Singlet Doublet
Dark Matter Freeze-in

Alberto Mariotti

Based on arXiv:1805.04423 with:
Lorenzo Calibbi, Laura Lopez Honorez, Steven Lowette

LHC Long Lived Particle workshop -- CERN
16-18 May 2018
Freeze-In Dark Matter

- Freeze in: alternative mechanism to obtain dark matter abundance
- It naturally involves small couplings (long-lived particles)

Hall, Jedamzik, March-Russell, West '09
Blennow, Fernandez-Martinez, Zaldivar '13
Bernal, Heikinheimo, Tenkanen, Tuominen, Vaskonen '17

See Bryan talk of yesterday

Freeze-in through decay

- Mother (mediator) A in thermal equilibrium
- Decay to Dark Matter and produce it

Width (lifetime) of the mediator A determines the DM abundance
FIMP (decay) phenomenology

\[ \Omega h^2 \sim 0.12 \left( \frac{5 \text{ cm}}{c \tau_A} \right) \left( \frac{600 \text{ GeV}}{m_A} \right)^2 \left( \frac{m_\chi}{10 \text{ keV}} \right) \]

Macroscopic decay visible at LHC

Mediator accessible at the LHC

Very light Dark Matter

Typical size for detector

Light Dark Matter regime

\( m_A = 600 \text{ GeV} \)
FIMP (decay) phenomenology

\[
\Omega h^2 \sim 0.12 \left( \frac{5 \text{ cm}}{c\tau_A} \right) \left( \frac{600 \text{ GeV}}{m_A} \right)^2 \left( \frac{m_\chi}{10 \text{ keV}} \right)
\]

- Macroscopic decay visible at LHC
- Mediator accessible at the LHC
- Very light Dark Matter

Typical size for detector

Standard Cosmology history

Displaced dark matter at LHC

WDM signatures

Light Dark Matter regime

\( m_A = 600 \text{ GeV} \)
Singlet Doublet Freeze-In

✦ Minimal model with few extra fermionic states  Mahbubani, Senatore '05

\[
(\psi_u)_{2, \frac{1}{2}} = \begin{pmatrix} \psi^+ \\ \psi_u \end{pmatrix}, \quad (\psi_d)_{2, -\frac{1}{2}} = \begin{pmatrix} \psi^0_d \\ \psi^- \end{pmatrix}, \quad (\psi_s)_{1, 0}
\]

✦ Lagrangian coupling with the Higgs

\[
- \mathcal{L} \supset \mu \psi_d \cdot \psi_u + y_d \psi_d \cdot H \psi_s + y_u H^\dagger \psi_u \psi_s + \frac{1}{2} m_s \psi_s \psi_s + h.c.
\]

✦ Regime for Freeze-in: \( |y_u|, |y_d| \ll 1, \quad |m_s| \ll |\mu|, \)

Simple spectrum and decay modes

Disappearing tracks

Displaced Z/h plus MET

Similar to Higgsino-Bino with tiny mixing

Radiative corrections

Long-lived states

Dark matter
Decay modes

Decays mainly to pions and chi_2,3 on relevant parameter space

\[ \psi^\pm \rightarrow \pi^\pm \chi_{2,3} \]

Typical decay length is cm

Disappearing track limit \( \sim 150 \text{ GeV} \)

Decay modes

Charged fermion decay

Neutral fermions decay

\[ y_u \equiv y \sin \theta, \quad y_d \equiv y \cos \theta. \]

Decays to Z and h almost democratically

\[ \chi_{2,3} \rightarrow h/Z + \chi_1 \]

Decay length ranges from 0.1 to 1000 cm

Displaced Z/h plus MET
The largest values of the coupling $\mathcal{d}$ which accounts for the correct relic abundance up to a few percent level error when these expressions into Eq. These expressions show that the combinations of the decay widths entering in the computation of the relic abundance do not depend on the SM thermal bath; (ii) the number of degrees of freedom of the charged fermion. On the other hand, for the charged fermion, only $\mathcal{d} = 10^2$ is the Planck mass. This result is obtained making the following simplifying assumptions:

1. The decay widths into dark matter are the only available decay modes.
2. Decay into the lightest states of the mother particle (e.g., the Higgs) is neglected.
3. The dark matter mass $m_{\chi}$ is much larger than the mass $m_{\psi}$ of the charged lepton.

