

Freeze-in and LLPs

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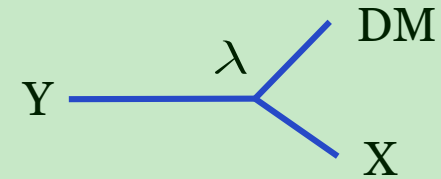
Displaced vertices and DM

Degenerate spectrum

Khoze, Plascencia, Sakurai, 1702.00750
 Mahbubani, Schwaller, Zurita, 1703.05327
 Buchmueller, De Roeck, McCullough,
 Schwaller, Yu, 1704.06515

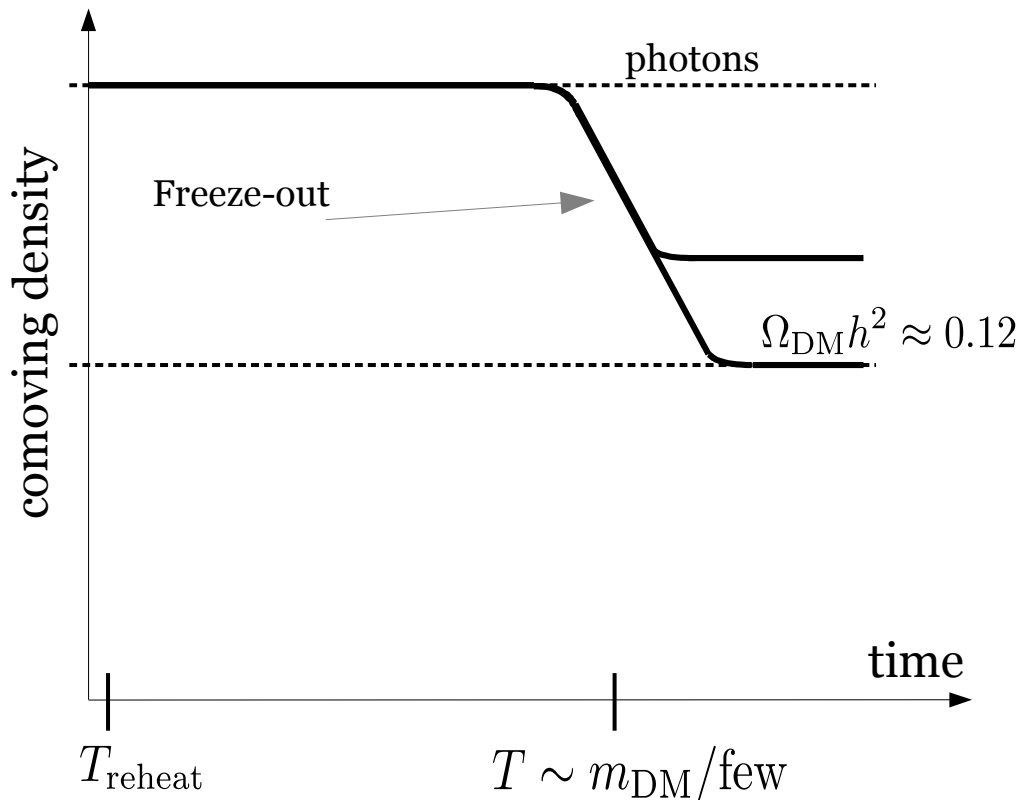
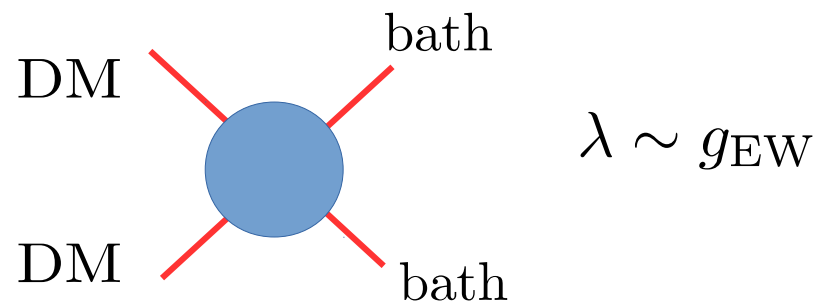
 (and growing)

Very small couplings



$\lambda \sim 10^{-9}$ for $m_Y \sim 1\text{TeV}$

Far from WIMP regime!



