# Minimal decaying Dark Matter and the LHC

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based on G.Arcadi and L. Covi, JCAP 1308 (2013) 005 arXiv: 1305.6587



in Visibles neutrinos, dark matter & dark energy physics

## DM searches





## Outline of the talk

Correlation of ID and collider DM detection for decaying Dark Matter:

- Case of study: SM + DM Majorana Fermion+Scalar field (partially) charged under SM group.

Similar setup proposed in Garny et al. 1011.3786, 1112.5155, 1205.6783, 1207.1431

- Identification of cosmological viable regions.

- Investigation of regions of parameter space accessible to contemporary ID and collider detection.

#### in view of their weaker limits. Moreover the next future energy update of the LHC will provide a consider interest. For the constant  $\boldsymbol{\nu}$  entimeters of the will consider The scalar field can couple as well to SM fermions only analogously to what happens the following two operators  $\blacksquare$ *qRu*¯*Rd<sup>c</sup> L*Σ*† <sup>d</sup>* + *h.c.* (1.2)  $D$ *d* $f$ <sup>*n*</sup> $i$ </sub>  $i$ *n* $i$   $f$ <sup> $f$ </sup> $f$ <sup> $h$  $f$ </sup> $i$ the following two operators with SM field are allowed: **definition of the model to a standard model to a standard model to a standard model fermion of the model standard model to a standard model fermion of the model**  $\blacksquare$

Minimal model: SM+Maiorana fermion+scalar field *RqL*Σ*† <sup>d</sup>* + λ *•* The scalar has the quantum numbers of the squark *u*˜*R*, leading only to the operator: **•** The scalar end of the square of the square  $\mathbf{r}$  and the square  $\mathbf{r}$ **a** scalar field  $\overline{A}$  , charged under at least part of the Standard Model gauge group, the **Experimental induction visit interaction whose general form is given by:**  $\frac{1}{2}$ 

$$
L_{\text{eff}} = \lambda_{\psi f L} \bar{\psi} f_L \Sigma_f^{\dagger} + \lambda_{\psi f R} \bar{\psi} f_R \Sigma_f^{\dagger} + h.c.
$$

With the aim of proposing a model with a rich collider phenomenology, it may seem

more promising to concentrate on hadronic models because of their direct coupling of the DM

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#### *•* The scalar field is an SU(2) singlet with electromagnetic charge equal to -1/3, thus **Additional interactions of the scalar** the following two operators with SM field are allowed: *A* designal interactions of the scal Additional interactions of the scalar field: *•* The last possibility is that we have a *SU*(2)*<sup>L</sup>* doublet: σ*u* Additional interactions of the scalar field: The DM is assumed to be a Majorana fermion  $\mathcal{L}$  . The set  $\mathcal{L}$

$$
L_{\text{eff}} = \lambda'_{qL} \bar{l}_{R}^{c} q_{L} \Sigma_{d}^{\dagger} + \lambda''_{qR} \bar{u}_{R} d_{L}^{c} \Sigma_{d}^{\dagger} + h.c.
$$
  
\n
$$
L_{\text{eff}} = \lambda''_{qR} \bar{d}_{R} d_{L}^{c} \Sigma_{u}^{\dagger} + h.c.
$$
  
\n**Hadronic realizations**  
\n
$$
L_{\text{eff}} = \lambda' \bar{d}_{R} l_{L} \Sigma_{q} + h.c.
$$

*<sup>e</sup>* + *h.c.* (1.6)

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*<sup>R</sup>* ≡ (*fc*)*<sup>R</sup>* is the adjoint of the charge conjugate

*dRqL*Σ*<sup>l</sup>* + *h.c.* (1.7)

$$
L_{\text{eff}} = \lambda_{lL} \bar{\nu}_L^c l_L \Sigma_e^{\dagger} + h.c.
$$
 Leptonic realizations  

$$
L_{\text{eff}} = \lambda_l \bar{e}_R l_L \Sigma_l + \lambda'_l \bar{d}_R q_L \Sigma_l + h.c.
$$

in which the scalar field is, respectively, an *SU*(2) singlet or doublet. In the previous

expressions, following the notiation of [3], we have labeled with the superscript *<sup>c</sup>* the charge

In the leptonic models instead, the scalar field features only EW interactions and couples

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! ¯ **L**<br>L<sup>il</sup>ler<br>L

to leptons according the following two operators:

conjugate of a spinor in such a way that ¯*f<sup>c</sup>*

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*•* The last possibility is that we have a *SU*(2)*<sup>L</sup>* doublet:

both hadronic and leptonic models in our study.

