Searching for dark radiation at the LHC

Based on 2204.01759

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A loving relationship...

LHC: power and versatility

↓

LHC can look for DM

DM hints to new physics

↓

DM can guide LHC

...with some LLP issues

Simple observation:
$H(T_{\mathsf{EW}}) \leftrightarrow$ LHC length

Interactions effective at the EW scale lead to macroscopic decay lengths!

But Ωh^2_{DM} is not compatible with that...

But there are other cosmological observations!

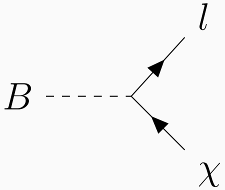
ΔN_{eff} in the near future: $\sigma_{\mathsf{CMB\text{-}S4}} = 0.03$

Model

New particle content: B, χ

B decays into almost massless χ

$B^T = (B_e, B_\mu, B_\tau)$ charged under SM



$$\mathcal{L}_{\text{NP}} \supset B^T \cdot y_l \cdot (\bar{l}_R\,\chi) + h.c.$$

$$y_l = \begin{pmatrix} y & 0 & 0 \\ 0 & y & 0 \\ 0 & 0 & y \end{pmatrix} \quad \text{with } y \lesssim 10^{-6}$$

Calculating ΔN_{eff} (standard)

ΔN_{eff} is the extra radiation added on top of SM

$$\Delta N_{\text{eff}}(x) = \frac{\rho_\chi(x)}{\rho_{1\nu}(x)} = \frac{Z_\chi(x)\, s_0^{4/3}}{\frac{7}{8}\left(\frac{4}{11}\right)^{4/3} \rho_{\gamma,0}}, \tag{1}$$

$$Z_\chi(x) \equiv \frac{\rho_\chi(x)}{s^{4/3}(x)} \tag{2}$$

IR freeze-in via parent decay: pretty easy!

$Z_\chi(x)$ can be derived by Boltzmann equation!

Calculating ΔN_{eff} (standard)

Common starting point
(non-integrated Boltzmann equation):

$$E\frac{\partial f_\chi}{\partial t} - Hp^2\frac{\partial f_\chi}{\partial E} = \hat{C}[f_\chi]\,, \tag{3}$$

Integrate over $g_\chi \frac{\mathrm{d}^3 p_\chi}{(2\pi)^3}$:

$$g_\chi \int \frac{\mathrm{d}^3 p_\chi}{(2\pi)^3}\hat{C}[f_\chi] = \frac{m_B\,\Gamma_B}{8\pi^4}\mathcal{I} \tag{4}$$

$$\mathcal{I} = \int \frac{\mathrm{d}^3 p_\chi}{2E_\chi}\int \frac{\mathrm{d}^3 p_\ell}{2E_\ell}\frac{2E_\chi}{E_B}\left(1 - \frac{f_\chi(E_\chi)}{f_\chi^{\text{eq}}(E_\chi)}\right) f_B^{\text{eq}}(E_B)\delta(E_B - E_\chi - E_\ell) \tag{5}$$

Calculating ΔN_{eff} (standard)

Usual assumptions:

- B decays while non-relativistic
- Backreaction χ SM $\to B$ is negligible

Then we have:

$$\tilde{H} x s^{4/3}(x) \frac{\mathrm{d}Z_\chi}{\mathrm{d}x} = \frac{m_B^4 \Gamma_B}{8\pi^2} \mathcal{I}(x) \tag{6}$$

$\mathcal{I}$ does not depend on the properties of the daughter particle!

$$Z_\chi \propto \Gamma_B = \frac{y^2 m_B}{16\pi} \tag{7}$$

Calculating ΔN_{eff} (refined calculation)

We relax these assumptions to get a better determination of the parameter space!