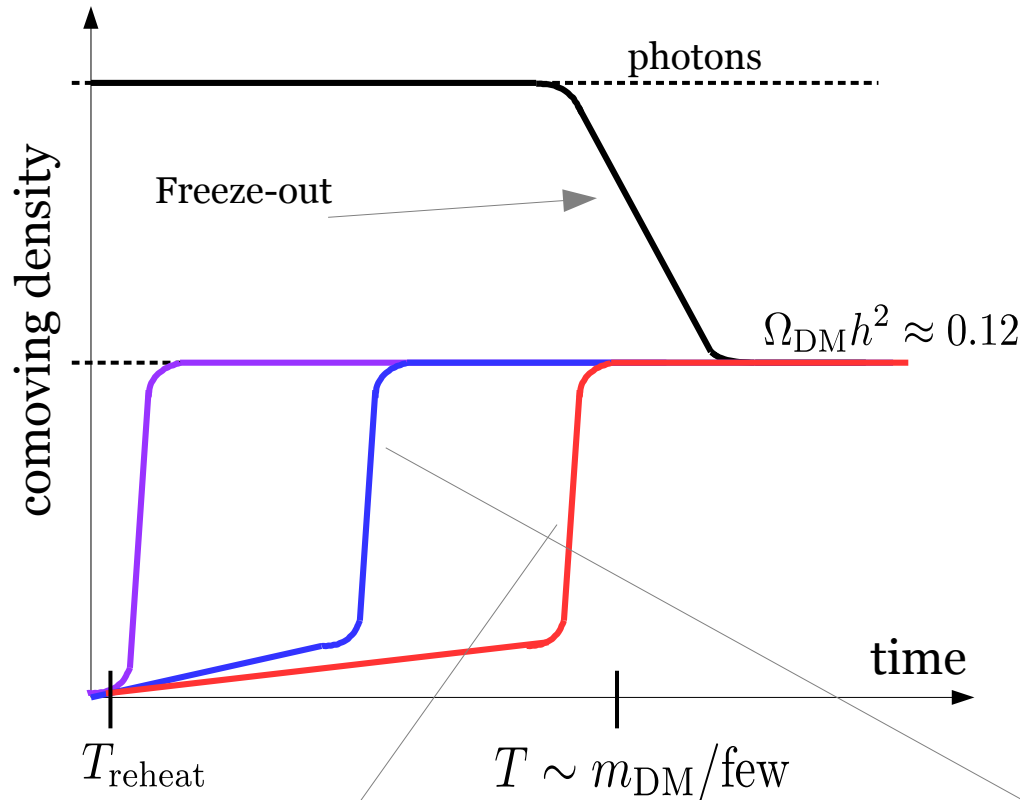
Freeze-in in a nutshell

$$\frac{dn_{\text{DM}}}{dt} + 3Hn_{\text{DM}} = n_{\text{bath}}\Gamma_{\text{prod}} - n_{\text{DM}}\Gamma_{\text{ann}}$$

negligible

interaction rates

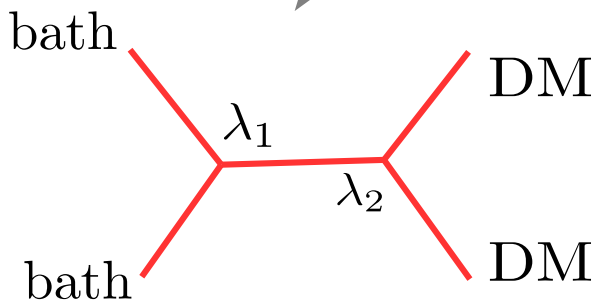
interaction rates



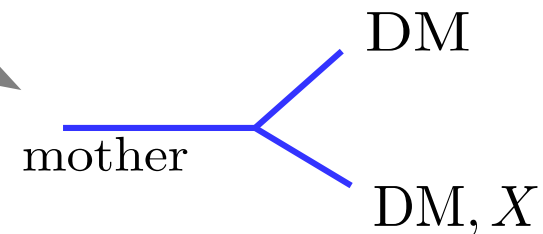
Characteristics:

