Observations are confirming the WIMP paradigm

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DOI: http://dx.doi.org/10.3204/DESY-PROC-2014-03/balazs_csaba

We present a model independent analysis of thermal dark matter constraining its mass and interaction strengths with data from astro- and particle physics experiments. We show that the observationally favored dark matter particle mass region is 1-1000 GeV with effective interactions that have a cut-off in the range of 1-10 TeV.

1 Introduction

We present the results of a model independent analysis of dark matter constraining its mass and interaction strengths with data from astro- and particle physics experiments. We use the effective field theory approach to describe interactions of thermal dark matter particles of the following types: real and complex scalars, Dirac and Majorana fermions, and vector bosons. Using Bayesian inference we calculate posterior probability distributions for the mass and interaction strengths for the various spin particles. The observationally favoured dark matter particle mass region is 1-1000 GeV with effective interactions that have a cut-off at 1-10 TeV. This mostly comes from the requirement that the thermal abundance of dark matter not exceed the observed value. Thus thermal dark matter in the light of present data implies new physics most likely under 10 TeV.

2 The effective field theory framework

We follow a minimalistic, model independent approach regarding the microscopic properties of dark matter. Relying on a few major tenets, we assume

- a single dark matter particle,
- annihilating with its anti-particle,
- reaching its relic abundance by thermal freeze-out.

We represent the interactions between the dark matter particle and standard fermions with effective, four particle vertices depicted in Figure 1. These interactions can be represented with a Lagrangian containing all Lorentz and gauge invariant operators of dimension-5 for real or complex scalar and vector boson, and dimension-6 for Dirac or Majorana fermion dark matter particles

$$\mathcal{L}_\chi = \sum_{i,f} C_i \mathcal{O}_{i,f}. \tag{1}$$

Here C_i and $\mathcal{O}_{i,f}$ denote a set of coefficients and operators relevant to different structures of χ interacting with SM fields. The explicit expressions of C_i and $\mathcal{O}_{i,f}$ are shown in Table 1 for the various spin dark matter particles. For generality we couple the dark matter field to over all standard fermions f with the exception of the neutrinos.

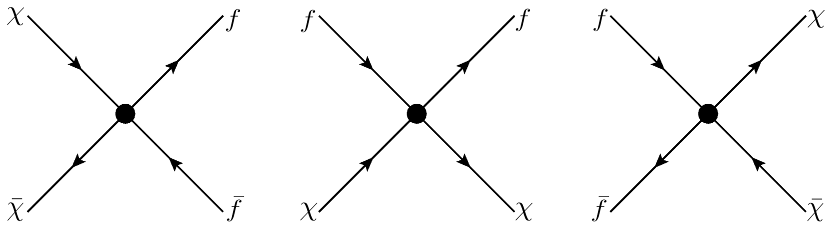


Figure 1: Effective interaction between a dark matter particle χ, its anti-particle $\bar{\chi}$, a standard matter particle f, and its anti-matter partner $\bar{f}$. The three different orientation of the same diagram shows the three different ways of observing dark matter: indirect detection (left), direct detection (middle) and collider production (right).

3 Constraint on the scale of new physics

Using the effective field theory framework the thermally averaged annihilation cross section of dark matter into standard fermions can approximately be calculated using

$$\langle \sigma_{\rm ann} v_{\rm rel} \rangle_{avg} = \frac{1}{\sqrt{8\pi}} \int_2^\infty \sigma_{\chi\chi \to f\bar{f}}(x) x^{3/2} (x^2 - 4) F_{x_F}(x) dx, \tag{2}$$

where the function $F_{x_F}(x)$ and the total annihilation cross section $\sigma_{\chi\chi\to f\bar{f}}$ are given in Ref. [1] for the various dark matter candidates we consider here.

With increasing dark matter mass and interaction cut-off scales either the relic abundance becomes too high or the resulting theory cannot be described as effective. There is thus a maximal cut-off scale at which the correct relic density can be satisfied in the effective field theory framework.

Model	m_χ (GeV)	Λ (GeV)
DF	3.0×10^4	4.7×10^3
MF	8.8×10^4	1.4×10^4
CS	4.5×10^4	7.1×10^3
RS	1.1×10^4	1.6×10^3
VB	4.8×10^4	7.7×10^3

Table 2: The maximal values for the dark matter mass and cut-off scale satisfying relic density constraint in the five considered models.

To find the approximate upper limit of the cut-off scale, we take a universal Λ in all operators for a given dark matter candidate. Then we perform the integration in Eq. (2) with a typical $x_F \equiv m_\chi/T = 30$ with T being the freeze out temperature. In order to guarantee the validity of the effective field theory framework, the cut-off scale has to be larger than the dark matter mass, i.e. $\Lambda > \frac{m_\chi}{2\pi}$. We thus set $m_\chi = 2\pi\Lambda$ in the calculation. This choice also gives the allowed upper limit of m_χ. The obtained upper limits of universal Λ and m_χ for the various dark matter models are summarized in Table 2. One can see that the upper limits of Λ are at the level of $10^3 - 10^4$ GeV with the consequent $m_\chi \sim 10^4$ GeV. The approximate numbers in Table 2 agree well with the more precise values we obtain numerically. During our numerical analysis we determine the preferred Λ ranges based on a micrOmegas calculation of the relic abundance.

