# Flavoured Majorana dark matter

### from freeze-out scenarios to LHC signatures

*based on 2312.09274 in collaboration with H. Acaro*ğ*lu, M. Blanke, M. Krämer, L. Rathmann*



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#### The model and the model of the model a discrete Z $\alpha$  symmetry. The Lagrangian is given by  $\alpha$ In order to analyse the constraints on our model we need to first parameter  $\mathbf{r}$ 0 **d** <sup>13</sup>*ei*<sup>13</sup> **discussed in the model** parametrization the rephasing of eq. (2.4) has already been used to remove three complex *ij* = cos ✓*ij* and *s*✓ *ij*  $\left| \cdot \right|$  . Note that in the single state in the singl parametrization the representation the representation of  $\mathbf{r}$

$$
\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{2} \left( i \bar{\chi} \partial \chi - M_{\chi} \bar{\chi} \chi \right) - \left( \widehat{\lambda}_{ij} \bar{\mu}_{Ri} \chi_{j} \phi + \text{h.c.} \right) + \left( D_{\mu} \phi \right)^{\dagger} \left( D^{\mu} \phi \right) - m_{\phi}^{2} \phi^{\dagger} \phi + \lambda_{H\phi} \phi^{\dagger} \phi H^{\dagger} H + \lambda_{\phi \phi} \left( \phi^{\dagger} \phi \right)^{2}
$$

- $\lambda_{ij}$ : Complex  $3 \times 3$  matrix  $\lambda_{ij}$ : Complex  $3 \times 3$ *i* matrix  $\alpha$  if  $\alpha$  and  $\alpha$  and  $\alpha$  and  $\alpha$  are parameterized as  $\alpha$  and  $\alpha$  are parameterized as  $\alpha$
- **18** parameters reduced to 15 by  $O(3)_\chi$  symmetry (Dirac:  $U(3)_\chi$ ) **i** 18 parameters reduced to 15 by  $O(3)_\chi$  symmetrical matrices **diagonal matrices 3**  $\frac{1}{2}$  $\frac{1}{2}$ *D* = diag(*D*1*, D*2*, D*3)*,* and *d* = diag(*ei*<sup>1</sup> *, ei*<sup>2</sup> *, ei*<sup>3</sup> )*.* (2.11)
- $P$ arametrization $\cdot$ **Parametrization: Example 1** natrization<sup>.</sup><br>'  $\overline{\phantom{a}}$ e<br>S

$$
\lambda = U\,D\,O\,d
$$

where  $\theta_{23}, \theta_{13}, \theta_{12}, \phi_{23}, \phi_{13}, \phi_{12}$  are mixing angles,  $(D_2, D_3)$  p h metrizes the coupling i  $\delta_{23},\, \delta_{13},\, \delta_{12},\, \gamma_1,\, \gamma_2,\, \gamma_3$  are complex phases, and  $D = diag(D_1, D_2, D_3)$  parametrizes the coupling strengths  $D = diag(D_1, D_2, D_3)$  parametrizes the coupling strengths  $\mathcal{O}(1/2)$  by pursuadies. The diagonal representation of  $\mathcal{O}(3)$ 3,  $0_{13}$ ,  $0_{12}$ ,  $\gamma_1$ ,  $\gamma_2$ ,  $\gamma_3$  ar<br>  $\overline{C}$   $\overline{D}$   $\overline{D}$   $\overline{D}$   $\overline{D}$  $L_1$ ,  $L_2$ ,  $L_3$  are complex phases, and<br> $L_4$ ,  $L_5$ ,  $L_6$ ,  $L_7$ ,  $L_7$ ,  $L_8$ ,  $L_7$ ,  $L$  $\delta_{23},\,\delta_{13},\,\delta_{12},\,\gamma_1,\,\gamma_2,\,\gamma_3$  are complex phases, and where  $\theta_{23}, \theta_{13}, \theta_{12}, \phi_{23}, \phi_{13}, \phi_{12}$  are mixing angles,  $D = diag(D_1, D_2, D_3)$  parametrizes the coupling strengths  $\theta_{23}, \ \theta_{13}, \ \theta_{12}, \ \phi_{23}, \ \phi_{13}, \ \phi_{12} \text{ \ are mixing angles,}$  $D = \text{diag}(D, D, D)$  parametrizes the squaling strengths  $L = \arg(\nu_1, \nu_2, \nu_3)$  parameter in our numerical and  $\alpha$  our original analysis, we have the parameter space in  $\alpha$ In total the coupling matrix then has the following 15 physical parameters:

#### e. **Particle spectrum** a discrete Z<sub>2</sub> symmetry. The L<sub>agrangi</sub>an is given by  $\frac{1}{2}$ Particle spectrum Flavour Violation (DMFV) hypothesis, which requires the flavour-violating coupling matrix **is a diagonal matrix entries and** *Particle spectrum* the mass matrix *M* is real. The necessary field redefinition *<sup>L</sup>* ! *W<sup>L</sup>* then transforms the

$$
\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{2} \left( i \bar{\chi} \partial \chi - M_{\chi} \bar{\chi} \chi \right) - (\lambda_{ij} \bar{u}_{Ri} \chi_j \phi + \text{h.c.})
$$

$$
+ (D_{\mu} \phi)^{\dagger} (D^{\mu} \phi) - m_{\phi}^{2} \phi^{\dagger} \phi + \lambda_{H\phi} \phi^{\dagger} \phi H^{\dagger} H + \lambda_{\phi\phi} \left( \phi^{\dagger} \phi \right)^{2}
$$

$$
M_{\chi} = m_{\chi} \left[ \mathbb{1} + \eta \operatorname{Re}(\lambda^{\dagger} \lambda) + \mathcal{O}(\lambda^4) \right] = \operatorname{diag}(m_{\chi_1}, m_{\chi_2}, m_{\chi_3})
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$$



## Freeze-out scenarios

### Dark matter freeze-out curves correspond to *Y*(1) = *Y* eq  $\overline{1}$





### Dark matter freeze-out curves correspond to *Y*(1) = *Y* eq (1).





### Dark matter freeze-out: coannihilation curves correspond to *Y*(1) = *Y* eq (1).



### curves correspond to *Y*(1) = *Y* eq (1). Dark matter freeze-out: coannihilation



## Dark matter freeze-out: coannihilation



 $\lambda_{i1}, \lambda_{i2}$  *gs* 

### curves correspond to *Y*(1) = *Y* eq (1). Dark matter freeze-out: coannihilation



### Dark matter freeze-out: small curves correspond to *Y*(1) = *Y* eq (1).  $\lambda_{i3}$

![](_page_12_Figure_1.jpeg)

### Dark matter freeze-out: very small curves correspond to *Y*(1) = *Y* eq  $\lambda_{i3}$

![](_page_13_Figure_1.jpeg)

### Dark matter freeze-out: very small curves correspond to *Y*(1) = *Y* eq (1).  $\lambda_{i3}$

![](_page_14_Figure_1.jpeg)

## Flavored dark matter: freeze-out scenarios

- `Canonical' freeze-out (with or w/o coannihilation)
- Conversion-driven freeze-out

## Flavored dark matter: freeze-out scenarios

- `Canonical' freeze-out
	- Single Flavour Freeze-Out (SFF):

![](_page_16_Figure_3.jpeg)

■ Quasi-Degenerate Freeze-Out (QDF):

 $m_{\phi}$  —

$$
m_{\chi_1}\,m_{\chi_2}\,m_{\chi_3} \rule[1mm]{1mm}{6.5mm}\rule[1mm]{1mm}{0.5mm}\Delta m_{\chi_i}/m_{\chi_3}<1\%
$$

**Example 2 Generic Canonical Freeze-Out (GCF)** 

## Canonical freeze-out

- **Example 2 Flavor constraints from D-meson mixing**
- **Direct detection constraints from LZ**
- **Indirect detection from cosmic-ray antiprotons**

![](_page_17_Figure_4.jpeg)

### The DM mass matrix *M* can thus be written as We further arrange the rows of  $\sim$  We always have the rows of  $\sim$  way that we always have the rows of  $\sim$ Canonical freeze-out

$$
M_{\chi} = m_{\chi} \left[ 1 + \eta \operatorname{Re}(\lambda^{\dagger} \lambda) + \mathcal{O}(\lambda^4) \right] = \operatorname{diag}(m_{\chi_1}, m_{\chi_2}, m_{\chi_3})
$$

![](_page_18_Figure_2.jpeg)

## Canonical freeze-out

![](_page_19_Figure_1.jpeg)

![](_page_20_Figure_1.jpeg)

![](_page_21_Figure_1.jpeg)

![](_page_22_Figure_1.jpeg)

![](_page_23_Figure_1.jpeg)

LHC signatures

#### $LHC$  signatures. The explicit constant indices are flavour in the final states at the final states at the final states and the final states at the final states and states at the final states and states at the final states is not identified. In principle, these enhanced cross-sections could be used to distinguish our could be used to distingui LHC signatures DM, studied in Refs. [14,23]. In practice, however, a distinction based solely on cross-sections

### Production:

![](_page_25_Figure_2.jpeg)

![](_page_25_Figure_3.jpeg)