- prod. period depends on benchmark:
 $m_{\text{DM}}, m_{\text{mother}}, T_{\text{reheat}}$
- dark sector never thermalises with itself
- prod. via **scatterings** or **decays**

-Hall, Jedamzik, March-Russell, West, 0911.1120
 -Blennow, Fernandez-Martinez, Zaldivar, 1309.7348
 -Bernal, Heikinheimo, Tenkanen, Tuominen, Vaskonen, 1706.07442

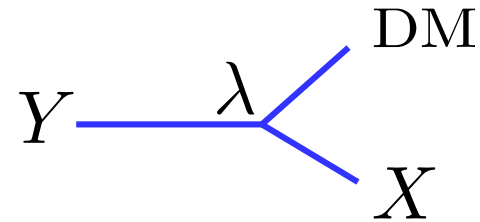


$$\lambda_1 \lambda_2 \sim 10^{-12}$$



FIMPs at the LHC

Y: BSM, Z_2 -odd, G_{SM} charged
 DM: BSM, Z_2 -odd, G_{SM} singlet
 X: SM



$$\Omega_{DM} h^2 \approx 3 \times 10^8 \left(\frac{m_{DM}}{\text{GeV}} \right) Y_{DM}$$

↓

$$s_0 / \rho_{crit}$$

$$Y_{DM} \propto \frac{M_{Pl} \Gamma_{Y \rightarrow X, DM}}{m_Y^2} \int_{x_{min}}^{x_{max}} dx x^3 K_1(x)$$

↓

$$x \equiv \frac{m_Y}{T}$$

↓

Boltzmann suppression

$$\lambda \sim 10^{-13} \underbrace{\sqrt{\frac{m_Y}{m_{DM}}}}_{\text{green}} \left(\underbrace{\frac{3\pi/2}{\int_{x_{min}}^{x_{max}} dx x^3 K_1(x)}}_{\text{blue}} \right)^{1/2}$$

(*) Two choices to increase coupling to $\sim 10^{-9}$

- Increase mass-ratio as much as possible
- Change production time lapse / cosmological history

Co, D'Eramo, Hall, Pappadopulo, 1506.07532
 Hessler, Ibarra, Molinaro, Vogl, 1611.09540
 Gosh, Mondal, Mukhopadhyaya, 1706.06815
This work, 1803.10379
 Calibbi, Lopez-Honorez, Lowette, Mariotti,
 1805.04423

Long-lived particles at the LHC and freeze-in dark matter

1803.10379

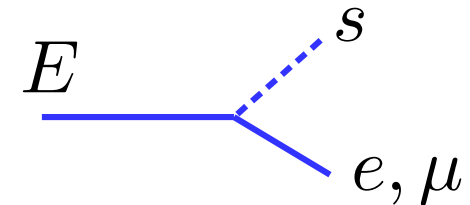
*G. Bélanger*¹, *H. Cai*², *N. Desai*³, *A. Goudelis*⁴, *J. Harz*⁴, *A. Lessa*⁵, *J.M. No*⁶, *A. Pukhov*⁷, *S. Sekmen*⁸, *D. Sengupta*⁹, *B. Zaldivar*¹ and *J. Zurita*^{10,11}

The model:

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + (\partial_\mu s) (\partial^\mu s) - \frac{\mu_s^2}{2} s^2 - \frac{\lambda_s}{4} s^4 - \lambda_{sh} s^2 (H^\dagger H) \\ + i (\bar{E}_L \not{D} E_L + \bar{E}_R \not{D} E_R) - \underbrace{(m_E \bar{E}_L E_R + y_e s \bar{E}_L e_R + y_\mu s \bar{E}_L \mu_R + \text{h.c.})}$$

free parameters:

$$m_E, m_s, y_e, y_\mu$$



constraints:

$$m_E > m_s \quad \text{So that } \mathbf{s} \text{ is the DM candidate}$$

$$m_E > m_Z/2 \quad \text{So that } \mathbf{Z} \text{ decay into } \mathbf{E} \text{ is forbidden}$$

