Theoretical models for Dark Matter

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Summary. — A brief review, focused on classes of models in which an interplay between Direct and Indirect searches of Dark Matter and searches of New Physics at the LHC can be established, is presented. Some simplified scenarios, featuring weakly as well as feebly/superweakly interacting dark matter, which can be embedded in many theoretically motivated particle physics frameworks, will be discussed.

PACS `12.60.-i` – Models beyond the standard model.
PACS `14.80.-j` – Other particles (including hypothetical).

1. – Introduction

The identification of the particle nature and of the generation mechanism of the Dark Matter (DM) component of the Universe is one of the biggest puzzles of Particle Phyiscs. A very powerful tool for getting an insight on the DM properties is the correlation of different search strategies: the Indirect Detection (ID) of the products of DM annihilation or decays in cosmic rays, the Direct Detection (DD) of scatterings of DM particles flowing through suitable detectors, or production at the LHC, either directly or from decays of other exotic states. In the following this kind of correlation will be illustrated in some simple, but general, theoretical frameworks.

2. – Monojet searches in effective Dark Matter models

The complementarity of different DM searches is particularly strong in the case of Weakly Interacting (WIMP) DM. A very powerful tool for investigating this complementarity is an effective theory description in terms of four field operators like *e.g.*: (for definiteness we consider a Dirac fermion DM) [1]:

$$\text{(1a)} \qquad \mathcal{O}_V = \frac{\overline{q}\gamma^\mu q \overline{\chi}\gamma_\mu \chi}{\Lambda^2}, \qquad \mathcal{O}_A = \frac{\overline{q}\gamma^\mu \gamma_5 q \overline{\chi}\gamma^\mu \gamma_5 \chi}{\Lambda^2},$$
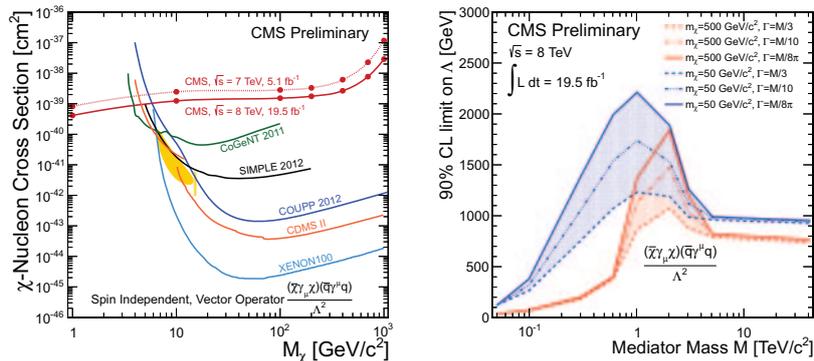
Fig. 1. – Left panel: Limit from monojet searches, effective vectorial operator, by CMS [2], translated into DM scattering cross-section together limits with current limits from DD experiments, reported in the plot. Right panel: Monojet limit re-expressed in function of the mass of a generic mediator for some values of the DM mass and of the width of the mediator reported in the plot.

with Λ representing the effective scale (including as well possible new couplings) of the new Physics originating DM interactions, possibly mimicing the mass of a heavy mediator. These operators describe pair production of DM at the LHC, which can be detected in events with missing energy plus initial state radiation, like monojets, as well as, by crossing symmetry, DM scattering on nucleons and annihilations into SM fermions, related to the relic density and possible ID. We show in the left panel of fig. 1 the limit from collider searches on Λ, reexpressed in terms of the DM scattering cross-section and compared with the constraints from dedicated experiments. Collider limits complement the ones from Direct Detection experiments since the latters are the most competitive for DM masses above $10\,\mathrm{GeV}$ while LHC searches can probe more efficiently the low mass region.

The effective theory description is however strictly valid only if there is a clear separation between the scale Λ and the one processes under study. This is not always the case for collider processes and the limits presented should be indeed modified according a more refined theoretical treatment. This kind of treatment, and a set of new limits associated, has been presented in [3]. The effective description is also unsatisfactory in the case in which the mediator is within the kinematical reach of LHC, since it can be produced on-shell, with a very strong enhancement of the monojet cross-section, with respect to the effective limit. We show indeed in fig. 1 how the limit on Λ is reformulated in terms of the mass M of a generic mediator, for some definite values its width. This result can be interpreted through this schematic expression of the monojet production cross-section:

$$(2a) \qquad \sigma\left(pp \rightarrow \overline{\chi}\chi + j\right) \approx \frac{g_{\chi}^2 g_q^2 E^2}{\left(q^2 - M^2\right)^2 + M^2\Gamma^2},$$

