Dark matter and long-lived particles at the LHC

Dark Matter @ LHC 2020

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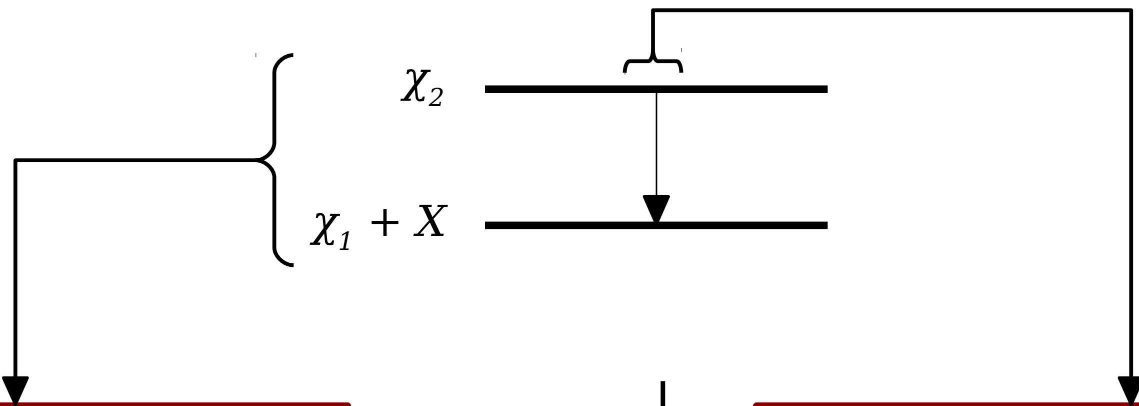
Outline

- Why long-lived particles?
- Where does dark matter kick in?
- What can we hope to see at the LHC?
- A few questions

Why Long Lived Particles?

Generically, if a decay $\chi_2 \rightarrow \chi_1 + X$ is allowed, its rate can be suppressed in two ways:

For a pheno-oriented overview *cf* *e.g.* arXiv:1903.04497



Phase-space suppression	Extremely weak interactions

· Standard example: quasi-degenerate members of a gauge multiplet.

E.g. in SUSY:
- Pure Winos $\tau \sim 0.2$ ns for $m_\chi \sim 3$ TeV
- Pure Higgsinos $\tau \sim 0.023$ ns for $m_\chi \sim 1$ TeV

· Protected by (approximate) symmetries

E.g. gauge, flavour, spacetime, only broken by small parameters

· Suppressed by a large mass scale

E.g. the Planck/seesaw/messenger/Peccei-Quinn or a generic heavy mediator mass

Connection to dark matter - 1

Phase-space suppression

Consider a dark (Z_2-odd) sector with two states (χ_0, χ_1), close in mass.

i) Coannihilation:

$$\chi_0 + \chi_1 \rightarrow \text{SM} + \text{SM}$$
$$\chi_1 + \chi_1 \rightarrow \text{SM} + \text{SM}$$

Phys. Rev. D 43 (1991)

χ_0 – χ_1 – SM coupling ~weak

ii) Conversion-driven freeze-out:

$$\chi_0 + \text{SM} \rightarrow \chi_1 + \text{SM}$$

arXiv:1705.09292
arXiv:1705.08450

χ_0 – χ_1 – SM coupling < weak

In both cases, relevant decay is: $\chi_1 \rightarrow \chi_0 + \text{SM}$

MET ← χ_0 SM → soft(-ish)

It can be displaced due to limited phase space + weaknes of relevant coupling.

Connection to dark matter - 2

Extremely weak interactions

Consider again a dark (Z_2-odd) sector with two states (χ_0, χ_1) and that all interactions of χ_0 (but not those of χ_1) with the SM(*) are extremely weak.

(*)And any particle in thermal equilibrium with it.

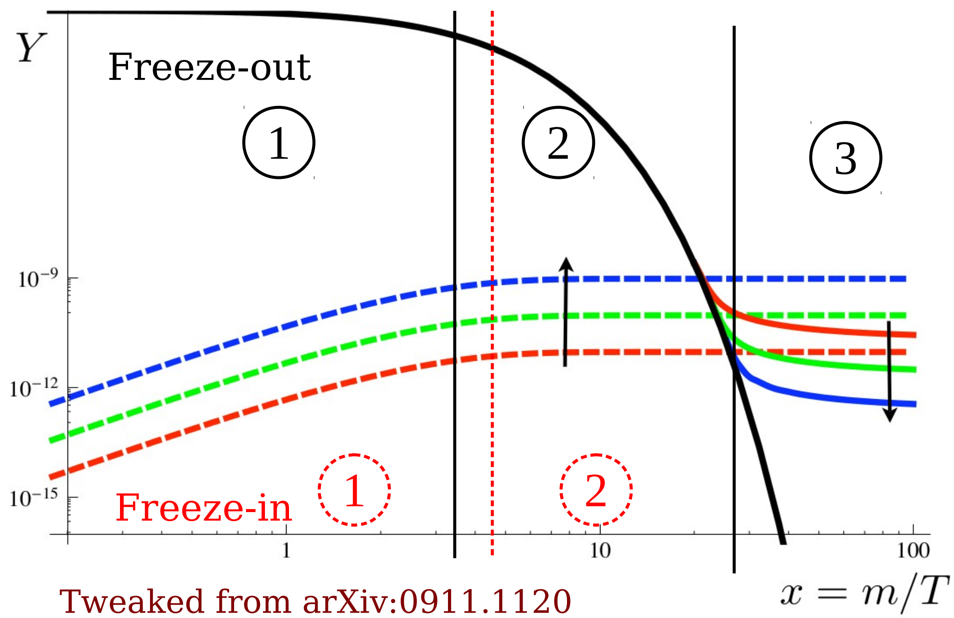
Feeble interactions → χ_0 never attains thermal equilibrium with the SM.