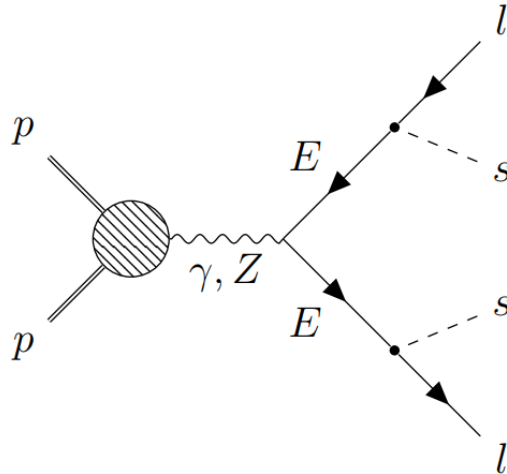
$$\mu \rightarrow e, \gamma \quad \text{Contribution at 1-loop, negligible for our case}$$

(*) experimental motivation for having two yukawas

Long-lived particles at the LHC and freeze-in dark matter

1803.10379

G. Bélanger¹, H. Cai², N. Desai³, A. Goudelis⁴, J. Harz⁴, A. Lessa⁵, J.M. No⁶, A. Pukhov⁷, S. Sekmen⁸, D. Sengupta⁹, B. Zaldivar¹ and J. Zurita^{10,11}



$$\mathcal{L} \supset y_e s \bar{E}_L e_R + y_\mu \bar{s} E_L \mu_R + \text{h.c.}$$

E : BSM, $Z_{2\text{odd}}$, $SU(2)_L$ singlet

S : DM, Z_2 -odd, SM singlet

Heavy Stable Charged Particles

1211.1597, 1411.6795, 1604.04520 (ATLAS)
1205.0272, **1305.0491**, CMS-PAS-EXO-16-036 (CMS)
(8TeV, 18.8/fb)

- non-ultrarelativistic highly ionised track
- anomalous TOF in muon chamber
- *this search has been recasted in this work*

Displaced Lepton Searches

1409.4789, **CMS-PAS-EXO-16-022** (CMS)
(13TeV, 2.6/fb)