where E is the center-of-mass energy, q the momentum transfer and g_{χ} and g_q are the couplings of the mediator with, respectively, DM and quarks. For M sensitively greater than $\sqrt{q^2}$ the effective approximation is valid with $\Lambda \equiv M/\sqrt{g_q g_{\chi}}$. For $M \sim \sqrt{q^2} \sim 1\,\mathrm{TeV}$ the cross-section is strongly enhanced, according to Γ, and the result is interpreted as a stronger limit on Λ. For $M < 2m_{\chi}$ only off-shell contributions are present in the monojet cross-section. This is intepreted as a very weak limit on Λ.
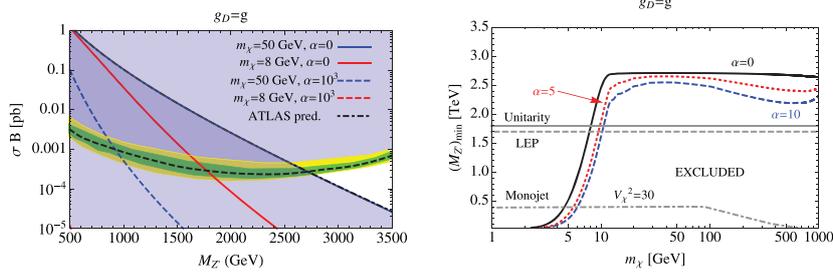
Fig. 2. – Left panel: ATLAS observed limit (dashed black line), with 1-2 σ uncertainty (green/yellow bands) on Z' production cross-section times branching fraction into a lepton pair. Red and Blue lines are the LUX exclusion limit for the values of α and DM mass reported on the plot. Minimum values of $M_{Z'}$ obtained by combining ATLAS and LUX limit for the values of $\alpha = \frac{A_D^\chi}{V_D^\chi}$ reported in the plot. Limits from monojet searches and from LEP have been reported as well. Points below the lines are excluded.

3. – Interplay between LHC and Direct DM searches in Z' scenarios

The same complementarity discussed above can be enforced as well in more refined scenarios in which specific mediators for the DM interactions with SM particles are introduced, possibly within the kinematical reach of LHC. In this case the relevant parameters are the DM and mediator masses and the new couplings. The possibility of direct production of the mediator allows to further signals which can complement the information from Dark Matter searches. A popular benchmark for searches of new physics at LHC are Z' models, consisting in extensions of the SM with an extra $U(1)$ gauge symmetry (see, *e.g.*, [4] for a theoretical review). Current experimental strategies rely on single Z' production possibly visible as resonances in, *e.g.*, dilepton distributions [5] and very severe limits have been already set. These limits are however relaxed in case of sizable coupling of the Z' with the DM since the resonances are sensitive to its visible branching fraction [6]. This effect can be studied by mean of the general Lagrangian

$$(3a) \qquad \Delta\mathcal{L} \supset g_D \bar{\chi}\gamma^\mu \left(V_D^\chi - A_D^\chi \gamma^5\right) \chi \, Z'_\mu + g_D \sum_f \bar{f}\gamma^\mu \left(V_D^f - A_D^f \gamma^5\right) f \, Z'_\mu,$$

which encompasses many existing Z' realizations in terms of five paramters: an overall gauge coupling g_D and the parameters $V_D^{f,\chi}$ and $A_D^{f,\chi}$ which represent the vectorial and axial couplings of the Z'. The parameters V_D^χ and A_D^χ, governing the invisible branching fraction of the Z', are upper bounded by DM direct detection limits. The correlation between different search strategies is again crucial.

