Correlation between ID signals and LHC

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Based on:
G.A and L. Covi
JCAP 1308 (2013) 005
G.A., L. Covi and F. Dradi
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G.A., L. Covi and F. Dradi
arXiv:1412.6351 (Mostly)

ERC Higgs@LHC

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invisibles
neutrinos, dark matter & dark energy physics

Decaying Dark Matter

Conventionally Dark Matter is assumed to be stable, typically as consequence of a symmetry.

In reality stability is required on cosmological scales.
A small population of DM can decay at present times and the products can be detected in cosmic rays.

Purpose of our study: Investigate scenarios of DM where a correlation between an hypothetical Indirect Detection (ID) of the decay of the Dark Matter can be correlated to searches of new physics at LHC.

The model

Minimal model: SM+ Majorana fermion (DM candidate)+ Scalar field

$$L_{\rm eff} = \lambda \bar{\psi} f \Sigma_f^{\dagger} + h.c.$$

$\Sigma_f =$ Scalar field, not trivially charged under the standard model gauge group

$\psi =$ Majorana field, Dark matter candidate

No symmetry is imposed to stabilize the DM. The scalar field has analogous couplings with two SM fermions.

$$L_{\rm eff} = \lambda' \bar{f}' f \Sigma_f^{\dagger} + h.c.$$

Our strategy

Identification of the regions accounting for the correct DM relic density ⟷ Requirement of observable DM decay, i.e. DM lifetime close to a reference value.

↓

Information on the couplings of the model as function of the masses

Requirement of LHC production of the scalar field (compatibly with current limits) → Determination of decay lenght and possible distinctive signatures.

Distinctive collider signature of our scenario is the detection of two kinds of decay channels of the scalar, i.e. SM+DM and SM only.

Possible scenarios

DM of the order of heavier than the GeV → DM decaying into three SM fermions. Reference sensitivity set by current constraints.

↘ Scalar field long lived with respect to LHC detector

DM with 7 KeV mass → Lifetime set by the (potential) detection of the 3.55 KeV line

↘ Scalar field promptly decaying at the LHC

Decays of the scalar field

Prompt decays $l_\Sigma \lesssim O(100\mu\mathrm{m})$

Case 1: Branching ratio into DM dominant: dijet (dilepton) event +missing energy. Signatures similar to RPC Susy

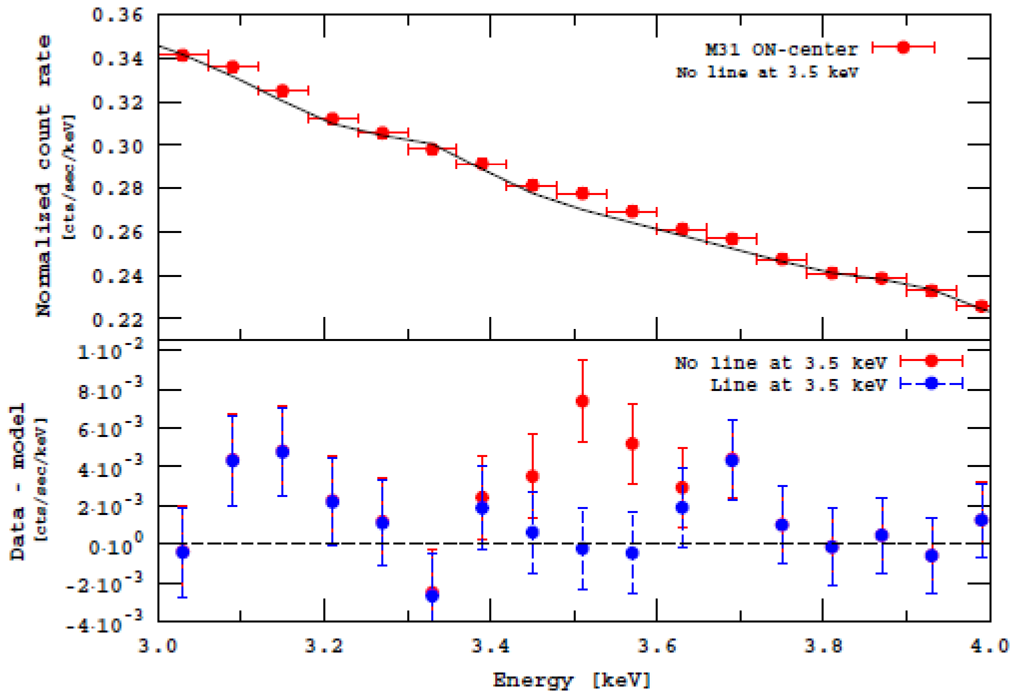
Case 2: Branching ratio into only SM dominant: Signatures similar to Leptoquarks

