Effective Theory Descriptions of Dark Matter Interactions

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This write-up covers an invited talk prepared for the Rencontres de Moriond QCD conference in 2012. It provides some theoretical thoughts regarding searches for new phenomena at high energy colliders, with some specific reference to signatures including missing transverse momentum, which provide natural probes of the nature of dark matter.

1 Introduction

There is over-whelming evidence that the Universe contains a large fraction of dark non-baryonic matter [1], yet its nature remains elusive. Among the variety of possibilities, weakly interacting massive particles (WIMPs) remain the most compelling vision for dark matter, because they offer a natural explanation of the observed abundance of dark matter which is roughly independent of the detailed thermal history of the Universe. WIMPs are also an interesting candidate because they have "large" (very roughly weak scale) interactions with ordinary matter, leading to good prospects for their detection by particle physics experiments.

Given a specific model containing a dark matter candidate particle, such as the neutralino [2] in a model of supersymmetry with R-parity, or the lightest Kaluza-Klein particle [3] in a model with Universal Extra Dimensions,[4] one can make detailed predictions for any observable (such as relic density, direct scattering rate, indirect annihilation rate, or production of a signature at colliders) in terms of the underlying model parameters. However, in the absence of a clear indication as to which model is correct, such predictions are difficult to put together into a coherent picture of the constraints on dark matter and interrelation of the various null searches for its presence.

2 Effective Theory Descriptions of WIMP Interactions

While the details of a given WIMP model are usually involved and depend sensitively on the nature of the particles which mediate interactions between WIMPs and the Standard Model (SM) particles, a particular simplification takes place when the mediating particles are heavy compared to the momentum transfer of the processes of interest. In this limit, the mediators never appear on-shell in processes, and their effects are well approximated by an effective field theory containing contact interactions between the WIMP and the SM fields. While there is no guarantee that nature need work this way, nonetheless the effective field theory offers the possibility to capture classes of similar models in a common framework, and to compare different kinds of WIMP searches in a consistent language which allows one to highlight the strengths and weaknesses of each one.

Table 1: The list of the operators defined in Eq. (1).

Name	Type	G_χ	Γ^χ	Γ^q
M1	qq	$m_q/2M_*^3$	1	1
M2	qq	$im_q/2M_*^3$	γ_5	1
M3	qq	$im_q/2M_*^3$	1	γ_5
M4	qq	$m_q/2M_*^3$	γ_5	γ_5
M5	qq	$1/2M_*^2$	$\gamma_5\gamma_\mu$	γ^μ
M6	qq	$1/2M_*^2$	$\gamma_5\gamma_\mu$	$\gamma_5\gamma^\mu$
M7	GG	$\alpha_s/8M_*^3$	1	-
M8	GG	$i\alpha_s/8M_*^3$	γ_5	-
M9	$G\tilde{G}$	$\alpha_s/8M_*^3$	1	-
M10	$G\tilde{G}$	$i\alpha_s/8M_*^3$	γ_5	-

The effective theory is constructed to contain the WIMP and the SM fields, and is subject to Lorentz invariance and the gauge invariance of the SM. In practice we realize only the $SU(3)_C \times U(1)_{EM}$ gauge symmetries and leave the electroweak $SU(2)_W \times U(1)_Y$ implicit. As an example, in Table 1 we present the leading interactions (in an expansion in the momentum transfer) of a Majorana WIMP χ which is a SM singlet interacting with quarks and/or gluons.[5] (see also [6,7]). The operators are specified as,

$$\mathcal{L}_{int} = \sum_q G_\chi \; [\bar{\chi}\Gamma^\chi\chi] \; [\bar{q}\Gamma^q q] + G_\chi \; [\bar{\chi}\Gamma^\chi\chi] \; \left(G^a_{\mu\nu}G^{a\mu\nu} \text{ or } G^a_{\mu\nu}\widetilde{G}^{a\mu\nu}\right) \quad (1)$$

where each G_χ, parameterized by a scale M_* to some power, is a separate coefficient for each operator. It is a simple (and similar) exercise to write down effective theories applicable to WIMPs which are real or complex scalars,[6,9], Dirac fermions,[6,8,9] or vector bosons.[10]

3 Monojet Searches

Interactions of the type shown in Eq. 1 allow WIMPs to be produced at hadron colliders. Since they escape undetected from a typical detector, the strategy is to look for events containing additional hadronic radiation from which the presence of the WIMPs can be inferred due to an imbalance in the transverse momentum of the visible particles.[11,12] Since a typical event contains one jet of hadrons as well as the undetected WIMPs, this signature is known as a "mono-jet search". The null results of past searches allow one to place upper limits on the value of M_* for each operator that mediates WIMP-SM interactions. An example of typical limits placed on the operators M5 and M6 are shown in Figure 1.[13] (Similar results have also been derived independently in Refs.[14,15] from mono- and di-jet plus missing momentum signatures). At Moriond this year, it was very heartening to see that the experimental collaborations themselves are now working in the EFT framework, with news results shown from CDF[16] and CMS.[17] By re-optimizing the search strategy (rather than repurposing existing mono-jet limits designed to search for large extra dimensions), better limits on M_* are possible.