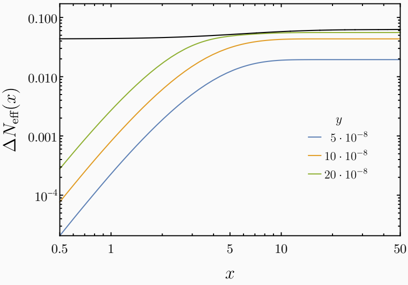
Relativistic treatment for DM already discussed in 1906.07659, 2003.12606

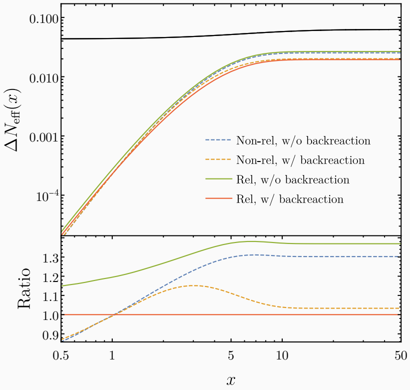
$$\tilde{H} x s^{4/3}(x) \frac{\mathrm{d}Z_\chi}{\mathrm{d}x} = \frac{m_B^4 \Gamma_B}{8\pi^2} \mathcal{I}(x, T_\chi, \text{spins}) \tag{8}$$

Also here there are some simplifications...

$\mathcal{I}$ can be tabulated and is provided at the arXiv link.

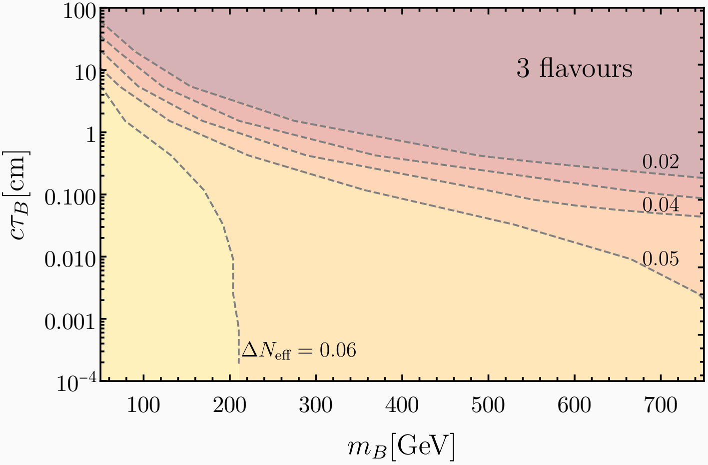
Effect of approximations



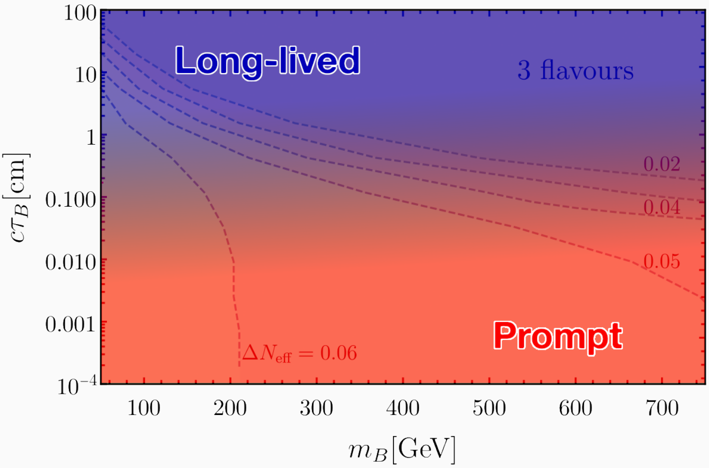


Not portrayed here: magnitude of corrections depends sensitively on the parameters!

ΔN_{eff} result and LHC parameter space



ΔN_{eff} result and LHC parameter space



Prompt searches

Recast SUSY searches for $l\,l + \not{E}_T$
1908.08215, 2012.08600

Central question: how does the sensitivity change for macroscopic decay lengths?

Particles should decay promptly (i.e. before some Δx):

$$p(x < \Delta x) = 1 - \exp\left(-\frac{\Delta x}{\beta\gamma c\tau}\right) \approx \frac{\Delta x}{\beta\gamma c\tau}\,, \qquad (9)$$

Lifetime effect enters in the impact parameter cuts!

Prompt searches

These cuts are different for ATLAS and CMS!