Displaced decays $O(100\mu\mathrm{m}) \lesssim l_\Sigma \lesssim O(10\mathrm{m})$

Detector stable particles $l_\Sigma \gtrsim O(10\mathrm{m})$

3.55 KeV line

The existence of an unidentified line in the combined spectrum of
Galaxy clusters, as well as the Perseus and Andromeda Galaxy has been reported. (arXiv:Bulbul et al. 1402.2301, Boyarsky et al. 1402.4119)



The line can be explained with a 7 KeV DM decaying into monochromatic photons.

The claim is still controversial (see e.g. 1408.1699) and most probably new data are needed for definitive confirm.

Dark Matter Production

Cosmological stability and limits from Indirect Detection require very weak coupling between the DM and the SM. Conventional WIMP paradigm hardly feasible.

Freeze-in: DM produced by the decay of scalar field while still in thermal equilibrium. Relic density depends on the decay rate of the field into DM.

$$\Omega^{FI} h^2 = \frac{1.09 \times 10^{27} g_\Sigma}{g_*^{3/2}} \frac{m_\psi \Gamma(\Sigma_f \to \psi f)}{m_{\Sigma_f}^2}$$

Hall et al 2009 (see also e.g. Asaka et al 2005, Kusenko et al. 2006)

→ Prediction of the coupling between the DM and the scalar field

Effectiveness of freeze-in sets by itself a constraint on the coupling between DM and the scalar field

Freeze-in active if:

$$\frac{\Gamma\left(\Sigma_f \rightarrow DM + SM\right)}{H} < 1$$

$$\longrightarrow \quad \lambda^2 < 8\pi\sqrt{g_*}1.66\frac{m_{\Sigma_f}}{M_{\rm pl}}g_{\Sigma}^{-1} \quad \longrightarrow \quad \lambda \lesssim 10^{-7}$$

For higher couplings DM can be a thermal relativistic relic and then overproduced.

