LHC prospects for minimal decaying Dark Matter

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Based on: G. Arcadi, L. Covi and F. D. - arXiv: 1408.1005 -

Outline

Introduction - model

We consider:

- a minimal model where a Majorana fermion DM ψ (SM-singlet) is coupled to a SM fermion f and scalar Σ_f (non-trivially SM-charged):
$$\mathcal{L}_{eff} = \lambda \bar{\psi} f \Sigma_f^\dagger + h.c. = \lambda_{\psi d} \bar{\psi} d \Sigma_d^\dagger + \lambda_{\psi e} \bar{\psi} e \Sigma_e^\dagger + \lambda_{\psi \ell} \bar{\psi} \ell \Sigma_\ell^\dagger + h.c.$$
- no symmetry to guarantee the stability of DM and, thus, Σ_f-only SM fermions couplings are allowed, e.g.
$$\mathcal{L}_{eff} = \lambda'_d \bar{d} \ell \Sigma_d + \lambda'_e \bar{\ell^c} \ell \Sigma_e^\dagger + \lambda'_\ell \bar{e} \ell \Sigma_\ell + \lambda'_\ell \bar{d} d \Sigma_\ell + h.c.$$
- three-body decays for DM (caused by these additional SM-interactions) with a rate given by:
$$\Gamma_{\rm DM} = \frac{c_f |\lambda|^2 |\lambda'|^2}{128 (2\pi)^3} \, x^4 \, m_\psi$$

with $c_f = \#$ of d.f. of the intermediate Σ_f, $x = \frac{m_\psi}{m_{\Sigma_f}}$

$$\Downarrow$$

4-relevant parameters: $m_{\Sigma_f}, m_{\rm DM}, \lambda, \lambda'$

Introduction - DM generation

DM can be produced in different way depending on the value of λ. Basically, two main scenarios are possible:

- $\lambda \simeq 1$: DM is in thermal equilibrium in the early universe and, therefore, produced through the freeze-out paradigm.
- $\lambda < 10^{-7}$: DM can not be in thermal equilibrium in the early universe. DM is generated from the Σ_f-decays either in thermal equilibrium (freeze-in) or out-of-equilibrium (sWIMP).

$$\Downarrow$$

We study the sWIMP and freeze-in mechanisms of DM production:

$$\Omega_{\rm DM} h^2 = \Omega_{\rm DM}^{\rm FI} h^2 + \Omega_{\rm DM}^{\rm SW} h^2 \approx x \mathrm{BR}_{\Sigma_f \psi} \left[\frac{1.09 \times 10^{27} g_\Sigma}{g_*^{3/2}} \frac{\Gamma_{tot.}}{m_\Sigma} + \Omega_\Sigma h^2 \right]$$

where $\mathrm{BR}_{\Sigma_f \psi} = \dfrac{\lambda^2}{\lambda^2 + \lambda'^2}, \;\; \Gamma_{tot.} = \Gamma_{\psi f} + \Gamma_{ff}, \;\; \Gamma_{\psi f (ff)} = \dfrac{\lambda^{(\prime)\,2}}{8\pi} m_\Sigma$

Introduction - production

Contributions of sWIMP and freeze-in mechanisms depend strongly on the Σ_f-properties $\rightarrow$ 3 different LHC Σ_f-productions via MG5 at $\sqrt{s} = 14$ TeV:

- Colored $\Sigma_f \implies \Sigma_d$ ($\tilde{b}_R$-quantum numbers)

  (Colored states are the most efficiently produced ones (gluon fusion). Production depends on m_{Σ_d})

- Electroweak $\Sigma_f \implies \Sigma_\ell$ & Σ_e ($\tilde{\ell}$ & $\tilde{\mu}_R$-quantum numbers)

  (EW states less produced (Drell-Yan) that colored ones. MP bounds are reduced ($\rightarrow m \simeq 300$ - 400 GeV). Production depends on m_{Σ_ℓ}.)