In the left panel of fig. 2 we compare the LHC exclusion limit from searches of dilepton resonances (the strongest in case that the Z' is coupled to both leptons and quarks) with the predictions of some realizazions of Z' coupled with the DM. V_D^χ has been fixed according the exclusion limit of the LUX experiment for the considered values of the DM mass, namely 8 and 50 GeV, corresponding, respectively, to the least and most severe limits, while we have assigned values ranging from 0 to 1000 to $\alpha = A_D^\chi/V_D^\chi$. The combinations $g_D V_D^f(A_D^f)$ have been fixed in order to coincide with the interactions of the Z boson (this scenario is dubbed Sequential Standard Model (SSM)). As evident
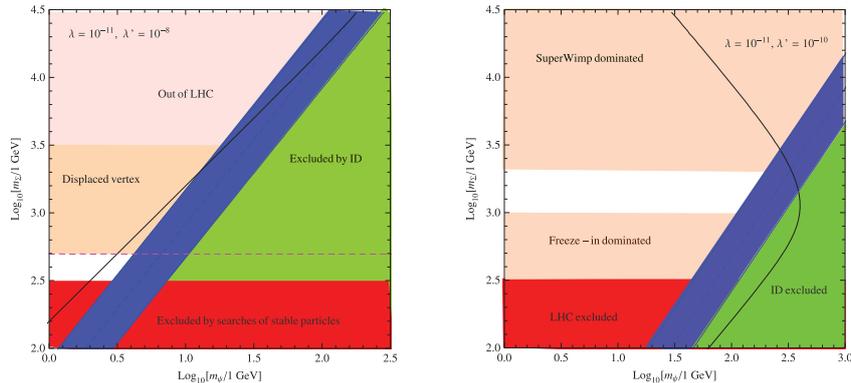
Fig. 3. – Summary plots in the plane (m_ψ, m_{Σ_f}) for two assignments of the pair (λ, λ'). The black solid lines represent the correct DM relic density while the blue bands represent a value of the DM lifetime within two orders of magnitude a reference value set to 10^{27} s. The red region is excluded by current searches of metastable particles.

LHC constraints on the mass of the Z' becomes weaker for configurations which allow for sensitive couplings, and thus sizable invisible branching ratio, of the Z' with the DM. The complementarity between LHC and DD searches is better evidenced in the right panel of fig. 2, in the plane $(m_\chi, m_{Z'})$. At high DM masses LUX limit is severe, allowing only a tiny invisible branching fraction. Current LHC limits thus apply and then the limit on the mass of Z' is independent on the DM mass. At lower DM masses the LUX limit weakens and the higher invisible branching fraction relaxes the limit on the mass of the Z'. On the other hand strong couplings with the DM make relevant the monojet production cross-section setting a lower limit to the Z' mass.

4. – LHC signals for FIMP/SuperWimp Dark Matter

An interesting alternative to conventional WIMP scenarios is constituted by feebly/superweakly interacting DM coupled to some exotic states, which can be pair produced at the LHC and are long-lived, such that decay vertices are displaced, with respect to the production ones, or might even lie outside LHC detectors. DM evades both LHC and DD detection; it is however possible to relax the assumption of exact stability of the DM and establish a correlation between Indirect Detection of DM decays LHC detection of the mediator. A simple realization has been illustrated in [7]. A scalar field, charged (at least partially) under the SM gauge group, features a Yukawa-type interaction with the DM and a standard model fermion as well as two standard model fermions (quarks or leptons according the assignment of quantum numbers):

$$(4a) \qquad L_{\mathrm{eff}} = \lambda\,\overline{\psi}f\Sigma_f^\dagger + \lambda'\overline{f}'f\Sigma_f^\dagger + \mathrm{h.c.},$$

where f, f', can be either quarks or leptons, according the assignment of the quantum numbers of Σ_f. This simple setup can be encorporated in several SuperSymmetric scenarios with Σ_f represented by a sfermion. The DM decays into three SM fermions with a rate prortional to $\lambda^2\lambda'^2$. The already strong constraints (see, $e.g.$, [8]) impose $\lambda\lambda' \leq 10^{-(16 \div 22)}$. Within this condition the conventional WIMP production is not effec-

tive. The DM can be nonetheless generated from the decays of Σ_f through a combination of freeze-in and SuperWimp production [7] and its relic density:

$$(5a) \qquad \Omega_{\mathrm{DM}}h^2 \approx \frac{m_\psi}{m_{\Sigma_f}} Br\left(\Sigma_f \to fDM\right) \left[\frac{7.17 \times 10^2 g_\Sigma}{g_*^{3/2}} \frac{\tau_\Sigma^{-1}}{m_\Sigma} + \Omega_\Sigma h^2\right]$$

is determined by the decay parameters of Σ_f which can be tested at the LHC. The LHC prospects of this scenario are summarized, through two examples, in fig. 3, in the plane (m_ψ, m_{Σ_f}). As already anticipated the possible signals of decay of the scalar field are displaced vertices or metastable tracks, the latters already probed by dedicated searches [9]. Remarkably, constraints from DM ID have already a very strong impact; in particular, by requiring an hypothetical next future contemporary LHC and ID signal it is possible to identify a rather definite region in the plane (m_ψ, m_{Σ_f}).

5. – Conclusions

The increasing experimental progress in DM searches should be accompaigned by an analogous progress of theoretical tools. Correlation between DM searches is a very powerfull tool. It has been illustrated in some simple, but theoretically motiviated, scenarios.

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