Above GeV scale DM decays into three fermions

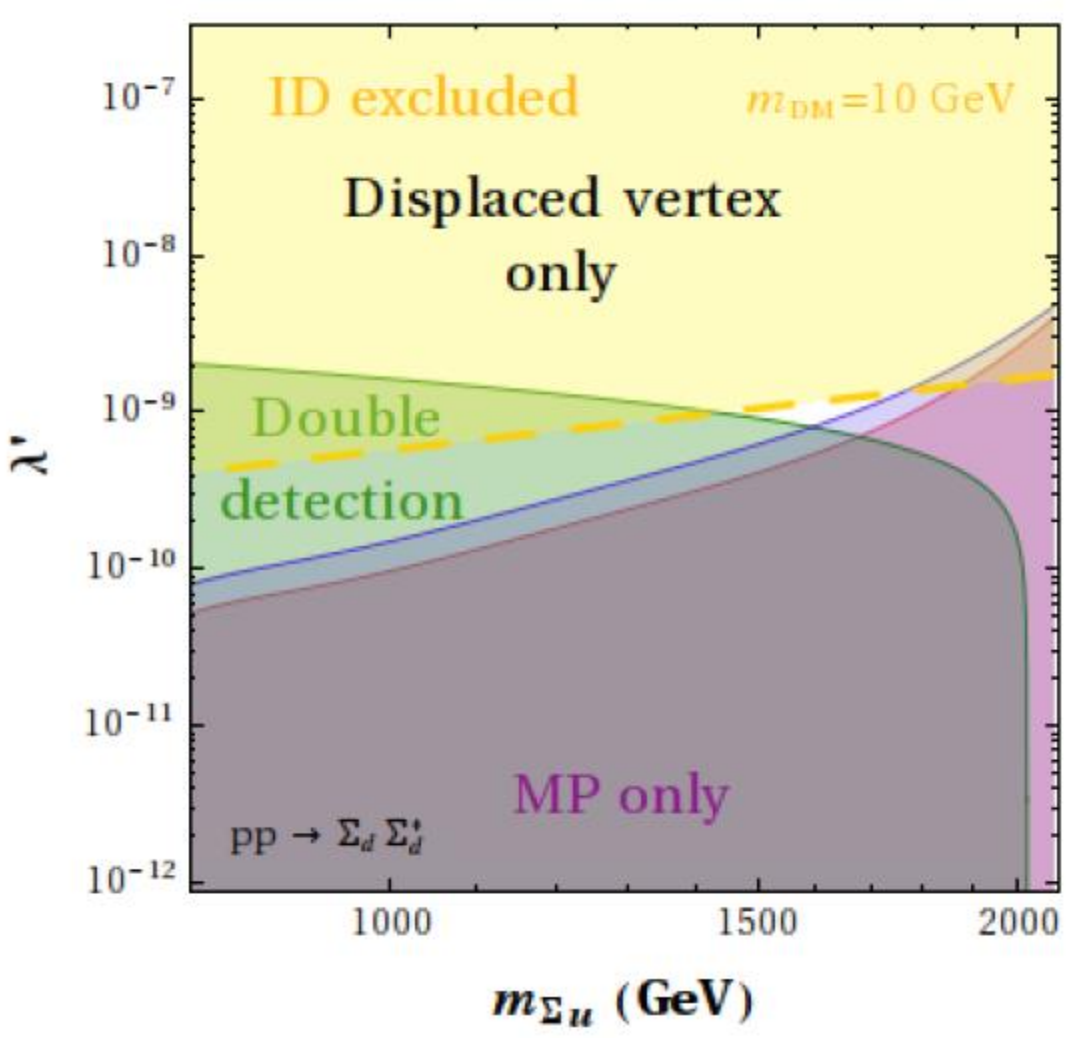
e.g. $\psi \to \bar{u}u\nu, \bar{d}d\nu$

$$\lambda \simeq 1.59 \times 10^{-12} x^{-1/2} \left(\frac{g_*}{100}\right)^{3/4} \left(\frac{\Omega^{\rm FI} h^2}{0.11}\right)^{1/2} g_\Sigma^{-1/2}$$

$$\lambda' \simeq 0.91 \times 10^{-12}\, x^{-2} \left(\frac{g_*}{100}\right)^{-3/4} \left(\frac{m_{\Sigma_f}}{1\,\rm TeV}\right)^{-1/2} g_\Sigma^{1/2} \left(\frac{\tau_\psi}{10^{27}\rm s}\right)^{-1/2}$$

$$x = m_\psi / m_{\Sigma_f}$$

The scalar field is very long lived. Decays through displaced vertices or even detector stable.