 $\delta u u \to \phi \phi$  large cross section Figure 3.1: Few of the *t*-channel **exception of the** *t***-channel intervalse production** modes of . The *t*-change production modes of . The *t*-change production modes of . The *t*-change production modes of . The *t*-chan [see also e.g. M. Garny, A. Ibarra, M. Pato, S. Vogl, 1306.6342]

![](_page_25_Figure_5.jpeg)

![](_page_25_Figure_6.jpeg)

 $\bar{q}_i$ 

 $\bar{q}_k$ 

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### Production:

![](_page_26_Figure_2.jpeg)

![](_page_26_Figure_3.jpeg)

 $\delta u u \to \phi \phi$  large cross section Figure 3.1: Few of the *t*-channel **exception of the** *t***-channel intervalse production** modes of . The *t*-change production modes of . The *t*-change production modes of . The *t*-change production modes of . The *t*-chan [see also e.g. M. Garny, A. Ibarra, M. Pato, S. Vogl, 1306.6342]

### Decay:

![](_page_26_Figure_6.jpeg)

 $\bar{q}_i$ 

 $\bar{q}_k$ 

#### LHC signatures. is not identified. In principle, these enhanced cross-sections could be used to distinguish our could be used to distingui  $L \sqcap C$  signatures DM, studied in Refs. [14,23]. In practice, however, a distinction based solely on cross-sections

Production:

![](_page_27_Figure_2.jpeg)

![](_page_27_Figure_3.jpeg)

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Decay:

![](_page_27_Figure_6.jpeg)

 $\bar{q}_i$ 

 $\bar{q}_k$ 

## Current constraints: canonical freeze-out

### sis. The first column column column contains the second the second the second the second the search report number,  $\mathbf{r}$ the third the center-of-mass energy of the LHC run the LHC run the respective data set is based of the respective

**Example 2018** [G. Alguero, JH, C. K. Khosa, S. Kraml *et al.* 2112.00769]

![](_page_28_Picture_141.jpeg)

![](_page_28_Figure_4.jpeg)

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**Example 2018** [G. Alguero, JH, C. K. Khosa, S. Kraml *et al.* 2112.00769]

![](_page_29_Picture_174.jpeg)

Excluded points: enhanced *t*-channel mediator production ATLAS-SUSY-2016-15 [51] 13 TeV tops+*E/ <sup>T</sup>*

 $2000$ 

 $m_{\chi_3}[\textrm{GeV}]$ 

## Current constraints: canonical freeze-out

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**Example 2018** [G. Alguero, JH, C. K. Khosa, S. Kraml *et al.* 2112.00769]

![](_page_30_Picture_175.jpeg)

aturalex decay patterns/non-prompt dec and the second of the second is the *F*  $\sigma$   $\sigma$   $\sigma$   $\sigma$ Allowed points: complex decay patterns/non-prompt decays

2000

1500

 $\begin{bmatrix} \text{GeV} \\ \text{GeV} \end{bmatrix}$ 

 $500$ 

#### Constraints: conversion-driven freeze-out ATLAS-SUSY-2013-21 [58] 8 TeV *cc* + *E/ <sup>T</sup>* ATLAS-SUSY-2014-03 [59] 8 TeV *cc* + *E/ <sup>T</sup>* ATLAS-SUSY-2016-07 [50] 13 TeV jets+*E/ <sup>T</sup>* C1*<sup>u</sup>* ATLAS-SUSY-2016-26 [60] 13 TeV *cc* + *E/ <sup>T</sup>* CH-GMYEN IFEEZE-OUL

#### ■ Small DM coupling: long-lived particles sis. The first column contains the scenario, the second the search report number, ATLAS-SUSY-2016-26 [60] 13 TeV *cc* + *E/ <sup>T</sup>* CMS-SUS-16-049 [61] 13 TeV tops+*E/ <sup>T</sup>* CMS-SUS-19-006 [45] 13 TeV jets+*E/ <sup>T</sup>*

![](_page_31_Figure_2.jpeg)

#### the third the center-of-mass energy of the LHC run the respective data set is based of the respective data set i  $\blacksquare$ CMS-SUS-20-002 [57] 13 Tev tops://www.gradeligraphy.com/

**Example 2016** [G. Alguero, JH, C. K. Khosa, S. Kraml *et al.* 2112.00769] CMS-SUS-16-036 [55] 13 TeV jets+*E/ <sup>T</sup>* C.Alguero, JH, C. K. Khosa, S. Krami *et dl. 2112.*00769]]]

![](_page_31_Picture_372.jpeg)

#### Constraints: conversion-driven freeze-out ATLAS-SUSY-2013-21 [58] 8 TeV *cc* + *E/ <sup>T</sup>* ATLAS-SUSY-2014-03 [59] 8 TeV *cc* + *E/ <sup>T</sup>* ATLAS-SUSY-2016-07 [50] 13 TeV jets+*E/ <sup>T</sup>* C1*<sup>u</sup>* ATLAS-SUSY-2016-26 [60] 13 TeV *cc* + *E/ <sup>T</sup>* CH-GMYEN IFEEZE-OUL