3.1 Applicability of the EFT Formalism

One legitimate concern that was raised during the discussion was how well the effective theory description is expected to capture the physics of WIMP production at a hadron collider. The essential assumption underlying the EFT is that the masses of the particles mediating the

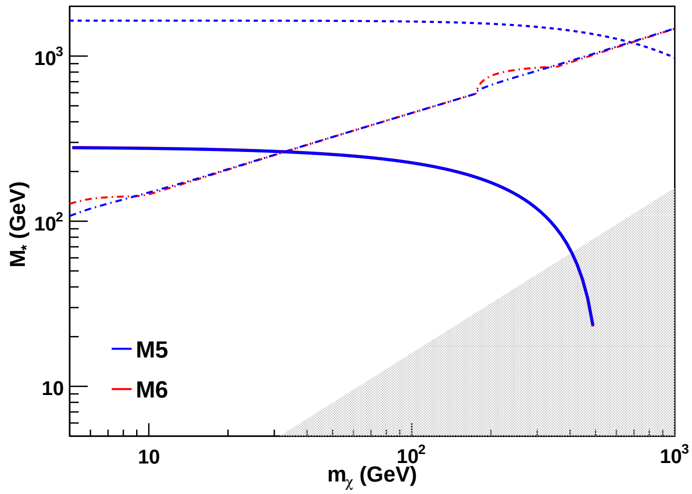

Figure 1: Tevatron bounds (solid curves) on M_* for the operators M5 (red) and M6 (blue) as a function of WIMP mass m_χ. Also shown are the M_* leading to the correct thermal relic density (dot-dashed curves) and long term (14 TeV, ~ 100 fb^{-1}) LHC prospects.

interaction (generically denoted M_ψ) are large compared to the momentum transfer of any process. In a collider mono-jet search, this requirement boils down to,

$$M_\psi \gg \max\left\{m_\chi, p_T^j\right\} \tag{2}$$

where p_T^j is the transverse momentum of the jet, which will typically cluster around the minimum jet p_T selected by the analysis (though perhaps with tails which reach higher p_T, the extent of which will depend on the collected luminosity).

For simple UV completions, one can imagine the coupling to quarks is mediated either by a neutral particle with interactions to pair of WIMPs as well as with a pair of SM quarks, or by exchange of a colored mediator which has interacts with a WIMP together with a SM quark. In the former case (which includes WIMPs whose primary interaction with the SM is by exchange of either a Z or light SM Higgs boson), the neutral mediator could either be heavy enough to use the EFT description or light enough that it will break down (for some specific investigations, see Refs.[8,14,18,19,20]) which will typically result in the EFT over-estimating the bound on M_*. A colored mediator must be heavier than the WIMP (or the WIMP would decay into it). It can be copiously produced at the LHC (and its rate is determined purely by QCD, together with the mass of the colored particle), and can decay into jets and a WIMP, resulting in jets + missing p_T signatures. Based on the null searches for new colored particles decaying into missing p_T, the LHC places bounds on the masses of such particles to be greater than about 1 TeV,[21] indicating that in this case the EFT formalism is likely to work for the current mono-jet analyses provided the WIMP mass is sufficiently below ~ 1 TeV.

It is also worth pointing out that "integrating out" the mediators is not a necessary requirement of the EFT formalism. One can build an effective theory containing the WIMP and the mediating particle, and since there are relatively few such candidate theories, one can still cover the space of such "simplified models".[22] From this point of view, the EFT as formulated here is just exploiting a universal behavior in the limit of heavy mediators inside the space of simplified models.

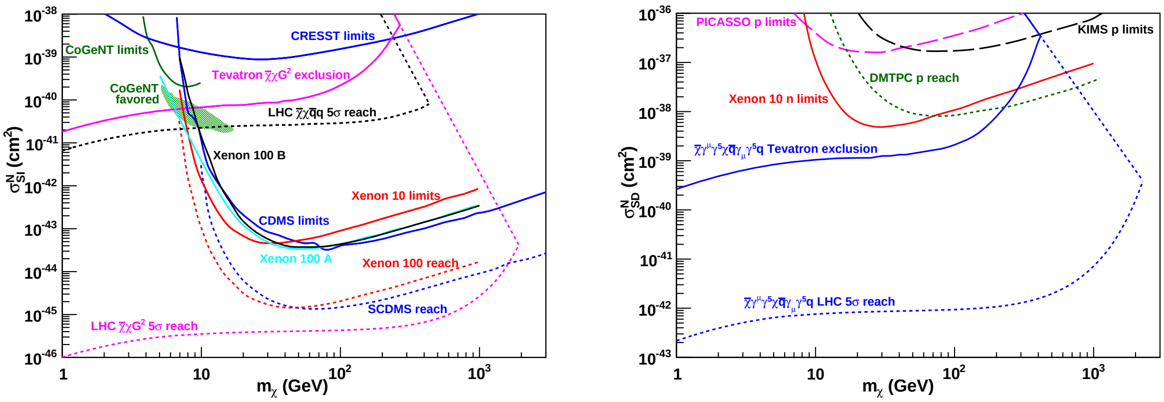

Figure 2: Bounds on the plane of spin-independent (left figure) and spin-dependent (right figure) scattering of WIMPs with nucleons versus m_χ, coming from Tevatron data and direct detection experiments, as labelled.

