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Cosmological constraints on Dark Sector models for colliders

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I discuss ways through which Cosmology can inform searches for Dark Sector models at colliders, most notably the Large Hadron Collider. I focus on two specific examples, namely on the observed dark matter matter abundance in the Universe as predicted in some freeze-in scenarios and on the constraints that primordial nucleosynthesis can place on models involving neutral scalars beyond the Standard Model of particle physics.

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1. Introduction

During the last decade or two, there has been increasing interest in the theory and phenomenology of extensions of the Standard Model of particle physics involving "Dark Sectors". Interestingly, and despite the substantial amount of literature that exists on the topic, it is fair to say that there is no strict definition of what constitutes a "Dark Sector". The term has been used rather loosely in order to describe, for instance:

- Exotic particles that transform differently than the Standard Model ones under some discrete symmetry. This usage is sometimes encountered within the dark matter community, with the Dark Sector including all particles that are odd under a $\mathbf{Z}_2$ symmetry that is often assumed to stabilise dark matter.

- Exotic particles that are not charged under the Standard Model gauge group. Models involving such particles can be motivated by numerous different questions in high-energy physics and the corresponding states often communicate with the Standard Model particles through "portal" interactions, an example of which we will discuss in the following.

Whatever the definition, more often than not Dark Sector models are either related to open questions in (particle) cosmology or can be constrained by cosmological and/or astrophysical observations. Providing a full account of the cosmological motivations for and constraints on Dark Sector models could be (and is/has been) the topic of entire workshops and collective volumes (for a recent account containing numerous such examples *cf e.g.* [1]). In this presentation we will limit ourselves to two such examples. First, we will consider a simple model of frozen-in dark matter and we will see that different assumptions concerning the history of the Universe can motivate different searches for long-lived particles (LLPs) at the Large Hadron Collider (LHC). Secondly, we will discuss a variant of a simple Higgs portal model which can motivate the construction of different experimental facilities in the vicinity of (or within) the LHC.

2. Frozen-in dark matter and long-lived particles at the LHC

The question of the nature and origin of dark matter has motivated numerous searches for New Physics at the Large Hadron Collider. Most of these searches involve final states consisting of missing energy (MET), typically due to the pair-production of some invisible particle (the dark matter candidate), accompanied by one or more visible objects (*e.g.* jets or leptons). Having been, for the most, motivated by the thermal freeze-out picture of dark matter genesis most of these searches have looked for the production of promptly decaying particles, sometimes re-designing and re-interpreting existing searches for other types of New Physics such as supersymmetry. The fact that no significant excess has been observed so far has, however, lead to the emergence (or, at least, popularisation) of alternative ideas.

One such idea is the so-called "freeze-in" mechanism [2, 3] in which the dark matter particles, say χ_1, only interact extremely weakly ("feebly") with the Standard Model ones (*i.e.* they are Feebly Interacting Massive Particles - FIMPs) and are produced out-of-equilibrium in the early Universe, *e.g.* through decays of the type $\chi_2 \to \chi_1 + \text{SM}$, where χ_2 is some exotic state which may interact fairly strongly with the Standard Model[1].

Consider, for example, an extension of the Standard Model by a real gauge-singlet scalar field s (our dark matter candidate) and a heavy vector-like fermion F that is a singlet under $SU(2)_L$ and which carries a non-zero hypercharge, both odd under a discrete $\mathbf{Z}_2$ symmetry under which the Standard Model particles are even. Under these assumptions, and for appropriate choices of the hypercharge of F, we may write down Yukawa-like interactions between s, F and the Standard Model fermions f as

$$\mathcal{L} \supset -\left(y_{sFf}\, s \bar{F}_L f_R + \text{h.c.}\right) \tag{1}$$

where f can be a quark or a lepton, depending on the hypercharge and on the $SU(3)_c$ transformation properties of F. Thanks to its gauge interactions, the heavy fermion F was kept in thermal equilibrium with the Standard Model particles in the early Universe, whereas if the coupling y_{sFf} is feeble enough, s was kept out-of-equilibrium and was predominantly produced in association with a Standard Model fermion through decays of the type $F \to s + f$. In this case[2], the lifetime τ of F can be simply related with the predicted density Ω_s of s through

$$c\tau \approx 4.5\text{m}\, \xi\, g_F \left(\frac{0.12}{\Omega_s h^2}\right)\left(\frac{m_s}{100\text{ keV}}\right)\left(\frac{200\text{ GeV}}{m_F}\right)^2 \left(\frac{102}{g_*(m_F/3)}\right)^{3/2} \left[\frac{\int_{m_F/T_R}^{m_F/T_0} dx\, x^3 K_1(x)}{3\pi/2}\right] \tag{2}$$

where m_s, m_F are the masses of s and F, respectively, $\xi = 2$ for a decaying particle that is not self-conjugate (otherwise $\xi = 1$), g_F are the internal degrees of freedom of F, g_* are the effective degrees of freedom for the energy density, T_R is the reheating temperature of the Universe (for the purposes of this discussion, the temperature at which DM production started), T_0 is the temperature of the Universe today and the function $K_1(x)$ is a modified Bessel function of the second kind of degree one.