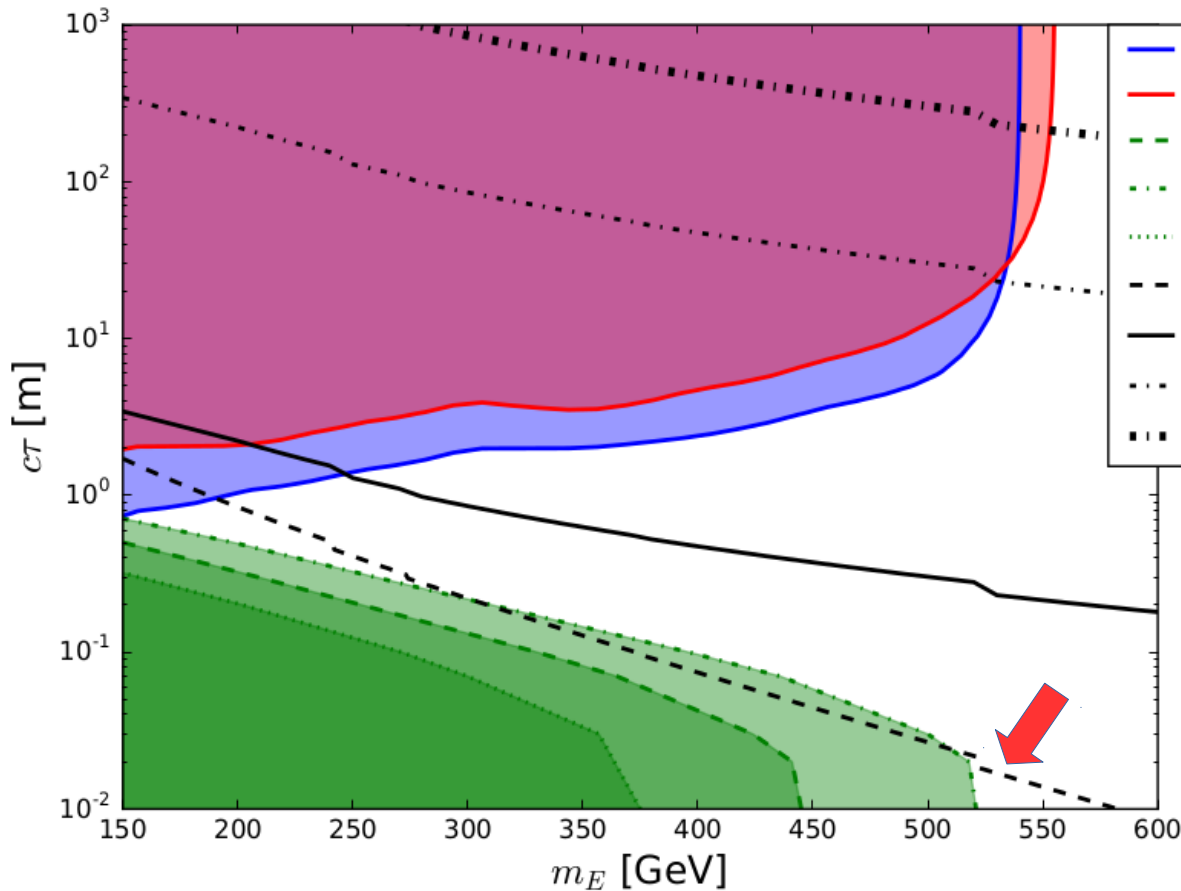
- tracks with non-zero impact param.
- events w/ one electron and one muon
- 3 signal regions (transv. impact param.)
- Likelihood analysis

Long-lived particles at the LHC and freeze-in dark matter

1803.10379

G. Bélanger¹, H. Cai², N. Desai³, A. Goudelis⁴, J. Harz⁴, A. Lessa⁵, J.M. No⁶, A. Pukhov⁷, S. Sekmen⁸, D. Sengupta⁹, B. Zaldivar¹ and J. Zurita^{10,11}