*L*eff = λ

*qL*¯*l*

*qL*¯*l*

*RqL*Σ*†*

### Lagrangians introduced above interved above intervention of the COII fermions. Unless explicitly stated final stated final stated final state particles will be assumed massless. I<br>In this case of thi Correlation between collider and ID



$$
l_{\Sigma,DM} \simeq 1.17 \,\mathrm{m} \left(\frac{m_{\Sigma_f}}{1\,\mathrm{TeV}}\right)^{-6} \left(\frac{m_{\psi}}{1\,\mathrm{GeV}}\right)^{5} \left(\frac{l_{\Sigma,SM}}{1\mathrm{m}}\right)^{-1} \left(\frac{\tau_{\psi}}{10^{27}\mathrm{s}}\right)
$$

 $\mathsf{Sible}\;\mathsf{scenario}\;\mathsf{ot}\;\mathsf{detection}\;\mathsf{ot}\;\mathsf{both}\qquad\qquad\qquad$ fermion contact interaction. This possibility is however not interesting for  $\sim$  $\mathsf{S}$  in detection of  $\mathsf{S}$  possible into a collider in  $\frac{1}{6}$  -4 -2  $\sqrt{2}$ are related to the production and subsequent decay of the scalar field Σ*<sup>f</sup>* whose mass thus **Possible scenario of detection of both** 100 ST LOCOCONOMIC SOUTH A PART decay.  $\frac{1}{2}$ a reference value *m*Σ*<sup>f</sup>* = 1TeV and, as already stated, a DM lifetime of 10<sup>27</sup> s. In order to *a* reference value in the USS and, and, a DM lifetime of 1027 stated, a DM lifetime of 1027 s. In order to 1027 s. In or decay channels together with ID of DM exceed the dimension of the dimension of  $10$   $\frac{1}{6}$ a scenario, occurring at DM masses of the order of the order of the order of  $1$ Possible scenario of detection of both

can note of few TeV's in order to lie with the value of  $\mathbb{R}$ | Study within a four parameter model: DM and scalar and the dimension of the <sup>my =</sup> masses and couplings  $\lambda$  and  $\lambda'$ . The potential correlation between DM Indirect Detection and collider is evidenced by channels of Σ*<sup>f</sup>* have similar decay lengths and potentially fall in the range of observability Study within a four parameter model: DM and scalar



Figure 2: Value of the Σ*<sup>f</sup>* decay length (in meters) into DM and one fermion respect to

*.* (3.5)

representing, respectively, the interactions of the scalar field Σ*<sup>f</sup>* with the dark matter and the

representing, respectively, the interactions of the scalar field Σ*<sup>f</sup>* with the dark matter and the

this requirement favors rather low values of the DM mass.

when cosmological cosmological cosmological constraints on DM are taken into account. The constraints on DM are





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

### with an enhancement factor of around αs*Qq/*αem. where *Q<sup>q</sup>* is the charge of the involved quark in units of *e*. Even in this case the scattering contribution is at most of the order of Cosmology

### We distinguish two opposite scenarios: scenarios:

$$
\lambda \lesssim 10^{-7}
$$

**References**<br>References DM never in thermal equilibrium in the Early Universe.

 $\vert$  (SuperWimp) (SuperVVImp) a. Ibarra, and D. Transmission Hadronically Decaying Dark Matter, "Constraints" Dark Matter, "Constra Production through freeze-in or non thermal

*Jess explored scenario* JWell known s  $\frac{1}{2}$  J<sub>S</sub> Recall C supersymmetry,  $P_{\text{A}}$  and  $P_{\text{B}}$  and  $P_{\text{C}}$  a Less explored scenario, possible peculiar signatures.



 $1 <sup>1</sup>$  ever in thermal  $\begin{array}{|c|c|} \hline \text{1} & \text{1} & \text{1} \\ \hline \text{2} & \text{3} & \text{4} \\ \hline \text{3} & \text{4} & \text{5} \\ \hline \text{4} & \text{5} & \text{6} \end{array}$ DM in thermal equilibrium in the Early Universe.