From our assumptions concerning the gauge transformation properties of F and from Eq. (2) we can see that

- If F is lighter than a few TeV then it can be produced at the LHC either through Drell-Yan or through QCD interactions, depending on whether it is coloured or not.
- If s is required to be a viable dark matter candidate, F is expected to decay with a macroscopic mean proper decay length which can range from a few centimeters up to many kilometers, depending on the precise value of m_F, on the dark matter mass and on our cosmological assumptions (notably the value of T_R).

In other words, explaining the observed dark matter abundance in the Universe within such a simple model motivates searches for long-lived particles at the Large Hadron Collider. The reach of these searches was studied in [4]. In Fig. 1 we show the constraints that can be obtained from existing LHC data in the $(m_F, c\tau)$ plane, assuming F is a singlet under $SU(3)_c$, from searches for displaced leptons (green region), disappearing/kinked tracks (red region) as well as searches for Heavy Stable Charged Particles (yellow region). We see that, depending on the lifetime of F, the

[1]There are other possibilities for dark matter production within the freeze-in framework, such as production through annihilations of Standard Model particles or other exotic states that could be in equilibrium with them.

[2]Note that here we are adopting the common freeze-in assumption that the initial abundance of s was negligible.

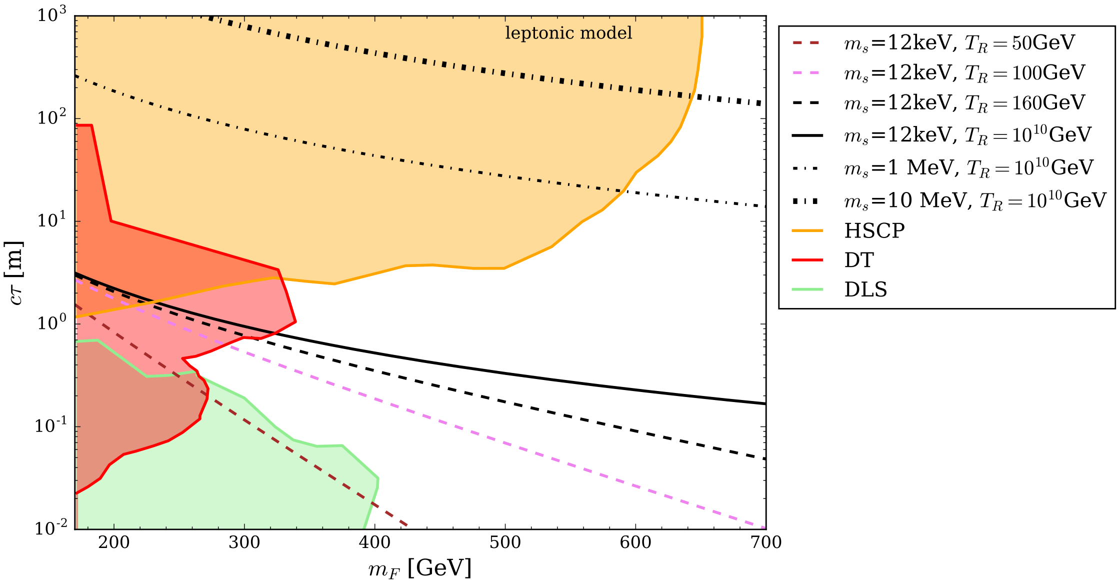

Figure 1: Summary of the LHC constraints for the lepton-like FIMP scenario. The lines correspond to contours of $\Omega_s h^2 = 0.12$ for the values of m_s and T_R given in the legend. Figure taken from [4].

LHC is already excluding m_F values that can reach values up to $\sim$ 600 GeV. A similar analysis for the case in which F transforms non-trivially under $SU(3)_c$, as well as the corresponding prospects for the High-Luminosity LHC Run can be found in [4]. An analysis of a similar scenario involving the decays of an electromagnetically (and colour-) neutral particle was presented, *e.g.*, in [5].

