A new variant of dark matter freeze-out predicting long-lived particles at the LHC

Jan Heisig (RWTH Aachen University)
Among key scientific goals of LHC:

- Pinpoint the nature of dark matter!

Needed: Predictions for possible signatures of dark matter models
Vanilla WIMP (Weakly Interacting Massive Particle)

**Nice features:**
- Works with simple models ✓
- Not sensitive to initial thermal conditions (reheating) ✓
- Allows us to directly connect relic density (freeze-out) and experimental observables ⇒ clear predictions ✓

**LHC WIMP-program:** MET-searches
Vanilla WIMP (Weakly Interacting Massive Particle)

Less nice features:

- Direct detection
- Indirect detection
- Collider detection

<table>
<thead>
<tr>
<th>DM Type</th>
<th>Axial vector mediator (Dirac DM)</th>
<th>Vector mediator (Dirac DM)</th>
<th>VV_{1/2} EFT (Dirac DM)</th>
<th>Mass</th>
<th>m_{\chi} (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>e, \mu</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>36.1</td>
<td>1.6 TeV</td>
</tr>
<tr>
<td>e, \mu, \gamma</td>
<td>0</td>
<td>0</td>
<td>1, \leq 1</td>
<td>36.1</td>
<td>1.2 TeV</td>
</tr>
<tr>
<td>e, \mu, 1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>3.2</td>
<td>700 GeV</td>
</tr>
<tr>
<td>e, \mu, 1, \gamma</td>
<td>0</td>
<td>0</td>
<td>1, \leq 1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Ackermann et al. (2015)
- Nominal sample
- Median Expected
- 68% Containment
- 95% Containment

- Fermi-LAT 1611.03184

- Ongoing support from a number of agencies and institutions.

- The anonymous referee for thoughtful and constructive comments.
Vanilla WIMP (Weakly Interacting Massive Particle)

Less nice features:

WIMPs severely under pressure

Indirect det.
Other ways to produce dark matter with same nice features?
Other ways to produce dark matter with same nice features?

Yes!

This talk: Consider slight departure from WIMP co-annihilation scenario

→ A new variant of dark matter production:

"Conversion-driven freeze-out"

[Garny, JH, Lülf, Vogl 2017]

[see also D’Agnolo, Pappadopulo, Ruderman, 2017]
Conversion-driven freeze-out

- Works with simple models
- Not sensitive to initial thermal conditions (reheating)
- Allows us to directly connect relic density (freeze-out) and experimental observables \( \Rightarrow \) clear predictions, specifically Long-lived particles at LHC

Other avenues beyond WIMPs: Secluded dark matter [Pospelov, Ritz, Voloshin 2007; Feng, Kumar 2008], Asymmetric dark matter [Kaplan, Luty, Zurek, 2009], Freeze-in [Hall, Jedamzik, March-Russell, West, 2009], SIMPs [Hochberg, Kuflik, Volansky, Wacker, 2014], Co-Decaying dark matter [Dror, Kuflik, Ng, 2016], Forbidden dark matter [Griest, Seckall, 1991; D’Agnolo, Ruderman, 2015], Pseudo-Dirac dark matter [Davolia, Simone, Jacquesa, Sanz 2017], ELDERs [Kuflik, Perelstein, Rey-Le Lorier, Tsai, 2016 & 2017], superWIMPs [Feng, Rajaraman, Takayama 2003], ...
Revisiting WIMP co-annihilation

dark matter $X_1$ $m_1 < m_2$ $X_2$ co-annihilation partner

$\lambda_1$ $\Lambda m \ll m_{1,2}$ $\lambda_2$

Annihilation $X_1 \rightarrow \text{SM}$

Conversion $X_1 \rightarrow X_2$

Co-annihilation $X_2 \rightarrow \text{SM}$

Usually (SUSY): $\lambda_1 \sim \lambda_2 \sim g_{SM} \Rightarrow$ conversion always efficient

$X_1 \leftrightarrow X_2$
Revisiting WIMP co-annihilation

Usually (SUSY): $\lambda_1 \sim \lambda_2 \sim g_{SM} \Rightarrow$ conversion always efficient

$X_1 \leftrightarrow X_2$

Larger effective annihilation cross section helps to reduce relic density:

$$\Omega h^2 \propto \frac{1}{\langle \sigma v \rangle_{\text{eff}}}$$
Conversion-driven freeze-out