 $\mathsf{p}_{\mathsf{readuction\text{-}three}$  through  $\mathsf{p}_{\mathsf{readuction\text{-}throu}$  through  $\mathsf{F}_{\mathsf{read}}$ atter of the product of the product<br>In a product of the p Production through Freeze-out mechanism.

possible peculiar<br>
and Dark Matter, Constraints on Hadronic realizations, Well known scenario, already strongly constrained in case of hadronic realizations.

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## DM relic density

Two mechanisms for DM generation:

- Freeze-in: DM produced by scalar decay still in equilibrium.

Relic density depends on decay rate into dark matter.

- SuperWimp: DM produced by decay of scalar after its chemical decoupling. Relic density depends on scalar field abundance and branching ratio of decay into DM.



The correct relic density is, however, achieved for a too low value of the mass to be a viable mass to be a viable  $\alpha$ 

Figure 6: Left panel: Dark matter and Σ*<sup>e</sup>* yields, represented respectively with dashed The two mechanisms act on two different time scales. Relic density  $116$ analytically computable as sum of two contributions. two mechanisms act on two different time scales. Relic density  $\qquad \parallel$ annihilation processes decouple. The DM relic decouple. The DM relic density is tighted to the decay rated to tup mechanisms act on two different time scales Relic density  $T$  is the second mechanism is the production of  $T$  and  $\alpha$  again from the decay of the scalar from the sca rically computable as sum of two contributions. *i* different three scales. Netter defisity f two contributions. For the latter when  $\blacksquare$ 

Freeze-in		
$\Omega^{FI}h^2 = \frac{1.09 \times 10^{27} g_{\Sigma}}{g_*^{3/2}} \frac{m_{\psi} \Gamma(\Sigma_f \to \psi f)}{m_{\Sigma_f}^2}$	\n        Hall et al. 0911.1120\n	
SuperWimp	$\Omega_{\psi}^{SW}h^2 = x Br(\Sigma_f \to \psi + SM)\Omega_{\Sigma}h^2$	$x = m_{\psi}/m_{\Sigma_f}$

=

<sup>1</sup>*.*<sup>09</sup> <sup>×</sup> <sup>10</sup>27*g*<sup>Σ</sup>

8π

*g* ∗

ΩFI*h*<sup>2</sup>

the relic density is proportional to the BR of decay of Σ*<sup>f</sup>* into DM.

coupled Boltzmann equations for the Σ*<sup>f</sup>* and ψ field. On the other hand the scalar field,

 $A$ lthough, in generation can be investigated by solving a system of  $\mathcal{A}$ 

No assumption on the size of the made but this will be determined by determined by  $\mathcal{L}_\mathbf{X}$ 

only from the requirement of  $D$  via  $\mathcal{L}$  and, in the next sections, from detections, from detection limits.

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above can be riexpressed as:



occurires, as expected, while the scalar field is still in the still in the still in the scalar field is still in the still in the

orgio Arcadi<br>Internacionalism for values of 10−11. By decreasing and 10−11. By decreasing and freeze-internacionalism and f contribution decreases in favor of the SuperWimp one. This last mechanism determines lunedì 23 settembre 2013

#### for direct comparison between the massive and massless cases. The constraints are quite similar, although not completely identical due to the different energy spectra in the ID constraints

The DM decays at three level into three fermions.



Cirelli et al. 1205.5283

CTA Fornax

 $\overline{\phantom{a}}$ 

10<sup>29</sup>



Hadronic realizations are constrained by Figure 5: Direct comparison of the constraints on the nearly mass-degenerate three-body antiprotons

Strongest limits on decay into leptons come from Cirelli et al. 1205.5283 gamma-rays correspond to the massive community case. The massive monetage  $-mn \leq n$ 

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# LHC prospects

In our framework collider phenomenology relies on production and decay of the scalar field.

Prediction of the decay lenght of the scalar field within the four parameter model compatible with cosmological and ID constraints.

Possible scenarios:

- Prompt decay

Case I: Domination of coupling with DM

 $\longrightarrow$  Dijet (Dileptons) events +Missing energy. Masses of the scalar excluded up to 800 (300) GeV

Case 2: Domination of coupling with only SM states. Lower amounts of missing energy. Limits from Leptoquark searches of 600-800 GeV. Some realizations weakly constrained.

- Displaced vertex

Very few searches employed.Yet unexplored scenario. Amount of missing energy again determined by the dominant coupling. (see e.g. ATLAS-CONF-2013-092)

### - Detector stable particle

Limits from detection of charged tracks of 300-400 GeV for only EW interacting particles, of above 1 TeV for color interacting particles. Alternative detection strategies under investigation.

