FIMP Dark Matter & Long Lived Particle Searches at the LHC

1. Classification of Possible Interactions & Phenomenology

Our starting point is the assumption of very feeble interactions between Dark Matter (DM) and the Standard Model (SM), in order for DM not to thermalize in the early Universe. We then assume that DM is a singlet under the SM gauge interactions, $F_{\rm DM}$. The interactions with the SM occur via a coupling

$$y_{\rm DM}\, X F_{\rm SM} F_{\rm DM} \tag{1}$$

where $F_{\rm SM}$ is a SM field and X is a new field which has the same properties as DM under a stabilizing symmetry (e.g. odd under a $\mathbb{Z}_2$). The DM-SM coupling is feeble, $y_{\rm DM} \ll 1$ (we have in mind $y_{\rm DM} \sim 10^{-9}$ for now, in connection to the DM freeze-in), and we also consider the scenario $m_X - m_{\rm DM} > v = 246$ GeV for now (freeze-in benchmarks that Bryan was using satisfy this).

The combination $X F_{\rm SM}$ must be a singlet under SM gauge interactions. We can then classify the possible concrete realizations of the interaction (1) (these can be found in [1], Table II). As a start, let's divide the realizations in two categories: **(I)** $F_{\rm SM}$ (and X) is an $SU(2)_L$ doublet. **(II)** $F_{\rm SM}$ (and X) is an $SU(2)_L$ singlet. In addition, we consider the case when X and $F_{\rm DM}$ have different spins (fermion-scalar or scalar-fermion), labelled **O**, vs the case when they have the same spin (fermion-fermion or scalar-scalar), labelled **S**.[1]

- **(I) O**: $F_{\rm SM}$ is a lepton doublet.[2]

  If $F_{\rm DM}$ is a scalar, then X is a fermion doublet with hypercharge $Y = 1/2$, $X = (\chi^+,\, \chi_0)$. A mass splitting between χ^+ and χ_0 is generated by loop corrections, $\Delta M_\chi = m_{\chi^+} - m_{\chi_0} = 341$ MeV [2]. As a result, the dominant decays of χ^+ are $\chi^+ \to \chi_0\, \pi^+$ and $\chi^+ \to \chi_0\, e^+ \nu_e$ via an off-shell W-boson. The width $\Gamma(\chi^+ \to \chi_0\, e^+\nu_e) \equiv \Gamma_e$ is

  $$\Gamma_e = \frac{G_F^2\, \Delta M_\chi^5}{24\, \pi^3} \sim 8 \times 10^{-13}\ \text{MeV} \tag{2}$$

  such that the decay length of χ^+ is $\sim$ 25 cm (I might have missed some factors of two in (2). Also, compute width and decay length for the dominant process $\chi^+ \to \chi_0\, \pi^+$). The decay $\chi^+ \to \ell^+ F_{\rm DM}$ is proportional to $y_{\rm DM}^2$ and thus extremely suppressed compared to Γ_e. At the same time, χ_0 is very long-lived but its decay $\chi_0 \to \nu\, F_{\rm DM}$ is purely invisible.

  Phenomenology? Charged track from χ^+, but decay products very soft! (triggering problem). Also, phenomenology is not connected to FIMP.

  If $F_{\rm DM}$ is a fermion, then X is a scalar doublet with hypercharge $Y = 1/2$, $X = (H^+,\, H_0 + iA_0)$. The situation now is different from the case above, since the scalar potential for X and the SM Higgs H

$$\begin{aligned} V(H,X) &= \mu_1^2\, |H|^2 + \mu_2^2\, |X|^2 + \frac{\lambda_1}{2}\, |H|^4 + \frac{\lambda_2}{2}\, |X|^4 \\ &+ \lambda_3\, |H|^2\, |X|^2 + \lambda_4 \left| H^\dagger X \right|^2 + \frac{\lambda_5}{2} \left[\left(H^\dagger X \right)^2 + \text{h.c.} \right] \end{aligned} \tag{3}$$

[1] We note that for **(II)**, there is only the **O** case.

[2] For phenomenology, it might be relevant to distinguish between heavy quarks/leptons (third generation) and light quarks/leptons (first & second generation). We will come back to this later on.

allows to split the masses of the states H^+, H_0 and A_0 in either direction (see e.g. [3, 4]). If $m_{H^+} > m_{A_0}, m_{H_0}$ the situation is as before.[3] For $m_{H^+} < m_{A_0}, m_{H_0}$, H^+ is long-lived and decays via $H^+ \to \ell^+ F_{\rm DM}$, yielding a displaced high-p_T lepton.