3. Primordial nucleosynthesis and LHC expectations for long-lived particles

In the previous section we discussed one example of how cosmological considerations (explaining the observed dark matter abundance in the Universe through the freeze-in mechanism) can motivate different searches for long-lived particles by means of the existing LHC detectors. Let us now turn to an even simpler model, which can exemplify how cosmology can provide input concerning the design and construction of novel experimental facilities altogether.

Consider an extension of the Standard Model by a real gauge-singlet scalar field s. The Lagrangian of this simple model reads

$$\mathcal{L} \supset \left(H^\dagger H\right)\left(As + \lambda s^2\right) \tag{3}$$

Note that, contrary to our previous example, in this case s *can* mix with the Standard Model Higgs boson: the Higgs boson can decay into s pairs and the latter can decay into Standard Model final states. Existing constraints on invisible Higgs decays restrict the $h \to ss$ branching ratio to be smaller than $\sim$ 10%. At the same time, if $Av \ll \lambda v^2$, where v stands for the Higgs vacuum expectation value, s can still be produced at substantial (but allowed) rates and only decay later on, potentially outside the LHC detectors. At which distance should we, then, place a detector in order to detect the decays of s?

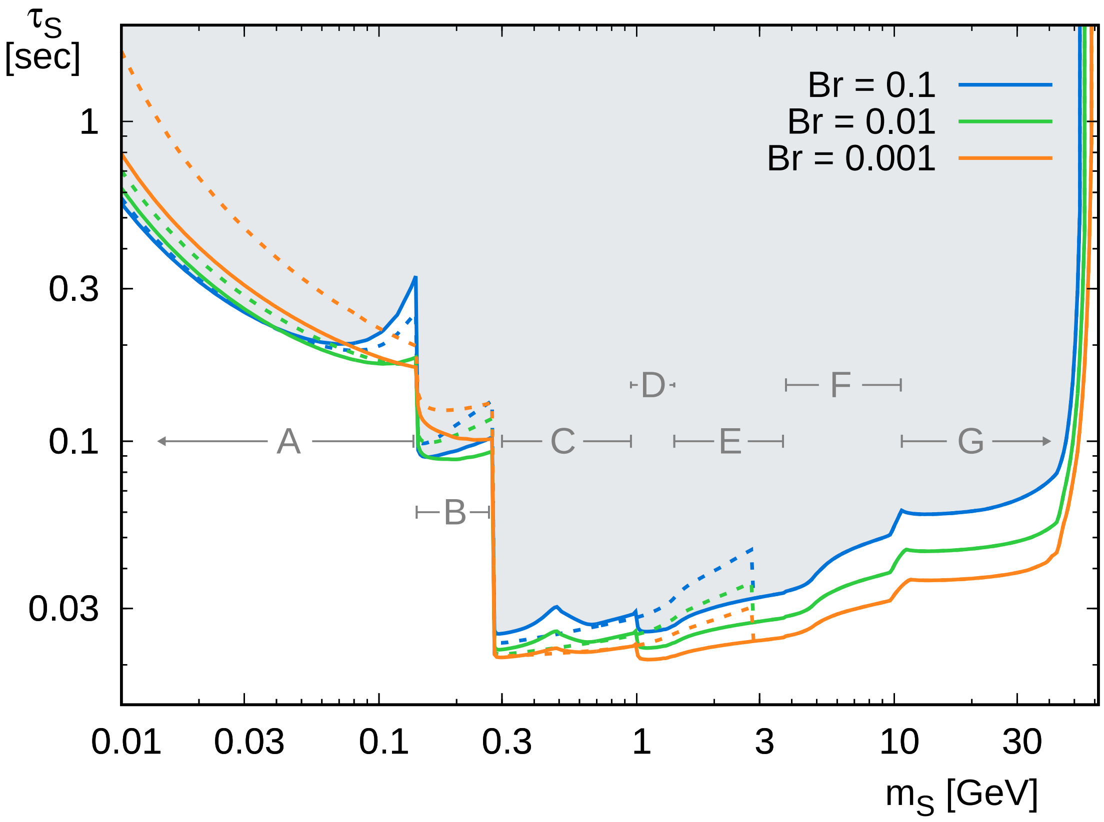

Figure 2: BBN constraints on the lifetime of s as a function of its mass, for different values of the $h \to ss$ branching ratio. Figure taken from [6], where we refer the reader for more details.

The authors of [6] showed that useful guidance in this direction can be provided by primordial nucleosynthesis (BBN). The scalar state s can be produced in the early Universe and, if its lifetime is too long, its decays may interfere with the cosmic formation of light elements which is, in turn, known to be well-described by Standard BBN theory. The amount of disruption that can be experimentally tolerated places upper limits on the lifetime of s which are summarised, as a function of its mass and for different values of the $h \to ss$ branching ratio, in Fig. 2.