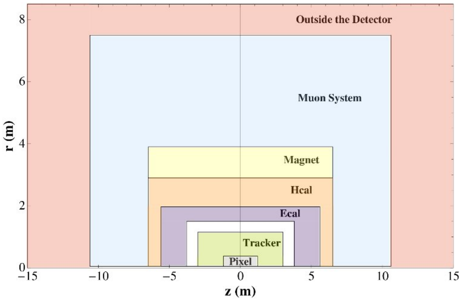
sWIMP and freeze-in mechanisms make λ, λ' tiny $\rightarrow$ No prompt decay!

$$\Downarrow$$

We concentrate on the prospects for discovery of Σ_f displaced vertices (d.v.) inside pixel (pi.), tracker (tr.) and outside CMS detector (out.)

Introduction - CMS design & purposes

Layout of two quarters of CMS used in this analysis is:



Purposes of this research are:

1) Parameter region where DM ID signal is within the future LHC reach and the produced DM abundance fits data

2) Possible collider detection of both Σ_f-decays:

$$\Sigma_f \rightarrow \text{DM} + \text{SM} \quad \& \quad \Sigma_f \rightarrow \text{SM} + \text{SM}$$

Σ_f-production at LHC

The numerical approach consists of:

- running MG5 for $\{m_{\Sigma_f}\}$ and Γ_{Σ_f} $(10,000$ events and kinematics$)$
- computing the decay length and direction of Σ produced
- circumventing the problem of launching MG5 for all of Γ_{Σ_f} by rescaling the dimensions of all parts of the detector consistently

In doing so, the spatial distribution of the Σ_f-vertices $\forall\ \Gamma_{\Sigma_f}$ is obtained !

Assuming the working hypothesis:

- background is negligible and the required minimum number of particles decaying within pi. and tr. or out. is $n_{min} = 10$

and using the formulas:

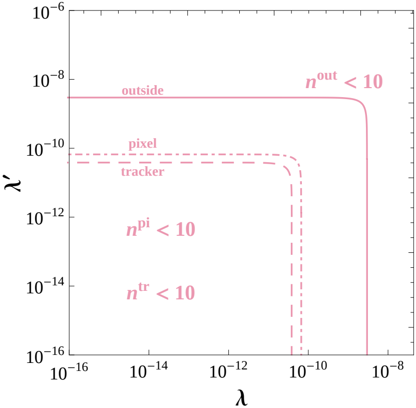
$$\lambda' = \sqrt{\frac{8\pi\hbar}{m_\Sigma \tau_\Sigma} - \lambda^2}, \quad \lambda = \sqrt{\frac{8\pi\Gamma_{tot.}}{m_\Sigma} \mathrm{BR}_{\Sigma_f\psi}}, \quad \lambda' = \sqrt{\frac{8\pi\Gamma_{tot.}}{m_\Sigma}(1 - BR_{\Sigma_f\psi})}$$

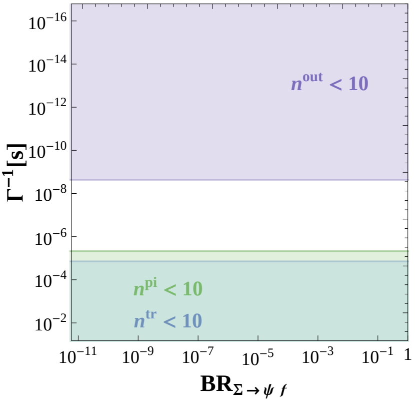
at $L = \{25, 300, 3000\}\,\mathrm{fb}^{-1}$, we achieve:

$$\Longrightarrow \boxed{\Sigma \text{ LHC reach in } \lambda\text{-}\lambda' \text{ and } \mathrm{BR}_{\Sigma_f\psi}\text{-}\Gamma^{-1}_{tot.} \text{ planes}}$$

Σ_d in λ-λ' and $\mathrm{BR}_{\Sigma_f \psi}$-$\Gamma^{-1}_{tot.}$ planes

Σ_d-production for $m_{\Sigma_d} = 800\,\mathrm{GeV}$ & $L = 300\,\mathrm{fb}^{-1}$:





N.B. Studies for d.v. and particles escaping from CMS are complementary!