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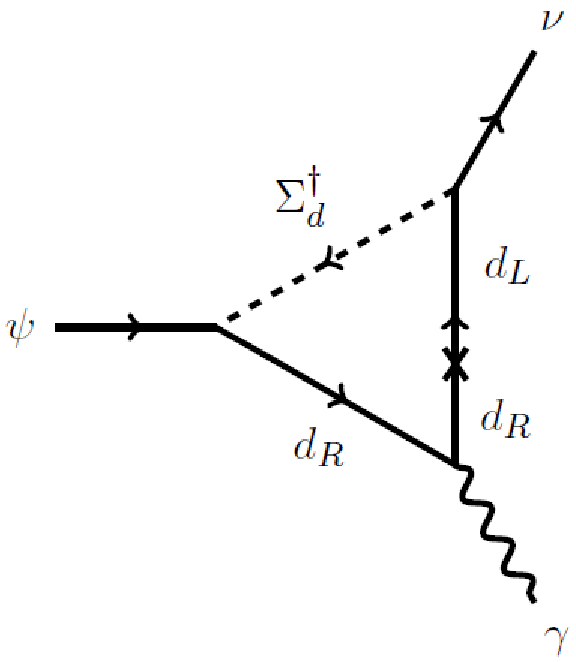
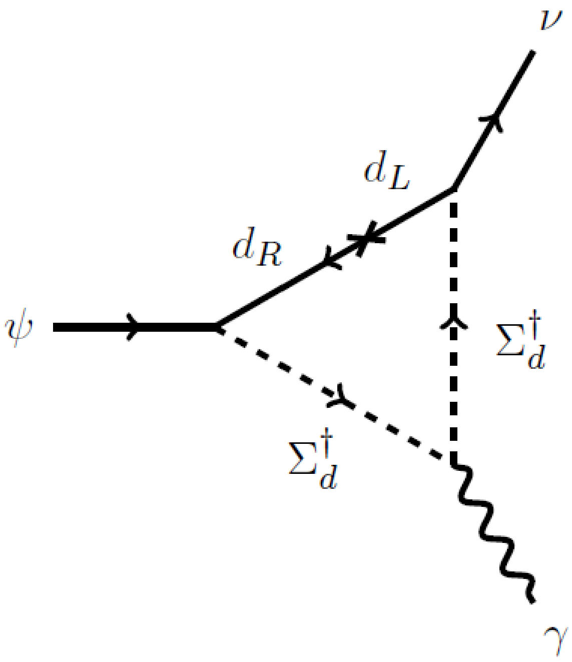
KeV line in minimal scenario

KeV scale DM decays (at one loop) into a photon and a neutrino.





$$L_{\rm eff} = \lambda' \bar{d}_R \ell_L \Sigma_q + h.c.$$

$$L_{\rm eff} = \lambda' \bar{\ell}_R^c q_L \Sigma_d^\dagger + h.c.$$

$$L_{\rm eff} = \lambda' \bar{\ell}_R^c \ell_L \Sigma_e^\dagger + h.c.$$

$$L_{\rm eff} = \lambda' \bar{e}_R \ell_L \Sigma_\ell + h.c.$$

Only a subset of the possible operators allow for decay into photons.

$$\Gamma(\psi \to \gamma\nu) = \frac{e^2 m_\psi^3}{2048\pi^5}\left(\sum_i \frac{m_i}{m_{\Sigma_f}^2}\lambda_i'\lambda_i f_1\left(\frac{m_i^2}{m_{\Sigma_f}^2}\right)\right)^2 \longrightarrow \tau\left(\psi \to \gamma\nu\right) \simeq 5.6 \times 10^6\,\mathrm{s}\left(\frac{m_\psi}{7\,\mathrm{keV}}\right)^{-3}\left(\frac{m_{\Sigma_f}}{1\,\mathrm{TeV}}\right)^4\left(\lambda\lambda'\right)^{-2}$$

$$\lambda \simeq 0.8 \times 10^{-8}\left(\frac{m_\psi}{7\,\mathrm{keV}}\right)^{-1/2}\left(\frac{m_{\Sigma_f}}{1\,\mathrm{TeV}}\right)^{1/2}\left(\frac{g_*}{100}\right)^{3/4}\left(\frac{\Omega h^2}{0.11}\right)^{1/2}$$

→ Fixed by freeze-in

$$\lambda' \approx 3 \times 10^{-3}\left(\frac{m_\psi}{7\,\mathrm{keV}}\right)^{-1}\left(\frac{m_{\Sigma_f}}{1\,\mathrm{TeV}}\right)^{3/2}\left(\frac{\tau\left(\psi \to \gamma\nu\right)}{10^{28}\,\mathrm{s}}\right)^{-1/2}$$