ATLAS:
$|d_0| < 3(5)\ \sigma(d_0)$ for e^- (μ^-),
where $\sigma(d_0) \simeq 20\,\mu$m

CMS:
$|d_0| < 0.5$mm for e^- and μ^-

Of course there are also other differences
(taken into account in DELPHES cards and analysis)

LLP searches

”Recast” SUSY searches for displaced leptons
2011.07812, 2110.04809

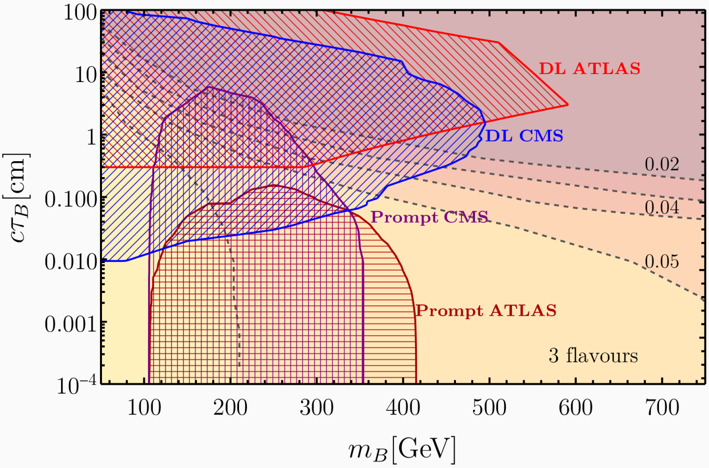
Limits provided as $\sigma_{BB}(m_B, c\tau_B)$

Still different cuts for ATLAS and CMS on the impact parameter

ATLAS: $|d_0| \in [3\text{mm}, 300\text{mm}]$
CMS: $|d_0| \in [0.1\text{mm}, 100\text{mm}]$

Warning: recasting here is more complicated for the single-flavour scenario

LHC constraints on $\Delta N_{\rm eff}$

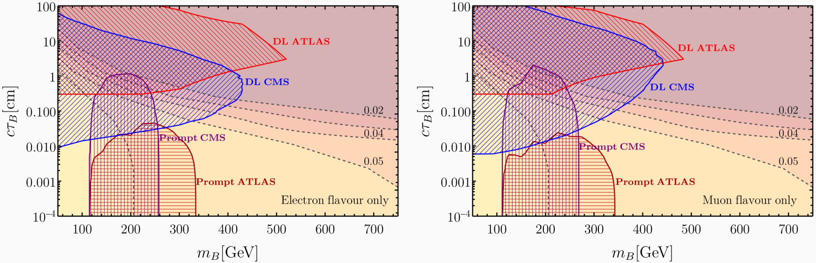


Conclusions

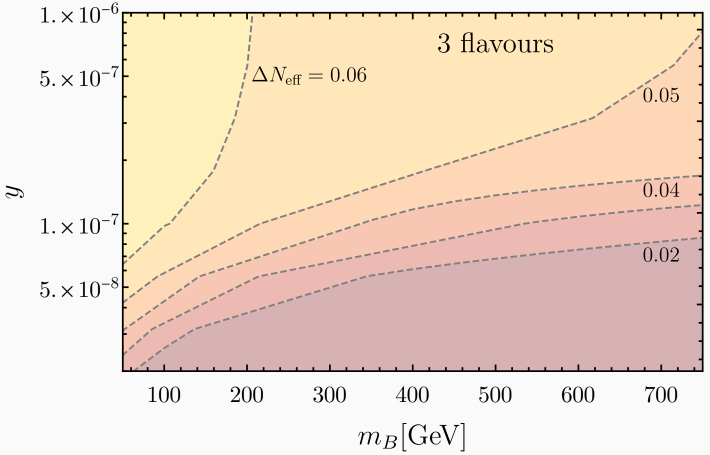
- Calculations of ΔN_{eff} has been improved to better determine the decay lengths
- The interesting parameter space lies at the boundary of prompt and long-lived searches $\rightarrow$ complementarity!
- ATLAS and CMS have different cuts which result in differences in parameter space probed

BACKUP

Single flavour case



Coupling parameter space



Other ATLAS-CMS differences

Prompt ATLAS:
bins in m_{T2}, $e\mu$ as signal region
$|z_0 \sin\theta| < 0.5$mm

Prompt CMS:
bins in p_T^{miss}, $e\mu$ as control region
$|z_0| < 1$mm

LLP CMS does not provide limits on $\sigma(m_B, c\tau_B)$ for the single flavour scenario, so an approximation on the mass dependence is used.