Consider $\lambda_1 \ll \lambda_2$: $X_1 \leftrightarrow X_2$

- Annihilation $X_1 \rightarrow \text{SM}$, negligible
- Conversion $X_1 \rightarrow X_2$
- Co-annihilation $X_2 \rightarrow \text{SM}$, large rate

Equilibrium? $X_1 \nleftrightarrow X_2$

[Garby, JH, Lülf, Vogl 2017]
Conversion-driven freeze-out

[Garney, JH, Lülf, Vogl 2017]

Consider $\lambda_1 \ll \lambda_2$: $X_1 \leftrightarrow X_2$

- Annihilation $X_1 \rightarrow \text{SM}$
- Conversion $X_1 \rightarrow X_2$
- Co-annihilation $X_2 \rightarrow \text{SM}$

negligible bottleneck!
large rate

$\Rightarrow$ Relic density is set by the size of the conversion rate
General back-of-the-envelope estimation:

Conversion rate (just) efficient at freeze-out:

\[ \Gamma_{\text{con}} \sim H \left( T_f \sim \frac{m_X}{30} \right) \]

If (inverse) 2-body decay \( X_2 \rightarrow X_1 + \text{SM} \) is allowed: \( \Gamma_{\text{con}} \sim \Gamma_{X_2} \)
General back-of-the-envelope estimation:

Conversion rate (just) efficient at freeze-out:

\[ \Gamma_{\text{con}} \sim H \left( T_f \sim \frac{m_X}{30} \right) \]

If (inverse) 2-body decay \( X_2 \xrightarrow{\text{SM}} \) is allowed:

\[ \Gamma_{\text{con}} \sim \Gamma_{X_2} \]

\[ \Rightarrow X_2 \text{ decay-length: } \frac{1}{\Gamma_{X_2}} \sim \frac{1}{H(T_f)} \sim 1\text{--}100 \text{ cm} \]

(for masses 100GeV to a few TeV)

\[ \Rightarrow \text{LHC: long-lived particles!} \]
A concrete example

- Specific model: \( \mathcal{L}_{\text{int}} = |D_\mu \tilde{q}|^2 - \lambda_\chi \tilde{q} \gamma^5 \frac{1 - \gamma^5}{2} \chi + \text{h.c.} \)

- SUSY-inspired simplified model:
  Choose Majorana DM and scalar bottom-partner

- Yukawa-type interaction: \( \tilde{b} \lambda_\chi \chi \)

\( \lambda_\chi \) is a free parameter here [see Ibarra et al. 2009 for SUSY realization]
Allowed parameter space

- Solve coupled set of Boltzmann equations
- Require Planck relic density

Decay length: $O(1\text{-}100\text{cm})$
LHC constraints

<table>
<thead>
<tr>
<th>Simplified model chapter:</th>
<th>Production</th>
<th>Decay</th>
<th>$j + \text{inv.}$</th>
<th>$jj(+\text{inv.})$</th>
<th>$j\ell$</th>
<th>$j\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>DPP: squark pair</td>
<td>DM</td>
<td>SUSY</td>
<td>SUSY</td>
<td>SUSY</td>
<td>SUSY</td>
<td>SUSY</td>
</tr>
<tr>
<td>or gluino pair</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1.3: Simplified model channels for LLPs with color charge.
LHC constraints

- Sbottom MET searches?
LHC constraints

- Sbottom MET searches?  Non-prompt decay!

\[ \begin{align*}
\text{\textit{p}} & \rightarrow b \\
\text{\textit{p}} & \rightarrow b
\end{align*} \]
LHC constraints

- Sbottom MET searches
- Mono-jet searches

\[ \text{Sbottom MET searches} \]
\[ \text{Mono-jet searches} \]

\[ \text{rates for standard coupling} \]

\[ \text{rates for standard coupling} \]

\[ \text{freeze out!} \]

\[ \text{ce satisfied!} \]

\[ \text{ATLAS} \]

\[ \text{CMS} \]

\[ \text{ATLAS} \]

\[ \text{CMS} \]

\[ \text{all limits at 95\% CL} \]

\[ \text{expected limit (±1σ}_{\text{exp}} \]

\[ \text{observed limit (±1σ}_{\text{SUSY}} \]

\[ \text{limits at 95\% CL} \]

\[ \text{all limits at 95\% CL} \]

\[ \text{expected limit (±1σ}_{\text{exp}} \]

\[ \text{observed limit (±1σ}_{\text{SUSY}} \]
LHC constraints

- Sbottom MET searches
- Mono-jet searches
- Displaced jets

[see also ATLAS 1504.03634; as well as Davolia, De Simone, Jacquesa, Sanz 1706.08985 for a recent re-interpretation]
LHC constraints