→ Fixed by Indirect Detection

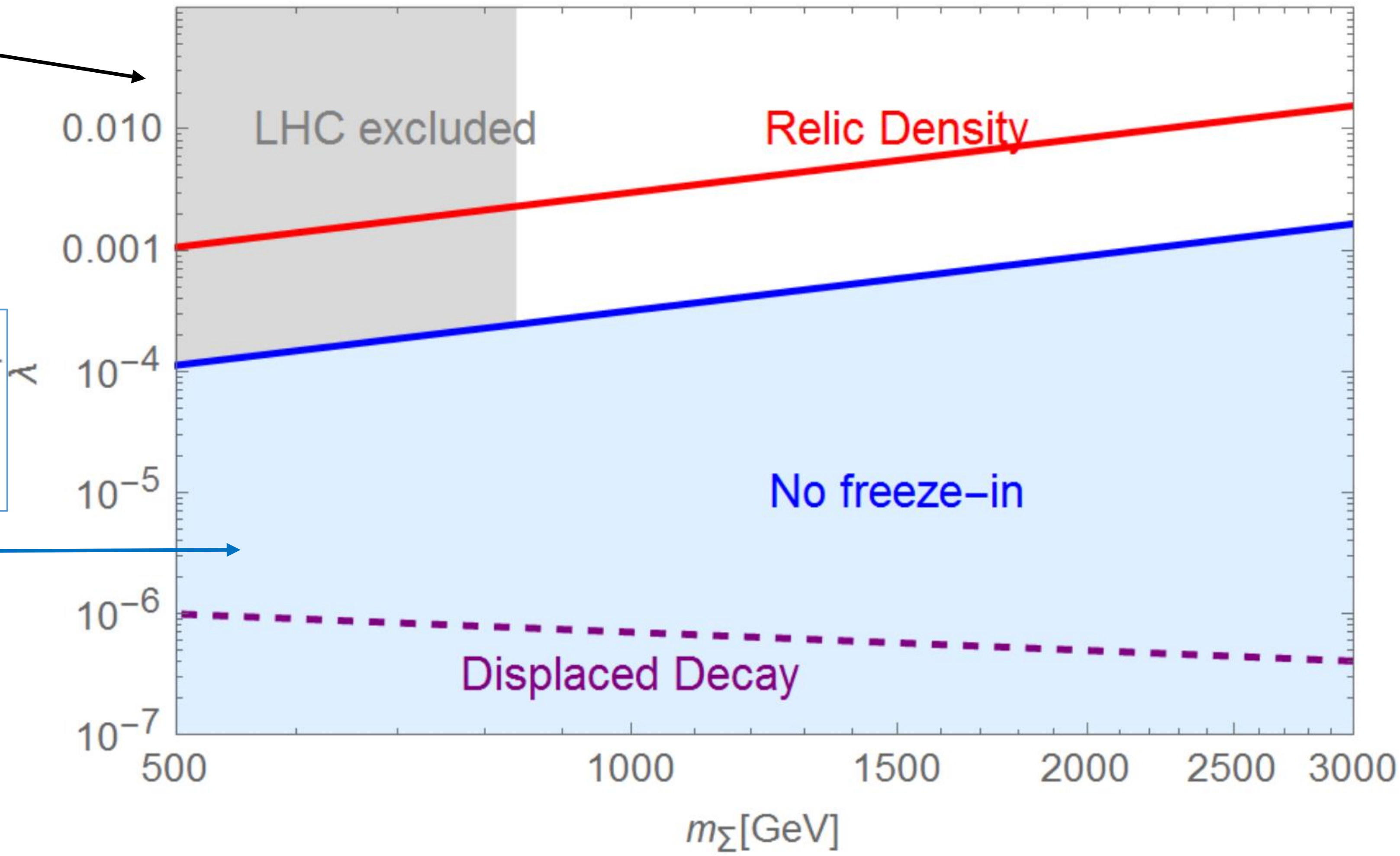
$$l_{\Sigma_f} \simeq 5.6 \times 10^{-11}\,\mathrm{cm}\left(\frac{m_\psi}{7\,\mathrm{keV}}\right)^2\left(\frac{m_{\Sigma_f}}{1\,\mathrm{TeV}}\right)^{-4}\left(\frac{\tau\left(\psi \to \gamma\nu\right)}{10^{28}\,\mathrm{s}}\right)$$

Scalar field promptly decays into only SM fermions. Limits from Leptoquark searches (colored scalar field) or SUSY searches (only EW interacting scalar).