As we can see, very long lifetimes are, indeed, excluded especially for s masses ranging from a few hundreds of MeV up to a few tens of GeV. A more extended analysis of this model was presented in [1], paying particular attention to the reach of different proposed experiments involving far detectors placed around the LHC main facilities. The results of this analysis are shown in Fig.3.

We can see that BBN (as well as other astrophysical and cosmological data) tightly constrain small values of the $s - h$ mixing angle for small (sub-GeV) exotic scalar masses, whereas existing LHC data probe, instead, larger values of m_s. The remaining, intermediate parameter space can be probed by proposed experiments such as MATHUSLA or SHIP, hence providing a more extended coverage of the allowed parameter space. Put simply, given the constraints stemming from BBN and the conventional LHC experiments, it is meaningful to choose the design of far detectors in order

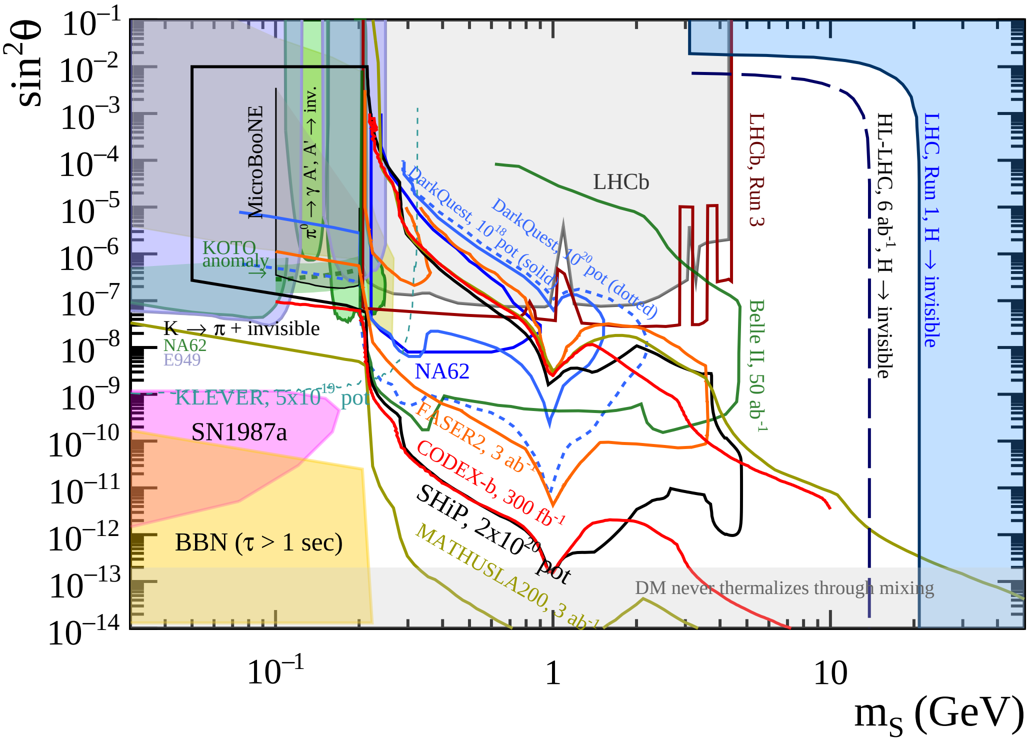

Figure 3: Constraints from existing data and reach of different proposed experiments on the mixing angle between s and h. Figure taken from [1], where we refer the reader for more details.

to probe regions of parameter space that cannot be covered by these two sources of experimental information.

4. Summary

Searches for "dark" particles have been carried out since decades but, with the exception of traditional WIMP-type dark matter searches, up to a few years ago this was perhaps slightly less the case within the collider community. Given the LHC results so far this is currently changing, with interest in Dark Sector searches at the LHC being on the rise. In this presentation we discussed two examples (and there are many more!) of how cosmology can inform these searches: we saw that freeze-in dark matter models can motivate new search channels in existing LHC detectors, notably those involving charged long-lived particles, whereas primordial nucleosynthesis can go as far as making suggestions for technical issues concerning the design of new experiments altogether (*e.g.* "at which distance from the LHC beam pipe should a detector be built?"). Cosmology has been one of the major sources of inspiration for New Physics searches at colliders. Searches for Dark Sectors at the Large Hadron Collider is no exception to this rule.

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