4 Implications for Direct and Indirect Detection

As a common language to talk about dark matter interactions with SM particles, the EFT also provides a means to translate the results of one experiment into the observables measured by another. Thus, the EFT allows one to directly compare searches at colliders with those from direct and indirect detection of dark matter. To illustrate these points, in Figure 2, we show the constraints on the direct detection plane, for dark matter interacting both independently dependently with the spin of the target nucleus.[5] A few important points of comparison emerge in the figures:

- For low mass WIMPs (m_χ less than about 10 GeV), direct detection has difficult registering the scattering, because the WIMPs carry too little energy to substantially affect the target nuclei. Colliders fill this region in, because for low masses the rate for producing relativistic WIMPs (needed for the mono-jet search) increases.

- Colliders see the colliding protons incoherently, implying that they are not subject to interference effects between dark matter interacting with quarks of various flavors (unlike in direct scattering, which sees the nucleus coherently). One side effect of this feature is that each operator for each quark flavor has a separate bound in the direct scattering plane, so one needs to label the collider bounds with the operator assumption when showing them in the direct detection parameter space.

- Collider constraints are stronger for gluon than for quark operators, which could potentially be used to learn more about a given observation in direct detection given what the LHC results turn out to be.

- Colliders are typically providing weaker bounds for theories where the WIMP interactions are coherent over the entire nucleus and WIMP masses are of order 100 GeV.

- For spin-dependent interactions, colliders provide the best bounds up to WIMP masses of order TeV, beyond which the LHC becomes energy-limited to produce dark matter relativistically (unlike direct detection experiments, which receive the dark matter for free).

This last point may be expanded: many operators lead to velocity-suppressed direct scattering for non-relativistic WIMPs. Collider searches do particularly well in such cases because they must produce the WIMPs relativistically to see them at all.

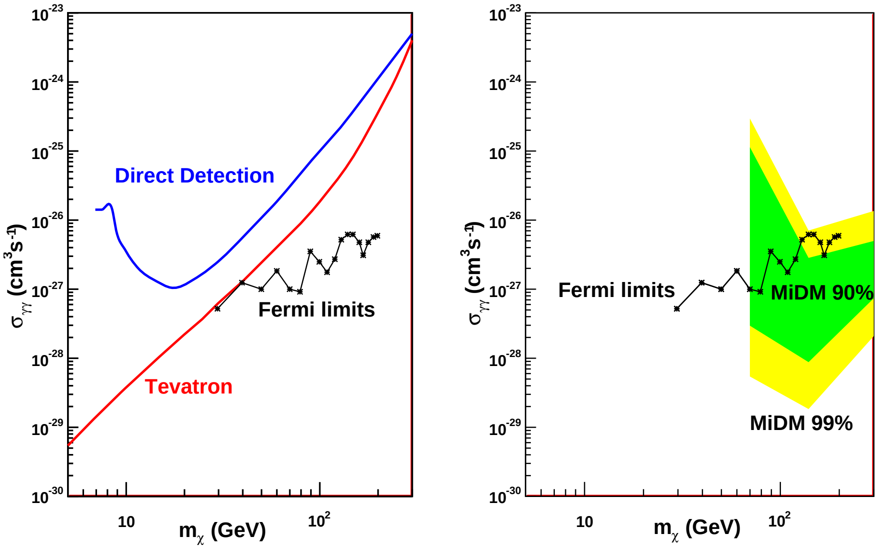

Figure 3: Bounds on the plane of the cross section for WIMP annihilation into two photons versus m_χ, coming from Tevatron data, the Fermi LAT line search, and direct detection experiments, as labelled.

Similarly, one may map collider and direct searches into the plane of indirect detection, including production of gamma rays,[23,24,25] and anti-protons.[25,26]. As an illustrative example, we compute the (loop) process of $\chi\chi \rightarrow \gamma\gamma$ for the operator M5 (which mediates spin-dependent direct scattering), closing the quarks into a loop and attaching photons. Though loop-suppressed, this process is considered a promising means to search for dark matter at a gamma ray observatory such as the Fermi LAT, because astrophysical processes have difficulty mimicking a line signal. In Figure 3, we show the line cross section for this operator, including bounds from direct searches, CDF, and Fermi itself (assuming the dark matter is distributed in an NFW profile in the galaxy).[23] The three experiments are largely complementary, with colliders providing the best bounds at low masses, the Fermi line search providing the best coverage of 30 GeV $\leq m_\chi \leq$ 200 GeV, and the direct detection experiments taking over for masses larger than around 2 TeV.

5 Outlook

Effective theories are new weapon in the theoretical arsenal to look for dark matter. Though every theory of dark matter may not be accurately parameterized in this language, it covers the limiting case of heavy mediators in a wide class of theories. Effective theories provide a powerful language through which results of different kinds of experiments may be compared, and ultimately can be used to build coherent picture of how dark matter interacts with the Standard Model.

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