Limit from third generation leptoquarks (CMS coll. 1408.0806)

The coupling between the DM and the scalar field is too strong. DM thermalizes

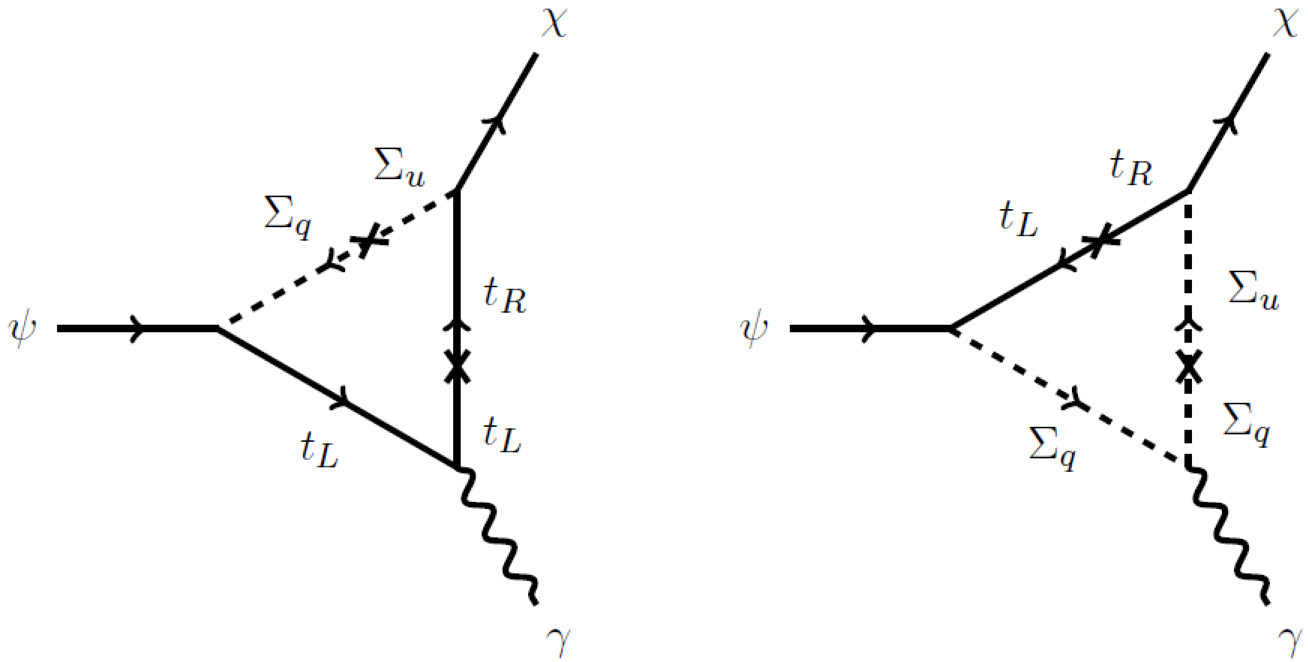
$$\frac{\Gamma}{H} > 1$$



Extensions of the model

Dark matter coupled to an additional (Majorana) light SM singlet.

$$L_{\rm eff} = \left(\lambda_{\rm L}\bar{\psi}q_L\Sigma_q^\dagger + \lambda_{\rm R}\bar{\psi}t_R\Sigma_u^\dagger\right) + h.c.$$
$$+\left(\lambda_L^{\prime}\bar{\chi}q_L\Sigma_q^\dagger + \lambda_R^{\prime}\bar{\chi}t_R\Sigma_u^\dagger + h.c.\right)$$
$$+\mu H\Sigma_q\Sigma_u^\dagger + h.c.$$



$$\tau\left(\psi \to \chi\gamma\right) \simeq 1.4 \times 10^{4}\ \mathrm{s}\left(\frac{m_\psi}{7\ \mathrm{keV}}\right)^{-3}\left(\frac{m_{\Sigma_1}}{1\ \mathrm{TeV}}\right)^{4}\left(\lambda\lambda'\right)^{-2}$$

→ Top loops enhance the DM lifetime

$$\lambda' \approx 1.5 \times 10^{-4}\left(\frac{m_\psi}{7\ \mathrm{keV}}\right)^{-1}\left(\frac{m_{\Sigma_1}}{1\ \mathrm{TeV}}\right)^{3/2}$$