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



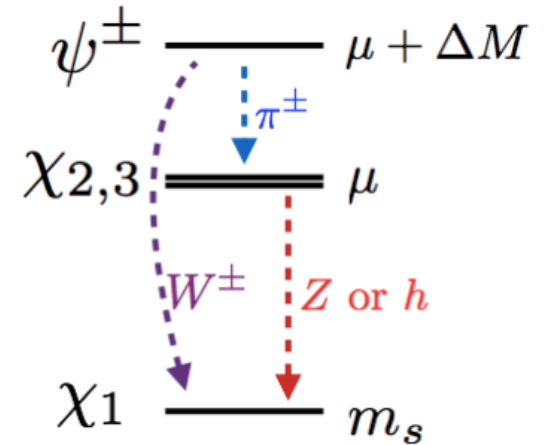
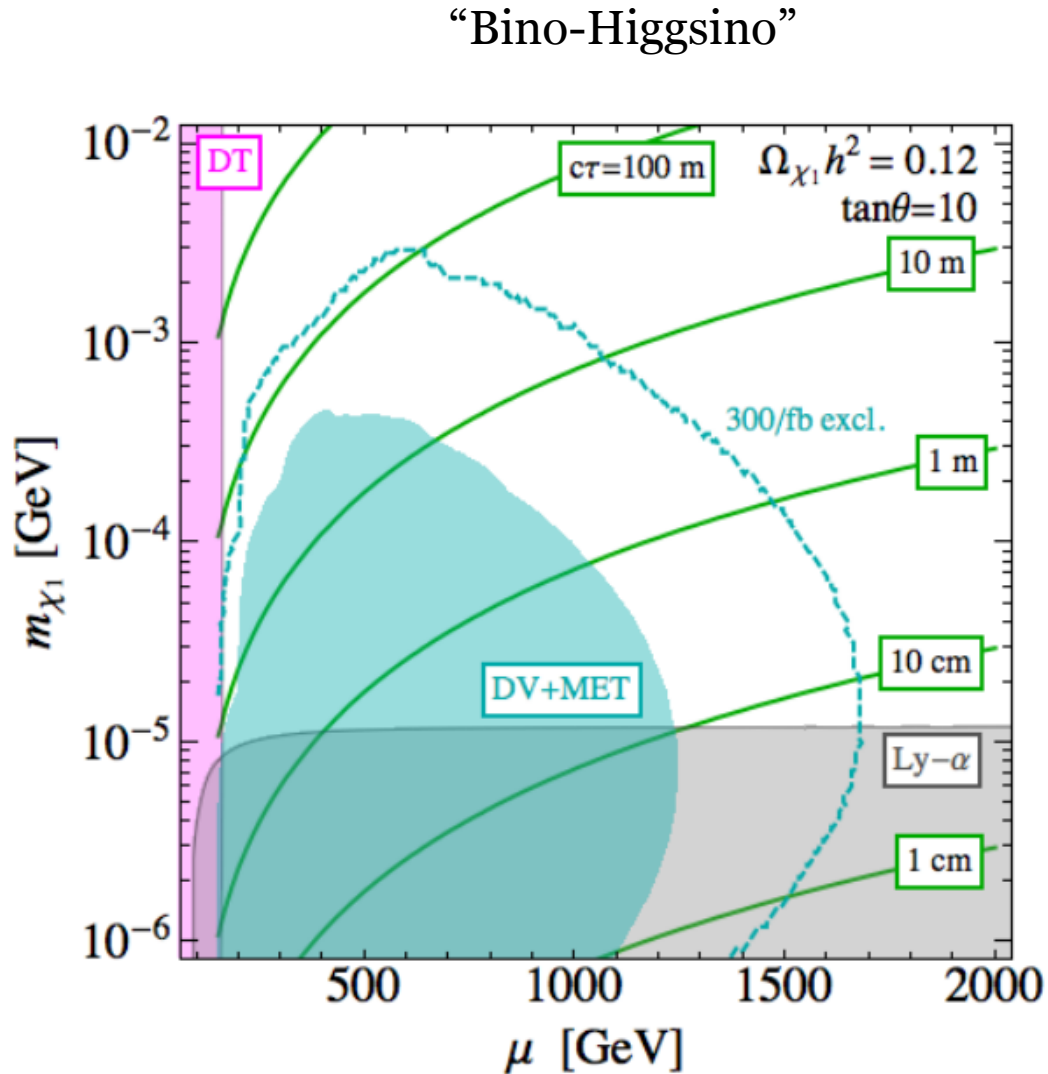
- HSCP(tracker-only)
- HSCP(tracker+TOF)
- - DLS ($k_s = 1$)
- · - DLS ($k_s = 2$)
- · · DLS ($k_s = 0.5$)
- - $m_s = 10 \text{ keV}, T_R = 100 \text{ GeV}$
- $m_s = 10 \text{ keV}, T_R = 10^{10} \text{ GeV}$
- · · $m_s = 1 \text{ MeV}, T_R = 10^{10} \text{ GeV}$
- · · $m_s = 10 \text{ MeV}, T_R = 10^{10} \text{ GeV}$

HSCP: Heavy Stable Charged Particle (CMS 8TeV, 1305.0491)

DLS: Displaced lepton searches (CMS 13TeV, PAS-EXO-16-022)

Singlet-Doublet Dark Matter Freeze-In: LHC displaced signatures versus cosmology

Calibbi, Lopez-Honorez, Lowette and Mariotti, 1805.04423



Upon recasting DV+MET search by ATLAS, 1710.04901

these are exciting times
for freeze-in dark matter!