Def. Double detection (d.d.): region with at least 10 events in one of the components of the inner detector and 10 tracks leaving the detector

Σ_f in cosmology

In order to investigate the parameter space where the model is both cosmologically viable and observable via multiple signals, we consider:

- bounds on the DM indirect detection (DM ID)

  (Correlation between DM ID and collider signals: λ' and λ, involved in $\Gamma_{\rm DM}$, also induce Σ_f-decays.)

  Constraints on $\tau_{\rm DM}$ as a function of m_ψ for DM decays into q-$\bar{q}$ pair and ν by Garny et al. (JCAP 1208 (2012) 025): $\tau_{\rm DM} = 10^{27-29}$ s, according as the propagation model used and $m_{\rm DM}$.

- sWIMP and freeze-in mechanisms generate $\Omega_{\rm DM} h^2 = 0.11$

  (We expect Ω_Σ to be very low for a charged relic because of efficient interactions of Σ_f. sWIMP contribution should be suppressed at lower m_{Σ_f}.)

  see e.g. Arcadi and Covi's paper (JCAP 1308 (2013) 005)

$$\Downarrow$$

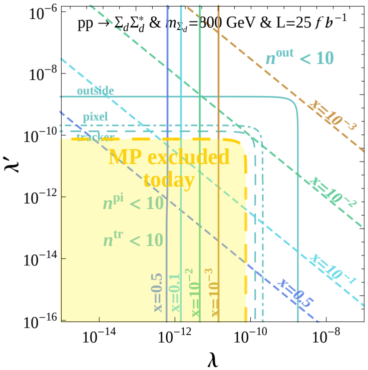
DM abundance and DM ID bounds in λ-λ' and $\mathrm{BR}_{\Sigma_f \psi}$-$\Gamma_{tot.}^{-1}$ planes

N.B. These bounds fix λ, λ' as a function of m_{Σ_f}, x $\rightarrow$ Plots for fixed m_{Σ_f}

Results - Σ_d & $m_{\Sigma_d} = 800\,\text{GeV}$

To study if the model parameter space is accessible from CMS and DM ID bounds where DM has the right abundance, we plot all together:

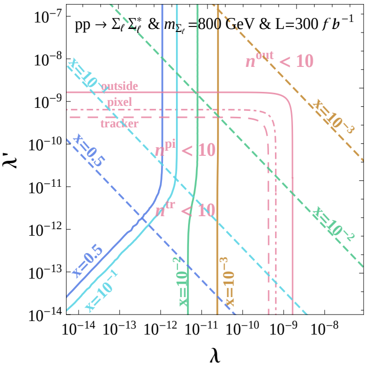
($\tau_\psi = 10^{28}$s has been used for ID bounds & MP (metastable particle) bound: JHEP 1307 (2013) 122)

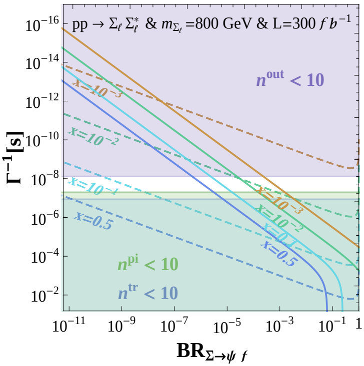


N.B. Double detection (d.d.) region with DM- and Σ_f- decays corresponds to a quite definite range: $10^{-2} < x < 10^{-1} \to$ Benchmark at $x \sim 10^{-2}$ (later)

Results - Σ_ℓ & $m_{\Sigma_\ell} = 800$ GeV

- Hierarchy in production: $\sigma_{\Sigma_\ell \Sigma_\ell^*} < \sigma_{\Sigma_d \Sigma_d^*}$
- Detector stable bounds are relaxed $\rightarrow$ No bounds for $m_{\Sigma_{\ell(e)}} = 800$ GeV





N.B. Contribution from sWIMP at $\lambda, \lambda' \sim 10^{-11}$- 10^{-14} $\rightarrow$ signal of MP & Tiny Σ_ℓ-d.d. region, smaller that the Σ_d-one for $m_{\Sigma_d} = 800$ GeV