→ Decay lenght of the scalar field still in the range of prompt decays

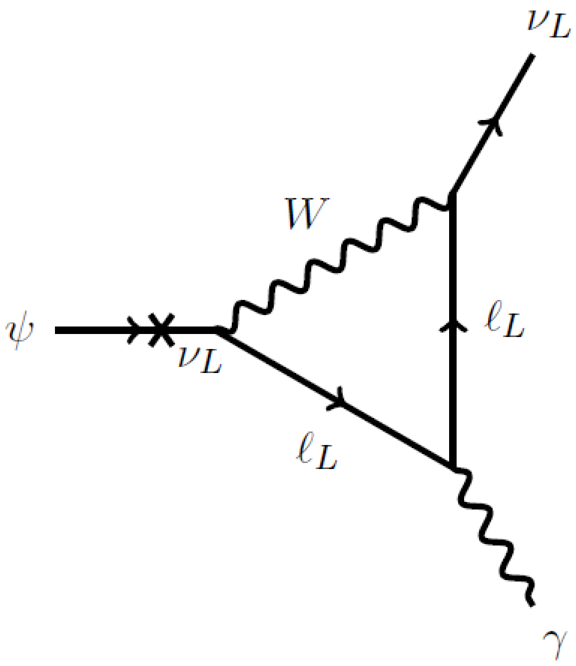
The new singlet is in thermal equilibrium in the Early Universe and decouples while relativistic. We have to require it to be very light (below eV).

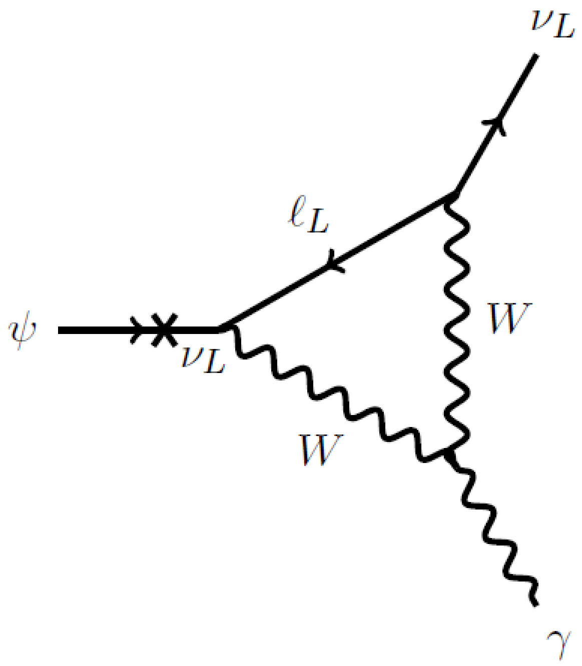
$$\Delta N_{\mathrm{eff}} = \frac{23.73}{\left(g_*^s(T_d)\right)^{4/3}}$$

Blennow et al. 1203.5803

Contribution to the effective number of neutrino species compatible with experimental limits due to high temperature of decoupling.

$\tilde{\lambda}\bar{\psi}H\ell$ ⟶ Additional interaction with the Higgs boson (DM as sterile neutrino)





$$\Gamma(\psi \to \nu\gamma) = \frac{9\alpha G_F^2 m_\psi^5}{256\, 4\pi^4} \sin^2 2\Theta$$