- Sbottom MET searches
- Mono-jet searches ✓
- Displaced jets ?
- Disappearing tracks ? [see also ATLAS 1310.3675, ATLAS-CONF-2017-017]

Interpreted for chargino → adapt to R-hadrons
LHC constraints

- Sbottom MET searches ✗
- Mono-jet searches ✓
- Displaced jets ?
- Disappearing tracks ?
- HSCPs: search for detector-stable R-hadrons
  → Reinterpretation for finite life-times
  rescale signal by fraction passing the relevant detector parts:
  \[ \sigma_{\text{pred}} \rightarrow \sigma_{\text{pred}} \times F_{\text{pass}} \]

Use [CMS 1502.02522] to estimate fraction
LHC constraints

- Sbottom MET searches ☠
- Mono-jet searches ✓
- Displaced jets ✗
- Disappearing tracks ✗
- HSCPs: search for detector-stable $R$-hadrons

→ Reinterpretation for finite life-times

rescale signal by fraction passing the relevant detector parts:

$$\sigma_{\text{pred}} \rightarrow \sigma_{\text{pred}} \times \mathcal{F}_{\text{pass}}$$

Use [CMS 1502.02522] to estimate fraction

---

Jan Heisig (RWTH Aachen University)
of disappearing tracks or displaced vertices at the LHCR mass of a few hundred GeV which predicts the signature of version rates.

We can already infer that the decay length is the decay width.

cf.

ing typical freezeout 1

or indirect detection experiments.

m

value of

between

and otherwise the same parameters as in Fig.

We show solutions for the choices.

FIG. 3. Dependence on the initial conditions for curves correspond to

on initial conditions.

are considered. The shaded areas highlight the dependence.

gray dashed line corresponds to the solution when only decays result that would be obtained when assuming CE. The red

m

FIG. 2. Relic density as a function of the coupling

χ

= 5 0 0

Y

h

u

λ

b

pr

These values lie far beyond the sensitivity of direct

HSCP searches

monojet

For the solutions providing the right relic density. durq

感应

from monojet searches is shown as the red dotzdotzdashed limits from

Constraints

∆m

χ

b

h

uo ft h e

q

qhadrons that decay after traversing the relevant

hadrons copiously produced. They will hadronize to form

the absolute mass scale is more moderate.

2

dotted lines in Figr

curve.

From this simple relation 1 and assuming that

= 100

b

(1) = 0

Y

χ

Ω

m

freezezout is conversion-driven. Above this black curve CE holds y while below this curve CE breaks down.

∆m

χ

b

t7

25 cm

10 cm

5 cm

5

8

2

3

25 cm

↓ 4-body decay

Ωh^2 = 0.12

Δm_{χ^0} [GeV]

Ωh^2 = 0.12

[Garney, JH, Lülf, Vogl 2017]

m_χ [GeV]

[Garney, JH, Lülf, Vogl 2017]
 Allowed parameter space

Displaced jets/disapperaing tracks?

mono-jet
HSCP searches

\( \Delta m_{\tilde{\chi}^0} \) [GeV]

\( m_{\chi} \) [GeV]

\( \Omega h^2 = 0.12 \)

\( \lambda \chi/10^{-7} \)

\( 2 \text{.5 cm} \)

\( 5 \text{ cm} \)

\( 25 \text{ cm} \)

\( 5 \text{ cm} \)

\( 10 \text{ cm} \)

\( 8 \text{ cm} \)

\( 4 \text{-body decay} \)

\( \uparrow \text{4-body decay} \)

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Summary

- Dark matter among key scientific goals for LHC
- Vanilla WIMP under pressure: Watch out for avenues beyond WIMPs with new LHC signatures!
- Conversion-driven freeze-out:
  - Shares nice features of WIMPs
  - Accommodates null-results from WIMP-searches
  - $H \sim \Gamma$: Lifetimes naturally $O(1-100\text{cm})$
    - Strong motivation for long-lived particles at LHC
- Our model: long-lived $R$-hadrons, other possibilities
- Interesting times for dark matter hunters lie ahead
Backup slide

Computation of the fraction of detector-stable $R$-hadrons:

$$F_{\text{pass}}^i = e^{-\ell/(c\tau\beta\gamma)},$$

$$\overline{F}_{\text{pass}} = \frac{\sum_i F_{\text{pass}}^i P_{\text{on}}^i P_{\text{off}}^i}{\sum_i P_{\text{on}}^i P_{\text{off}}^i}.$$