(see e.g. ATLAS-CONF-2013-069; JHEP07(2013)122)

#### **values of** *Definite example* hadronic mode SuperWimp contribution. The latter grows in importance by increasing *m*Σ*<sup>e</sup>* and becomes More involved is instead the other scenario. In the case of the colored Σ*q,u,d* within LHC reach, we have dominance of the FIMP mechanism. By reverting the FIMP mechanism. By reverting the FIMP mechani decay length in terms of the DM relic decay length in terms of the DM relic density giving:<br>The DM relic density giving: the DM relic density giving: the DM relic density giving: the DM relic density gi Definite example: hadronic models

This expression evidence that the decay length into  $\frac{1}{2}$  and  $\frac{1}{2}$  and  $\frac{1}{2}$  and size of the size of  $ID$  and relic dens function of the masses.  $22.2$  **and 2**.1 **a** *m* 2<sup>1</sup> *m* −2<sup>1</sup> 1.11 **1.12** €1.12<br>1.11 **1.12**<br>1.11 **1.12** ID and relic density constraints identify the ranges of the couplings as

**deta** wall a very low value of the collider details for values of *x*, namely less than 10−6. On the other hand, by interesting a ID signal (see fig. 5) we obtain a ID signal (see fig. 5) we obtain an enhancement of  $\mathcal{L}$ , responsible of decays of decays of several orders of several orders of several orders of several orders of s<br>Στην αναφέρεια το διαφορείο του διαφορείου του διαφορείου του διαφορείου του διαφορείου του διαφορείου του δι  $\overline{\mathbf{M}}$  can get a prodiction of the collidar decovilents  $\longrightarrow$   $\cdots$  can go  $\alpha$  p  $\blacksquare$ We can now verify the relic density constraint on the prospects of indirect on the prospects of ind  $\begin{array}{c} \begin{array}{c} \bullet \end{array} \end{array}$  is the decay length into DM largely exceeds the detector of the except for very low values of *x*, namely low values of *x*, namely less than 10−4. On the other hand, by imposing a set of  $\alpha$ We can get a prediction of the collider decay lenght of the scalar field.

adronic models are dominat In order to have a estimate of the decay length associated to the decay decay mediated to the decay mediate of the decay mediated by t detection. As just evidenced, in the case of colored Σ*<sup>f</sup>* the SuperWimp contribution is Hadronic models are dominated by the FIMP mechanism, a rather precise determination ID signal (see fig. 5) in the near future, we obtain an enhancement of the coupling  $\frac{1}{\sqrt{2}}$ of the coupling is achieved.



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0.01<br>0.01 its decay does not affect Big-Bang Nucleosyntesis (BBN). In fig. (1) we have the fig. (1) we have the fig. (1)  $\sum_{n=4}^{\infty}$  in fig. (1)  $\sum_{n=4}^{\infty}$  in fig. (1)  $\sum_{n=4}^{\infty}$  in fig. (1)  $\sum_{n=4}^{\infty}$  in fig. (1)  $\$ lunedì 23 settembre 2013



corresponding to a decay length:

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below 1 GeV, since they do not feature a peculiar phenomenology with respect to the one

of decays into DM (right panel). The coupling have been fixed according eq. (4.10) and  $\alpha$  and mechanism are nevertheless active in this case 3, both involving in the decay of *interactive into Dark in the decay of a funedì* 23 settembre 2013 and a *funedì 23 settembre 2*013

#### Leptonic models <sup>1</sup>*.*<sup>09</sup> <sup>×</sup> <sup>10</sup>27*g*<sup>Σ</sup> *m*ψΓ(Σ*<sup>f</sup>* → ψ*f*)  $-12$

SuperWimp mechanism can be realized in leptonic models because of the lower annihilation rate of the scalar field. Ω*F Ih*<sup>2</sup> = *g* 3*/*2 ∗ *i*<sub>2</sub>  $\left(\frac{1}{2}\right)^{2}$ where **g** are the number of internal degrees of freedom of freedom of freedom of  $\frac{1}{2}$  . By using (3.4) the expression of  $\frac{1}{2}$ because of the lower annihilation rate of the scalar fi  $-44 \div 7 = 1.4 \times 10^{-10}$  $\text{Leq}_{10}$ Λ