* In Σ_ℓ-d.d. region for $m_{\Sigma_\ell} = 400$ GeV, crossing of $\Omega_{\rm DM}$ and $\tau_{\rm DM}$-lines at $BR \lesssim 10^{-3}$

** Σ_e-d.d. region is closed (open) for $m_{\Sigma_e} = 800\,(400)$ GeV

Results - Most favorable benchmark of Σ_d

Looking at the plots for $m_{\Sigma_d} = 800\,\text{GeV}$ and $L = \{25, 300, 3000\}\ \text{fb}^{-1}$, a benchmark where the DM ID signal, d.v.- and MP- signals and a not too small BR can be found:

Σ_d: $\lambda = 1.8 \times 10^{-11}$, $\lambda' = 5.5 \times 10^{-10}$, $x \sim 10^{-2}$			
Part of detector	Total	$\Sigma \to DM$	$\Sigma \to$ SM only
$\mathcal{L} = 25\text{fb}^{-1}$			
Pixel	63	0	63
Tracker	125	0	125
Out	907	1	906
$\mathcal{L} = 300\text{fb}^{-1}$			
Pixel	757	0	757
Tracker	1504	2	1502
Out	10889	11	10878
$\mathcal{L} = 3000\text{fb}^{-1}$			
Pixel	7571	8	7563
Tracker	15043	15	15028
Out	108892	113	108779

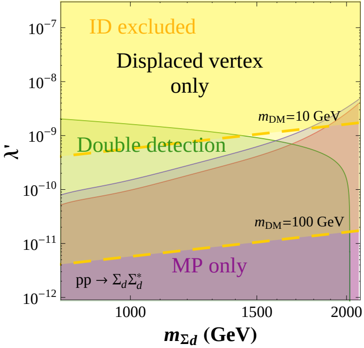
$\Downarrow$

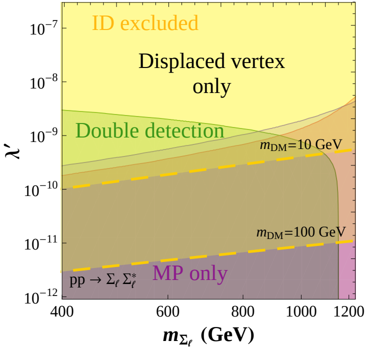
CMS Σ_d-double-signal with an acceptable cosmology at $L = 3000\,\text{fb}^{-1}$

* The analogous benchmark for the case of Σ_ℓ has a smaller number of expected events than the colored one $\to$ No detection of "$\Sigma_f \to \text{DM}$"

Results - Summary

To summarize the outcome of this analysis and discuss if the next future LHC signal can distinguish the two studied Σ-decay channels, the LHC reach has been showed for Σ_ℓ and Σ_d scenarios at $L = 300\,\text{fb}^{-1}$ in λ'-m_Σ plane.





N.B. Double detection is ruled out for $m_{\Sigma_d} > 100\,\text{GeV}$ and $m_{\Sigma_\ell} > 10\,\text{GeV}$ & Only MP expected at $m_{\rm DM} = 100(10)\,\text{GeV}$ in $\Sigma_{d(\ell)}$ scenario & Σ_d: future ID region is in the double detection corner: $m_{\rm DM} = 10\,\text{GeV}$ and $m_{\Sigma_d} < 1500\,\text{GeV}$

Conclusions

- Decaying DM in a very simple setup (i.e. DM Majorana, scalar $\Sigma \rightarrow$ 4 relevant param.) is cosmologically well-motivated
- LHC detection prospects of such a simple setup: Σ_f-displaced vertices (both decay channels) and Σ_f-metastable particles
- DM ID and DM density bounds on our scenarios lead to particular values of x and τ_{DM} for Σ_d (Σ_ℓ) which are cosmologically consistent
- Combination of DM cosmological bounds and LHC reach draws 3 regions in λ'-m_Σ: double detection/displaced vertex only/MP only $\rightarrow$ Benchmark for Σ_d (Σ_ℓ)
- A collider detection of both Σ decay channels with a consistent cosmology can be obtained for Σ_d!!

Thank you!