· Starting from a negligible initial abundance DM produced from χ_1 decays.

In the end: dark matter *freezes in*

· Predicted abundance *increases* with increasing coupling strength.

· *Super-WIMP* variant: χ_1 decays *after* it freezes-out.



Tweaked from arXiv:0911.1120

Types of signatures

Three considerations:

- Dark matter → Expect MET in the final state.
- Coloured/charged/neutral LLP (parent particle)?
- Nature of accompanying visible objects?

Potential final states include:

- γ+MET ($\sim B \to \gamma + \sim G$)
- $\gamma\gamma$+MET ($\sim S \to s^{(*)}(\to \gamma\gamma) + \sim G$)
- j+MET ($\sim Q \to q + \sim\chi_1$)
- jj+MET ($\sim\chi_2 \to H^{(*)} + \sim\chi_1$)
- l+MET ($\sim L \to l + \sim\chi$)
- ll+MET ($\sim\chi_2 \to Z^{(',*)} + \sim\chi_1$)
- Just MET ($\sim\chi_2 \to Z^{(',*)} + \sim\chi_1$ outside the detector)
- HSCPs ($\sim L \to l + \sim\chi$ outside the detector)

And note that:

- Depending on masses, some of the visible products may be soft.
- Depending on lifetime/boost, decays may occur in different sub-detectors

Experimentally, many different signatures

A charged parent model example

Extend the SM by a Z_2-odd real singlet scalar s (DM) along with a Z_2-odd vector-like SU(2)-singlet lepton F (parent).

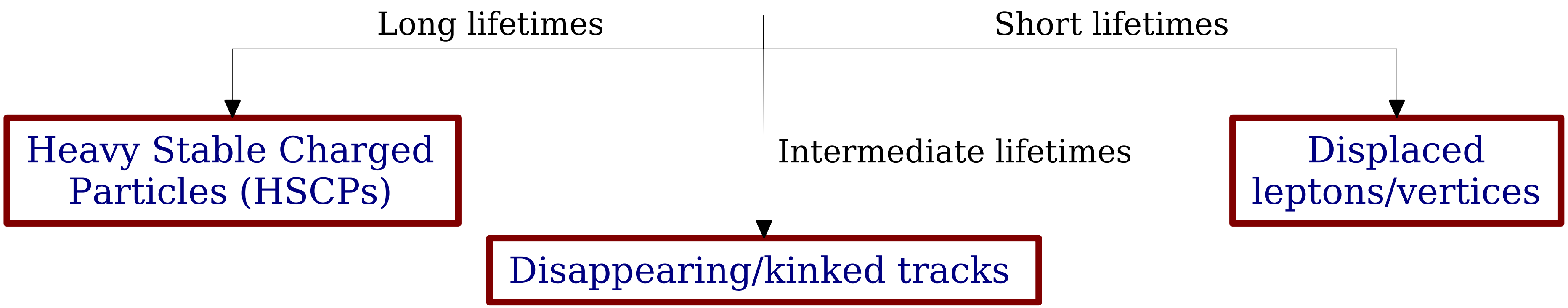
arXiv:1809.10135
arXiv:1811.05478

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \partial_\mu s\ \partial^\mu s - \frac{\mu_s^2}{2} s^2 + \frac{\lambda_s}{4} s^4 + \lambda_{sh} s^2 \left(H^\dagger H\right) + \bar{F}\left(i\not{D}\right) F - m_F \bar{F} F - \sum_f y_s^f \left(s \bar{F} \left(\frac{1+\gamma^5}{2}\right) f + \text{h.c.} \right)$$

· Heavy lepton production: Drell-Yan.

· Final state (eventually): l+MET pairs.