It occurs for moderate hierarchy between the DM and the scalar field and for comparable values of the coupling.  $\begin{bmatrix} -6 \ \end{bmatrix}$  sensitive to the interactions between the DM and the scalar field, mediated by  $\begin{bmatrix} -6 \ \end{bmatrix}$ It occurs for moderate hierarchy between the  $DT$  $\begin{CD} \begin{pmatrix} -8 \\ -8 \end{pmatrix} \end{CD}$  as encoded in the branchings  $\begin{CD} \begin{pmatrix} -8 \\ -8 \end{pmatrix}$ Scalar theid and for comparable values of the coupli  $10^{27} s$  $-8$  $-6$ 10<sup>27</sup> *s*  $\begin{CD} -8 \end{CD}$  $-6$  $F_{\rm eff}$  , solid lines: curves of the cosmologically favored value of the DM relic density.  $F_{\rm eff}$ hy hetween the DM and the  $\,$ warues of the coupling.  $\blacksquare$ are obtained for  $\mathcal{P}(\mathcal{P}(\mathcal{P}))$  is fixed at 1  $\mathcal{P}(\mathcal{P})$  is fixed at 1  $\mathcal{P}(\mathcal{P})$ 

 $10^{31}$  *s*<sup>2</sup>

 $10^{29}$  *s* 

 $\sim 10^{-3}$  $10^{-5}$ 

 $10^{-7}$ 

 $-10$  . On general grounds, we expect  $\frac{1}{2}$  to  $\frac{2}{9}$   $-10$  for a charged relic subsequence  $\frac{1}{2}$  .  $\frac{29}{25}$   $\frac{1}{2}$ 

 $-12$ 

 $-10$ 

 $\mathsf{Lop}_{50}$  $\approx$ 

 $10^{31}$  *s* 

 $10^{29} s$ 

 $\frac{1}{\sqrt{10^{31}}}\int_{0^{31}}$   $\frac{1}{\sqrt{10^{31}}}\int_{0^{31}}^{10^{7}}$   $\frac{1}{\sqrt{10^{31}}}\int_{0^{31}}^{10^{7}}$   $\frac{1}{\sqrt{10^{31}}}\int_{0^{31}}^{10^{7}}$  Desy Th Giorgió Arcadi

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apart from restricted regions of the part from regions of the parameter space. In order to a set the parameter space. In order to a set the parameter space. In order to a set of the parameter space. In order to a set of t  $10 - 5$  $-1/2$ lunedì 23 settembre 2013

will be object of the next future  $\sum_{i=1}^n \frac{1}{i}$  and  $\sum_{i=1}^n \frac{1}{i}$  searches. In these scenarios can be objected in the searches. In the searches

 $-12$ 

#### An analogous outcome is obtained as well for the leptonic models. In fig. (11) we have  $\mathbf{1}_{\text{max}}$ **plotted the total decay length of the scalar SU(2) doublet to some relevant to some relevant to some relevant** C dataction of lantonic models. LHC detection of leptonic models



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1 TeV. For definiteness we have assumed 2000 assumed 2000 assumed 2000 assumed 2000 assumed 2000 assumed 2000<br>Definite assumed 2000 assumed 20

 $\frac{1}{2}$ 

achievable at very low masses, i.e. lower than  $\text{L}_6$ MeV. Combined detection of decay into DM and only SM fields is Figure 10: Solid lines: cosmological value of the DM relic density. Dashed lines: values of the DM lifetime assessment portes in the DM and only SM fields is  $\mathbb{P}^{10^{31}s}$ 



**of the DM lifetime too high.** But DM lifetime too high. reported in the plot. Dot-Dashed lines values of Σ*<sup>f</sup>* decay length. *m*Σ*<sup>f</sup>* have been fixed to 1

Figure 11: Solid lines: cosmological value of the DM relic density. Dashed lines: values

 $10^{31}$  s<sup>3</sup>

## Summary of Fimp/SuperWimp scenario

In the Freeze-in/SuperWimp scenario the coupling between the scalar field and only SM particles dominates collider phenomenology over most of the parameter space.

Detection of DM decay is associated to observation of displaced vertices of detector stable particles.



## Conclusions

We have explored the correlation among ID and collider detection in a simple scenario.

We have identified the regions accessible by contemporary ID and LHC detection.

Freeze-in/SuperWimp is promosing scenario not yet fully explored at the LHC.

Unlikely only one coupling seems accessible at collider compatibly with observable DM lifetime.

This statement requires however a detailed study of the detector response.

