LHC sensitivity for non-thermalised hidden sectors

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Based on **arXiv:1801.07621**

Motivation

- LHC possesses substantial sensitivity to weakly-interacting DM particles (WIMPs)
- So far no conclusive evidence for WIMPs in any type of experiment
- Time to consider alternatives to the thermal freeze-out paradigm!
- What if the DM particle was never in thermal equilibrium with the SM?
  - Out-of equilibrium decays
  - Freeze-in mechanism (e.g. via dark photon)
- Can we use the LHC to probe these models?

A few definitions

- *Hidden sector* refers to
  - particles beyond the SM that are either stable or sufficiently long-lived to appear stable in the Early Universe
  - unstable particles that decay dominantly into hidden sector states

- *Thermalisation* between a hidden sector and the SM requires some kind of process connecting the two sectors

- The *reaction rate* of such a process is given by $\Gamma \equiv \langle \sigma v \rangle \, n^{\mathrm{eq}}$

- Thermalisation will occur if the reaction rate exceeds the *Hubble rate* at some point in the Early Universe:

$$\Gamma(T) > H(T)$$

Basic idea

1) Consider a specific process with cross section $\sigma(s)$ connecting SM and hidden sector
2) Assume that this process does not lead to thermalisation in the Early Universe
3) Calculate an upper bound on the number of times this process can occur at the LHC

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- Central observation: calculation of reaction rates in the Early Universe is formally very similar to calculation of event rates at the LHC
  - Early Universe: Convolute cross section with thermal distribution

$$\gamma(T) \equiv \frac{\Gamma(T)}{H(T)} = \int \mathrm{d}\sqrt{s} \sqrt{\frac{45}{\pi\, g_*}} \frac{N_c\, M_{\mathrm{pl}}\, s^2\, K_1(\sqrt{s}/T)}{8\pi^3\, T^4} \sigma(\sqrt{s})$$

  - LHC: Convolute cross section with parton distribution functions

$$N_{\mathrm{LHC}} = \int \mathrm{d}\sqrt{s}\, \frac{\mathrm{d}x}{x} f_1(x)\, f_2\left(\frac{s}{s_{\mathrm{tot}}\, x}\right) \frac{2\,\mathcal{L}\sqrt{s}}{s_{\mathrm{tot}}} \sigma(\sqrt{s})$$

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Imposing non-thermalisation (i.e. γ(T) < 1 for all T) yields an upper bound on N_{LHC}

A few assumptions

A quantitative comparison between the LHC and the Early Universe requires assumptions on the cosmological history:

1) The same physics can be used to describe the Early Universe and the LHC

2) The Early Universe once had a temperature comparable to LHC energies

3) SM particles give the main contribution to the energy density at these temperatures

Interesting LHC phenomenology possible if one or more of these assumptions are violated!

Co et al., arXiv:1506.07532

Baker et al., arXiv:1608.07578; arXiv:1712.03962

D'Eramo et al., arXiv:1712.07453

First example

- Consider a cross section strongly peaked at a specific centre-of-mass energy:

$$\sigma(\sqrt{s}) = \sigma_0 \sqrt{s_0}\, \delta(\sqrt{s} - \sqrt{s_0})$$

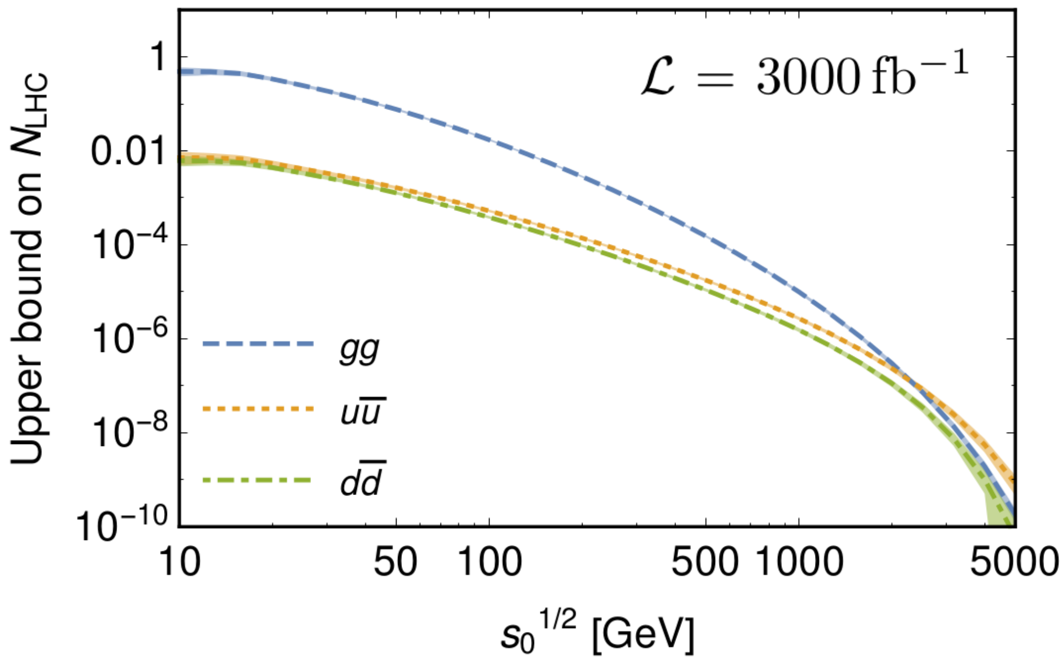
  Example: resonant production of hidden sector states

- Non-thermalisation constraint implies

$$\sigma_0 < 6.45 \cdot 10^{-6}\,\mathrm{fb} \left(\frac{1\,\mathrm{GeV}}{\sqrt{s_0}}\right) \frac{1}{N_c} \left(\frac{g_*(T_0)}{106.75}\right)^{1/2}$$

- Tiny cross section - impossible to observe at the LHC!

First example



- Tiny cross section - impossible to observe at the LHC!
  - Constraint gets weaker if the process happens at lower energies (i.e. lower temperatures and lower densities in the Early Universe)
  - But soft processes are also harder to observe at the LHC!

General cross sections

- It is possible to write any arbitrary cross section as a (potentially large) sum of delta-functions

$$\sigma(\sqrt{s}) \approx \sum_i \sigma_i \sqrt{s_i}\,(\Delta - 1)\,\delta(\sqrt{s} - \sqrt{s_i})$$

- The problem of comparing the Early Universe and the LHC then becomes a well-known optimisation problem:

Find the positive values σ_i that maximise $N_{\mathrm{LHC}} = \sum_i b_i\,\sigma_i$

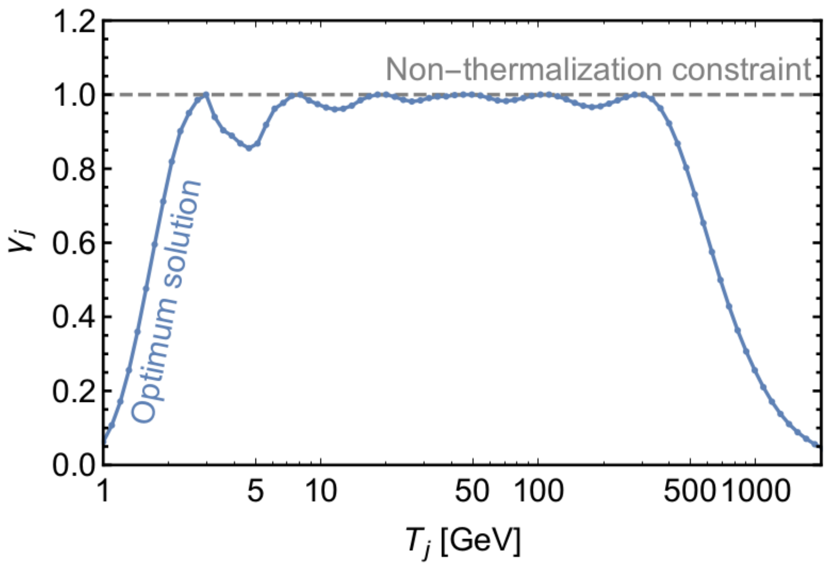
while satisfying the constraint $\gamma(T_j) = \sum_i a_{ji}\sigma_i < 1$