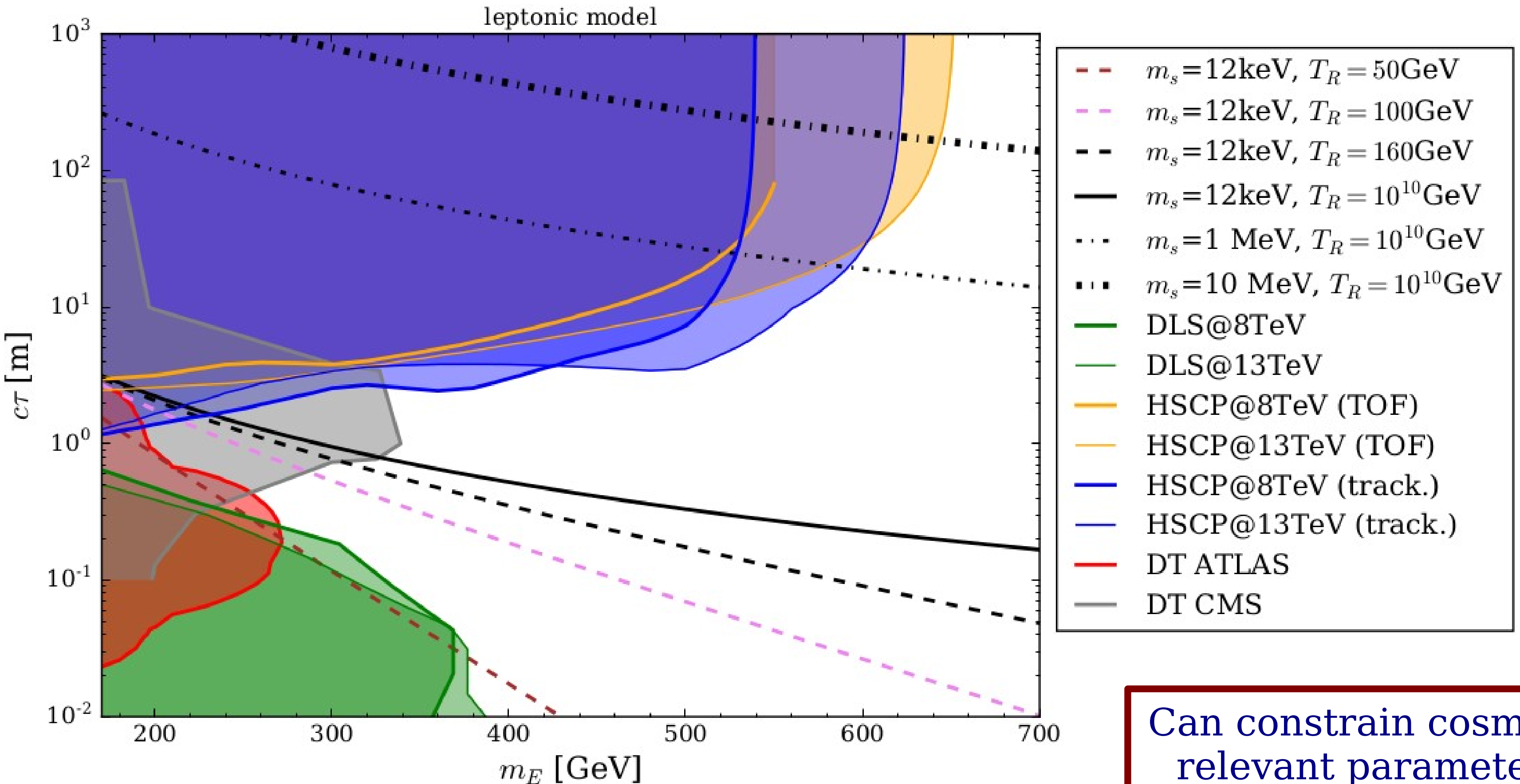
Experimental signature:



Example of constraints

Connection between the relic abundance with the parent particle lifetime:

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



arXiv:1811.05478

Can constrain cosmologically relevant parameter space.

Summary

· Many dark matter scenarios predict the existence of long-lived particles, e.g.

- coannihilation,
- conversion-driven freeze-out,
- freeze-in,
- asymmetric dark matter,
- strongly interacting massive particles,
- dark photon models

· These models give rise to a plethora of different LLP signatures, based on their structure and particle content.

Many challenges for the experimental community

· In many cases LHC searches are already probing the cosmologically interesting parameter space, even more possibilities for the next Runs.

· Not discussed in this talk: synergy between the "main" LHC experiments and the more "peripheral" ones (MATHUSLA, FASER, CODEX-b etc).

cf talks on Wednesday and later today

A couple of questions:

1) In coannihilation and CDFO, some of the decay products are expected to be soft.

How well can the LHC perform for displaced, soft objects?

2) In the simple model that we saw, the DM abundance can be approximated as:

$$\Omega_s h^2 \approx \frac{m_s \Gamma}{3.6 \times 10^{-9}\ \text{GeV}} \frac{45\,\xi\, M_{\text{Pl}}}{8\pi^4 \cdot 1.66} \frac{g_F}{m_F^2} \int_{m_F/T_R}^{m_F/T_0} dx\ x^3 \frac{K_1(x)}{g_*^s(m_F/x)\sqrt{g_*(m_F/x)}}$$

i.e. it depends on:
- · The DM mass
- · The parent particle mass
- · The parent particle lifetime

In case of discovery, measuring these is crucial to assess the cosmological relevance of what is being observed.

How well can we measure these quantities?

For a recent study *cf* arXiv:1912.06669