Label	Operator $\mathcal{O}_{i,f}$	Coefficient C_i
D1	$\bar{\chi}\chi\bar{f}f$	$\frac{m_f}{\Lambda_{D1}^3}$
D2	$\bar{\chi}\gamma_5\chi\bar{f}f$	$\frac{im_f}{\Lambda_{D2}^3}$
D3	$\bar{\chi}\chi\bar{f}\gamma_5 f$	$\frac{im_f}{\Lambda_{D3}^3}$
D4	$\bar{\chi}\gamma_5\chi\bar{f}\gamma_5 f$	$\frac{m_f}{\Lambda_{D4}^3}$
D5	$\bar{\chi}\gamma^\mu\chi\bar{f}\gamma_\mu f$	$\frac{1}{\Lambda_{D5}^2}$
D6	$\bar{\chi}\gamma^\mu\gamma_5\chi\bar{f}\gamma_\mu f$	$\frac{i}{\Lambda_{D6}^2}$
D7	$\bar{\chi}\gamma^\mu\chi\bar{f}\gamma_\mu\gamma_5 f$	$\frac{i}{\Lambda_{D7}^2}$
D8	$\bar{\chi}\gamma^\mu\gamma_5\chi\bar{f}\gamma_\mu\gamma_5 f$	$\frac{1}{\Lambda_{D8}^2}$

Label	Operator $\mathcal{O}_{i,f}$	Coefficient C_i
V1	$\chi^\mu\chi_\mu\bar{f}f$	$\frac{m_f}{2\Lambda_{V1}^2}$
V2	$\chi^\mu\chi_\mu\bar{f}\gamma_5 f$	$\frac{im_f}{2\Lambda_{V2}^2}$
V3	$X^{\mu\nu}X_{\mu\nu}\bar{f}f$	$\frac{m_f}{4\Lambda_{V3}^4}$
V4	$X^{\mu\nu}X_{\mu\nu}\bar{f}\gamma_5 f$	$\frac{im_f}{4\Lambda_{V4}^4}$

Label	Operator $\mathcal{O}_{i,f}$	Coefficient C_i
M1	$\bar{\chi}\chi\bar{f}f$	$\frac{m_f}{2\Lambda_{M1}^3}$
M2	$\bar{\chi}\gamma_5\chi\bar{f}f$	$\frac{im_f}{2\Lambda_{M2}^3}$
M3	$\bar{\chi}\chi\bar{f}\gamma_5 f$	$\frac{im_f}{2\Lambda_{M3}^3}$
M4	$\bar{\chi}\gamma_5\chi\bar{f}\gamma_5 f$	$\frac{im_f}{2\Lambda_{M4}^3}$
M5	$\bar{\chi}\gamma^\mu\gamma_5\chi\bar{f}\gamma_\mu f$	$\frac{1}{2\Lambda_{M5}^2}$
M6	$\bar{\chi}\gamma^\mu\gamma_5\chi\bar{f}\gamma_\mu\gamma_5 f$	$\frac{1}{2\Lambda_{M6}^2}$

Label	Operator $\mathcal{O}_{i,f}$	Coefficient C_i
R1	$\chi\chi\bar{f}f$	$\frac{m_f}{2\Lambda_{R1}^2}$
R2	$\chi\chi\bar{f}\gamma_5 f$	$\frac{im_f}{2\Lambda_{R2}^2}$
C1	$\chi^\dagger\chi\bar{f}f$	$\frac{m_f}{\Lambda_{C1}^2}$
C2	$\chi^\dagger\chi\bar{f}\gamma_5 f$	$\frac{im_f}{\Lambda_{C2}^2}$
C3	$\chi^\dagger\partial_\mu\chi\bar{f}\gamma^\mu f$	$\frac{1}{\Lambda_{C3}^2}$
C4	$\chi^\dagger\partial_\mu\chi\bar{f}\gamma^\mu\gamma_5 f$	$\frac{1}{\Lambda_{C4}^2}$

Table 1: Utilized operators $\mathcal{O}_{i,f}$ and coefficients C_i, in the context of Eq. (1), for a pair of Dirac and Majorana fermion (labeled with D1-8 and M1-6), vector boson (V1-4), real and complex scalar (R1-2 and C1-4) dark matter coupling to SM fermions.