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![](_page_32_Figure_2.jpeg)

#### sis. The first column contains the scenario, the second the search report number,  $\blacksquare$ CMS-SUS-19-006 [45] 13 TeV jets+*E/ <sup>T</sup>*

#### **individual Merce,** *i***,** *i, g, i, and in are flagorana-specific signatures* **and**  $\alpha$ is not identified. In principal case enhanced cross-sections could be used to distinguish our could be used to distinguish Majorana-specific signatures

![](_page_33_Figure_1.jpeg)

DM, studied in Refs. [14,23]. In practice, however, a distinction based solely on cross-sections

#### ne-sign quark searches promising. Such an analysis has found in the such an analysis has found in the performa CMS search for same-sign top signatures of Ref. [68]. ➔ Same-sign quark searches promising

### ¯ + *E/ <sup>T</sup>* . However, since this search assumes a small mass splitting of roughly 20 GeV Majorana-specific signatures

Same-sign top searches in SUSY  $ttjj+\cancel{E}_T$  and  $\;\overline{t}\overline{t}jj+\cancel{E}_T$ CMS-SUS-19-008 [2001.10086]<br>
<u>CMS-SUS-19-008</u> [2001.10086]

![](_page_34_Figure_2.jpeg)

#### Single-top charge asymmetry In the case of Dirac DM only opposite-sign *†* pairs are produced, and therefore the crosstop quark in the final state, opening up the final state, opening up the possibility to straightforwardly extend<br>The possibility to straightforwardly extend it with the possibility extend it with the possibility of the pos Single-top charge asymmetry In the case of Dirac DM only opposite-sign *†* pairs are produced, and therefore the crosssection of final states with a top or anti-top and top or anti-top are equality and top are equality are equal: In the case of Dirac DM only opposite-sign *†* pairs are produced, and therefore the cross- $\overline{O}$

$$
\sigma_{\rm Dirac}(tj+\rlap{\,/}E_T)=\sigma_{\rm Dirac}(\bar{t}j+\rlap{\,/}E_T)
$$

For Majorana,  $\phi\phi$  production present and enhanced compared to  $\phi^\dagger\phi^\dagger$ (due to valence up-quark content in  $p$ ) (due to valence up-quark content in  $p$ ) Majorana(*tj* + *E/ <sup>T</sup>* ) *>* Majorana(*tj*¯ + *E/ <sup>T</sup>* )*,* (5.2) ia,  $\varphi\varphi$  production present and ennanced compared to  $\varphi^{\shortparallel}\varphi^{\shortparallel}$ nce up-quark content in  $p$ ) and the measure of this e $p\in\mathbb{R}$ 

$$
\sigma_{\rm Majorana}(tj+\rlap{\,/}E_T) > \sigma_{\rm Majorana}(\bar{t}j+\rlap{\,/}E_T)
$$

Consider charge asymmetry: as its coupling strength to  $u$  and the  $u$   $\alpha$   $\alpha$   $\beta$   $\alpha$   $\beta$   $\beta$   $\beta$   $\alpha$   $\beta$   $\beta$   $\alpha$   $\beta$   $\beta$   $\alpha$   $\beta$   $\beta$   $\beta$   $\alpha$   $\beta$   $\beta$   $\beta$   $\beta$   $\beta$   $\beta$ charge asymmetry asymmetry Consider charge asymmetry: as its coupling strength to  $\alpha$  and  $\alpha$  and the this electronic this e $\alpha$ ect, we introduce the this e $\alpha$ Consider charge asymmetry:

$$
a_{tj} = \frac{\sigma(tj + \not{E}_T) - \sigma(\bar{t}j + \not{E}_T)}{\sigma(tj + \not{E}_T) + \sigma(\bar{t}j + \not{E}_T)}
$$
Dirac DM  $\Rightarrow a_{tj} \ge 0$   
Majorana DM  $\Rightarrow a_{tj} > 0$ 

## Single-top charge asymmetry

![](_page_36_Figure_1.jpeg)

## Summary

- **Example 7 Flavored Majorana Dark Matter:** Large regions of viable parameter space
- Canonical and conversion-driven freeze-out
- **Example 2 Current gaps in LHC searches:** 
	- **Examplex decay chains**
	- **E** Long-lived particles (intermediate lifetimes)
- **EXPECE Majorana-specific signatures** 
	- **E** Same-sign tops suffer from extra jets required
	- **E** Single-top charge asymmetry

# Backup

## Flavored dark matter vs simple t-channel model

![](_page_39_Figure_1.jpeg)