In order to reproduce the observed dark matter density, in the right panel of Figure 4, we obtain as a result

$$\Omega_{\chi_1} h^2 \approx 0.11 \left( \frac{105}{g_*} \right)^{3/2} \left( \frac{y}{10^{-8}} \right)^2 \left( \frac{m_{\chi_1}}{10 \text{ keV}} \right) \left( \frac{700 \text{ GeV}}{\mu} \right)$$

which we will denote $\mathcal{d}$. This observation will allow for very light dark matter candidates.

**Typical coupling size for displacement**

**Doublet mass scale accessible at the LHC**

**Very light DM mass, complementary cosmological constraints**
Collider signatures

Production modes at the LHC

\[ pp \rightarrow \chi_2 \chi_3 + X, \quad pp \rightarrow \psi^+ \psi^- + X, \quad pp \rightarrow \chi_{2,3} \psi^\pm + X. \]

Doublets production modes

Displacement in region of parameter space with correct relic abundance (from 1cm to 1Km)

Displaced Z/h+MET is main signature of the model!
Recasting ATLAS DV+MET

✦ Follow object selection of auxiliary materials

\[ E_T^{\text{truth}}, d_0, n_{\text{tracks}}, m_{DV}, R_{\text{decay}}, z_{\text{decay}} \]

✦ Apply the efficiency grids

✦ Validate recasting with model in ATLAS paper as advocated in Les Houches 2017

G. Cottin, N. Desai, J. Heisig, A. Lessa

See Nishita Desai talk of yesterday
See Hideyuki Oide talk of yesterday
Recasting ATLAS DV+MET

ATLAS arXiv: 1710.04901

✦ Follow object selection of auxiliary materials

\[ E_T^{\text{truth}} , d_0, n_{\text{tracks}}^{DV}, m_{DV}, R_{\text{decay}}, z_{\text{decay}} \]

✦ Apply the efficiency grids

✦ Validate recasting with model in ATLAS paper as advocated in Les Houches 2017

G. Cottin, N. Desai, J. Heisig, A. Lessa

See Nishita Desai talk of yesterday
See Hideyuki Oide talk of yesterday

Simplified models with fixed BR into \( h(+\text{MET}) \) or \( Z(+\text{MET}) \)

DV+MET search has strong reach on EW states in SD-FI

\( m_{\chi_{2,3}} \) [GeV] vs. \( c\tau_{\chi_{2,3}} \) [m]

ATLAS arXiv: 1710.04901

8TeV limits
Z.Liu, B.Tweedie, '15
CMS PAS EXO-12-038
Figure 12: Combined constraints on the mediator mass vs DM mass plane ($m_2$, $m_3 = m_1$). The ATLAS DV + E/T exclusion is shaded in cyan ("DV+MET"), the magenta region is excluded by disappearing tracks ("DT"), the Lyman-α bound is shown in gray ("Ly-α"). Green contours correspond to the average $m_2$, $m_3$ decay length. The cyan dashed line is the estimated exclusion of LHC with 300 fb$^{-1}$. The coupling $y$ is fixed such that $\Omega h^2 = 0.12$ everywhere.

As discussed above, such constraint lies however in a zone of the parameter space where the frozen-in dark matter scenarios with masses above the Lyman-α bound give an overabundant dark matter relic density.

We can now combine the LHC limits and the cosmological bound derived in the previous sections, in order to characterise the experimental sensitivity on the viable parameter space of the freeze-in Singlet-Doublet model. As at the end of Section 3, we represent results in the DM mass vs mediator mass plane fixing in each point the coupling $y$ to the value that accounts for the observed relic abundance through the freeze-in mechanism. On the same two-dimensional plane, we can show the combination of the existing (and future) constraints on the model. Our summary plot is shown in Figure 12. As before, the green lines indicate contours of fixed average decay length of the neutral fermions, which controls the phenomenology at colliders. The magenta shading at low mediator masses represents the region excluded by searches for disappearing charged tracks (DT) [64, 65]. It does not exclude the region delimited by the dot dashed purple line of Figure 11. As discussed above, such constraint lies however in a zone of the parameter space where the frozen-in dark matter scenarios with masses above the Lyman-α bound give an overabundant dark matter relic density.

LHC can be competitive in large displacement region!
Conclusions

- **FIMP links to long-lived/displaced signatures**
- **Interplay with cosmology and WDM constraints**
- **We explored Singlet-Doublet DM model**
- **Motivate dedicated h/Z+MET displaced search**
- **Several classes of models can be considered**
- **Different long-lived/displaced type of signatures**