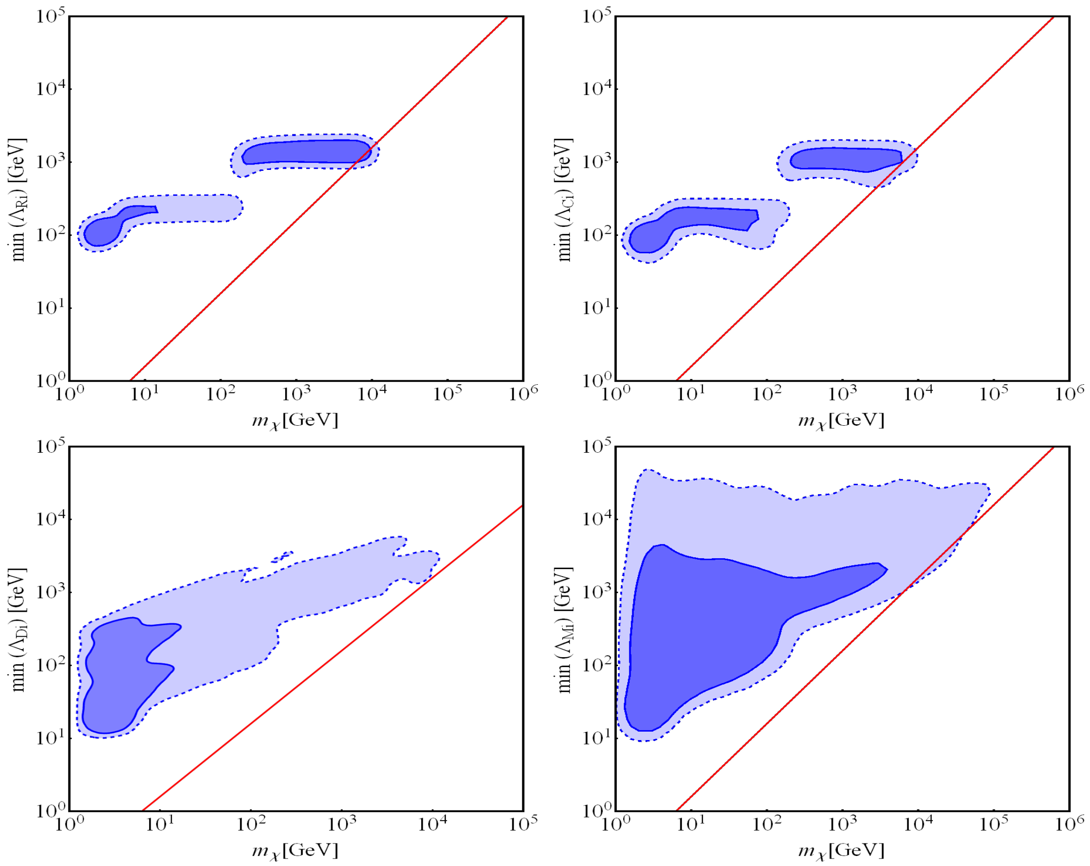
4 Preferred dark matter mass and new phyiscs scale

Using dark matter abundance, direct and indirect detection data we infer the most likely values of the dark matter mass m_χ and new physics scale Λ_i. To find the central value and credibility interval of the parameter values we use Bayesian parameter estimation. Further details of our analysis, including our likelihood function, priors and details of the evidence calculation can be found in Ref. [1].

The resulting posterior probability distributions, marginalized to the minimal cut-off scale and the dark matter mass, are shown in Figure 2. The minimal cut-off is taken to capture the dominant operator, contributing the most to the relic abundance or the direct detection cross section, at each point in the parameter space. As Figure 2 shows a light dark matter mass is favoured, in the region of 10-100 GeV. The scale where new physics cuts off the effective theory is predicted to be $10^3 - 10^4$ GeV at 1σ credible level.

5 Acknowledgments

The work of C.B. and T.L. was supported by the ARC Centre of Excellence for Particle Physics at the Terascale. J.N. was supported by an Australian Postgraduate Award and the U.S. DOE.



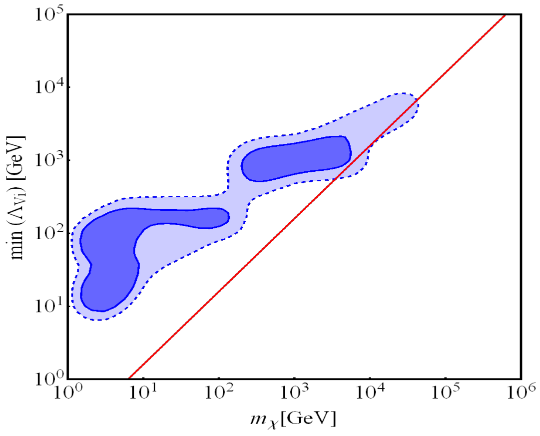


Figure 2: Posterior probability distribution marginalized to the minimal Λ scale and the mass of the dark matter particle. The light and dark regions show the 1 and 2σ credible regions, respectively. The red line indicates $\Lambda = \frac{m_\chi}{2\pi}$. The frames correspond to RS, CS, DF, MF, and VB dark matter candidates, respectively. According to these results a light dark matter mass is favoured observationally, in the region of 10-100 GeV. The scale where new physics cuts off the effective theory is predicted to be $10^3 - 10^4$ GeV at 1σ credible level.

References

[1] C. Balázs, T. Li and J. L. Newstead, JHEP **1408**, 061 (2014) [arXiv:1403.5829 [hep-ph]].