$$\Theta = \frac{\tilde{\lambda} v}{m_\psi}$$

Line is reproduced for

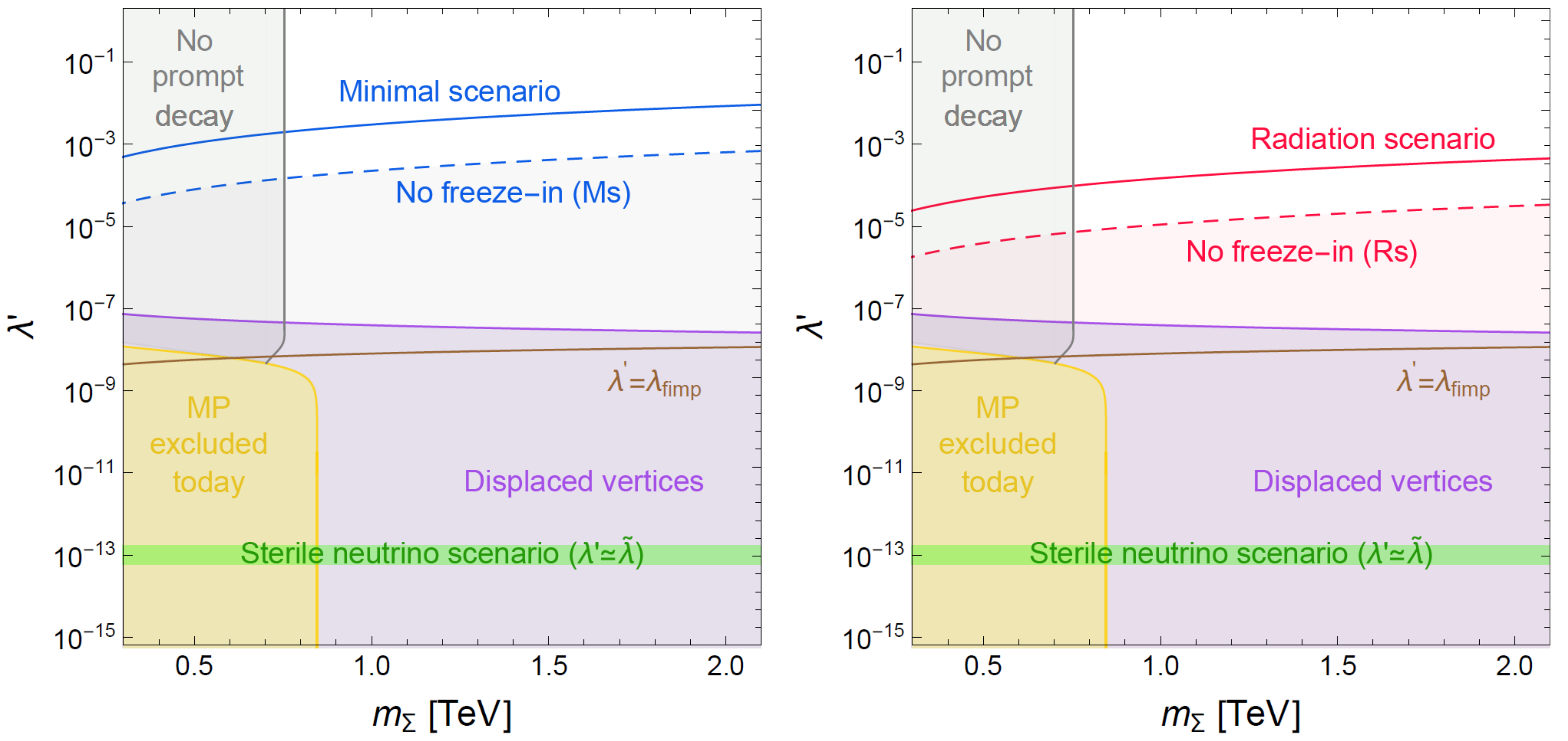
$$\sin^2 2\Theta = 2 - 20 \times 10^{-11}$$

↓

$$\tilde{\lambda} \simeq 10^{-13}$$

The scalar field is not anymore involved in DM decay but still provide a simple and economic production mechanism.

Two decay channels can be observed at the LHC assuming all the couplings of the same order.



No prompt decay
Minimal scenario
No freeze−in (Ms)
λ'=λfimp
MP excluded today
Displaced vertices
Sterile neutrino scenario (λ'≃λ̃)
λ'
mΣ [TeV]
No prompt decay
Radiation scenario
No freeze−in (Rs)
λ'=λfimp
MP excluded today
Displaced vertices
Sterile neutrino scenario (λ'≃λ̃)
λ'
mΣ [TeV]

Conclusions

We have explored the correlation between ID and collider detection in a very simple case of study: decaying dark matter accounting for the KeV line.

In the minimal realization of the model the combination of ID and DM relic density leads to a scalar field promptly decaying into SM fermions at the LHC.

Alternative distinctive signatures can be achieved in extensions of the model.