Phenomenology: For $m_{H^+} < m_{A_0}, m_{H_0}$, heavy charged LLP decaying to high-p_T lepton + DM.
MATHUSLA is most probably irrelevant in this case! (charged LLP will not reach MATHUSLA)

- **(I) O**: $F_{\rm SM}$ is a quark doublet.[2]

  Now the long-lived lighter state of the X doublet hadronizes (yields an $R-$hadron) and then decays to a quark-jet plus DM (this is the case for X being both fermionic/bosonic).

  Phenomenology: Heavy $R-$hadron decaying to high-p_T quark-jet + DM.
  MATHUSLA is most probably irrelevant in this case! ($R-$hadron will not reach MATHUSLA)

- **(I) S**: $F_{\rm SM}$ is the SM Higgs doublet.

  If $F_{\rm DM}$ is a fermion, then X is a fermion doublet with hypercharge $Y = 1/2$, $X = (\chi^+, \chi_0)$. Loop corrections generate a mass splitting $\Delta M_\chi = 341$ MeV. After EW symmetry breaking, χ_0 and $F_{\rm DM}$ mix (a tiny bit), the mixing being

$$s_\theta \simeq \frac{y_{\rm DM}\, v}{m_{\chi_0}} \tag{4}$$

  This mixing uplifts the value of m_{χ_0} by an amount $(y_{\rm DM}\, v)^2/m_{\chi_0}$ (the heavy mass eigenstate is a tiny bit heavier than the original χ_0), which is however negligible compared to ΔM_χ (I also keep calling the mass eigenstates χ_0 and $F_{\rm DM}$). So, as for **(I) O**, χ^+ decays to $\chi_0\, \pi^+$ (not very interesting). However, now the dominant decays of χ_0 are $\chi_0 \to h\, F_{\rm DM}$ and $\chi_0 \to Z\, F_{\rm DM}$ (this last one through the singlet-doublet mixing (4)). We note that both h and Z are expected to be on-shell (since we assume $m_{\chi_0} - m_{\rm DM} > v$. It would be interesting to explore the region of the FIMP parameter space where this assumption does not hold). The respective partial widths are

$$\Gamma_h \simeq \frac{y_{\rm DM}^2\, m_{\chi_0}}{32\,\pi} \qquad \Gamma_Z \simeq \frac{m_{\chi_0}^3}{64\,\pi\, v^2} s_\theta^2 \qquad (m_{\chi_0} \gg m_h, m_Z, m_{\rm DM}) \tag{5}$$

  which are shown to be comparable by using (4).

  Phenomenology: Heavy neutral LLP decaying to a $b\bar{b}$ pair (h) or to a $jj/\ell\ell$ pair (Z) + DM.
  MATHUSLA is relevant (Neutral LLP)

  If $F_{\rm DM}$ is a scalar, then X is a scalar doublet with hypercharge $Y = 1/2$, $X = (H^+, H_0 + iA_0)$. If $m_{H^+} > m_{A_0}, m_{H_0}$ the situation is as for the fermion case: neutral state H_0/A_0 decaying to $h + F_{\rm DM}$ and $Z + F_{\rm DM}$. If $m_{H^+} < m_{A_0}, m_{H_0}$, then H^+ is an LLP and decays via $H^+ \to W^+ + F_{\rm DM}$ (via the singlet-doublet mixing).

  Phenomenology: Heavy neutral LLP decaying to a $b\bar{b}$ pair (h) or to a $jj/\ell\ell$ pair (Z) + DM.
  Otherwise, Heavy charged LLP decaying to W + DM.

- **(II) O**: $F_{\rm SM}$ is a lepton or quark singlet.

  Discussion identical to **(I) O** but without the complication of X being a doublet.

References

[1] M. J. Baker *et. al.*, *JHEP* **12** (2015) 120, [1510.03434].

[3] The only difference is that now the mass splitting is not necessarily small, which will lead to a prompt decay of H^+ unless very fine-tuned.

[2] M. Cirelli, N. Fornengo, and A. Strumia, *Nucl. Phys.* **B753** (2006) 178–194, [hep-ph/0512090].

[3] R. Barbieri, L. J. Hall, and V. S. Rychkov, *Phys. Rev.* **D74** (2006) 015007, [hep-ph/0603188].

[4] L. Lopez Honorez, E. Nezri, J. F. Oliver, and M. H. G. Tytgat, *JCAP* **0702** (2007) 028, [hep-ph/0612275].