in the case of model B for example, we identify $M_{\text{cut}}$ with the mass $\tilde{m}$ of the scalar mediators, and $M_\star$ turns out to be equal to $2\tilde{m}/g_{\text{DM}}$, where $g_{\text{DM}}$ is a coupling parameter. Therefore the exclusion limit shown in fig. 3 can be directly recast as the blue line in fig. 4.

The bound obtained by using the full Simplified Model is shown by the purple lines. It can be seen that they are sensibly different from the bound of the truncated EFT only for mediator massed of the order of 1 TeV. This suggests that the enhanced exclusion power of the Simplified Model is due to the resonant production of the mediator, which enhances the cross section of the signal and thus leads to stronger exclusion bounds. This supposition is confirmed by the red lines, which show the exclusion limit that is obtained by restricting the Simplified Model signal to the events for which the mediator is resonantly produced 1. As it is evident from fig. 4, the red lines reproduce the bound from the purple ones in the region where they differ from the truncated EFT.

This means that the difference between the bound obtained within the EFT, used in a consistent and robust way with the truncation procedure we propose, and the bound obtained within the Simplified Model approach, is due only to the presence of the mediator in the latter description.

1More precisely, this condition is defined as follows: if $q^n$ is the 4-momentum flowing on the mediator line, we say that the mediator is resonantly produced if $|q^2 - \tilde{m}^2|$ is smaller than twice the mediator width.
Figure 4: Exclusion limits on $M_*$ as function of the mediator mass $\tilde{m}$ for $m_X = 50$ GeV. The blue line shows the recasting, in the Simplified Model, of the limit obtained within the truncated EFT. The purple lines are obtained in the full Simplified Model, while the red ones represent the limit obtained by using the subset of simulated events where the mediator was resonantly produced. Solid and dashed lines correspond to two different values of the mediator width, respectively $\tilde{m}/(8\pi)$ and $\tilde{m}/3$.

4 Conclusions

In ref. 2) we propose a method to derive bounds from the EFT in a consistent and robust way, by reducing the simulated signal to the events for which the centre-of-mass energy $E_{cm}$ is smaller than the cut-off scale $M_{cut}$ of the EFT, which is a free parameter, and using only those events to set a constraint. These bounds, although more conservative than the ones obtainable with the full EFT or with a Simplified Model, can be easily recast in any full theory one can think of.

As a second important point, we show that the enhanced exclusion power of Simplified Models with respect to what achieved with the truncated EFT is due only to the resonant production of the mediator in the Simplified Model. The search of the mediators is clearly better addressed by dedicated searches. Therefore we argue that the most robust and effective way to study exclusion limits on Dark Matter at particle colliders is to interpret mono-particle searches (as monojet ones) with the Effective Field Theory, restricted to its regime of
validity, and to complement them with the direct dedicated searches of the mediator(s) between DM and Standard Model, as for example di-jet and multi-jet searches.

References

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2. D. Racco, A. Wulzer and F. Zwirner, JHEP 1505 (2015) 009.

3. ATLAS Collaboration, ATLAS-CONF-2012-147.