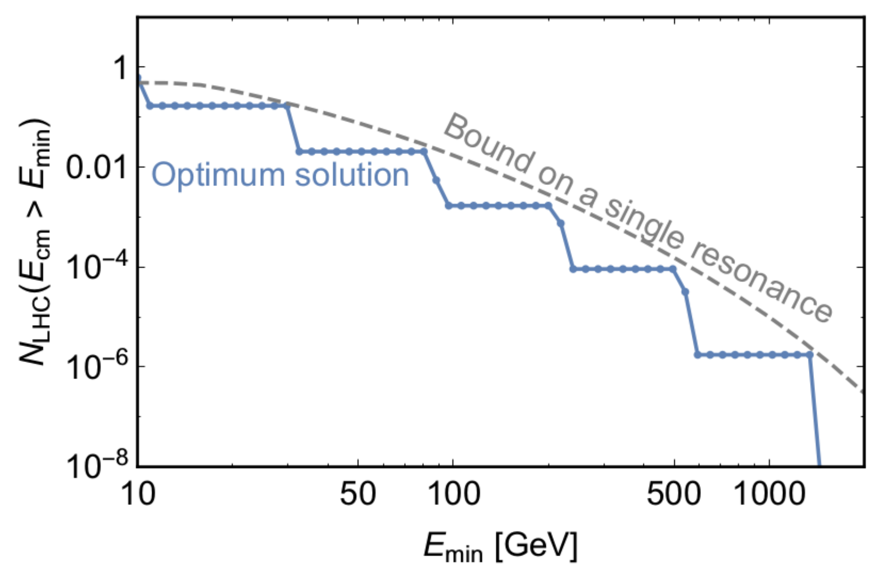
- Optimum solution can be easily found with methods from linear programming

$$\left(a_{ij} = (\Delta - 1)\sqrt{\frac{45}{\pi\, g_*}}\frac{N_c\, M_{\mathrm{pl}}\,\sqrt{s_i}^5\, K_1(\sqrt{s_i}/T_j)}{8\pi^3\, T_j^4}\ ,\quad b_i = (\Delta - 1)\int \frac{\mathrm{d}x}{x} f_1(x)\, f_2\left(\frac{s_i}{s_{\mathrm{tot}}\, x}\right)\frac{2\,\mathcal{L}\, s_i}{s_{\mathrm{tot}}} \right)$$

Optimum solution

- (Nearly) saturates the non-thermalisation constraint over a wide range of temperatures
- Depends on the assumed minimum centre-of-mass energy that can be observed at the LHC (here E_{min} = 10 GeV)
- Depends on the initial state under consideration (here *gg*)





Result: $N_{\text{LHC}} < 0.62$ for $\mathcal{L} = 3000\,\text{fb}^{-1}$

Loophole: Partially thermalised hidden sectors

- Non-thermal DM may be observable at the LHC if produced via the decays of a metastable particle

- Such a metastable particle may reach thermal equilibrium with the SM if

$$\Gamma_{\text{production}} > H(T) > \Gamma_{\text{decay}}$$

Super-WIMP mechanism (e.g. gravitino)

Feng et al., arXiv:hep-ph/0306024

- Generic predictions:
  - Long-lived particles
  - Displaced vertices
  - Many exciting new signatures!

Conclusions

- Any particle that can be directly produced at the LHC must have been in thermal equilibrium in the Early Universe (for standard assumptions on cosmology)
- Non-thermalised hidden sectors are generally unobservable at the LHC *unless there is an intermediate (long-lived?) state*
- It is very challenging (if not impossible) to test (simple) freeze-in models at the LHC
- Most promising search region: soft events with very low centre-of-mass energy
- Will be very interesting to perform a (model-independent) comparison between the LHC and *B*-factories