Update on DM t-channel signatures

Luca Panizzi

with embedded contributions by
C. Arina, M. Baker, A. Cornell, R. Costa Batalha Pedro and J. Heisig
Motivation

Joint effort TH-EXP to provide guidelines and benchmarks for new analysis during Run 3 and future upgrades

Coordinators
Benjamin Fuks, LP (theory)
Benedikt Maier, David Yu (CMS)
Rute Pedro, Dominique Trischuk (ATLAS)
and 50+ authors

Study of scenarios based on the schematic interaction

- mediator ($Y$)
- dark matter ($X$)
- SM
Guiding questions

mediator \((Y)\)

- mass
- spin
- total width
- how many

dark matter \((X)\)

- mass
- spin
- how many

SM
Guiding questions

- mass
- spin
- total width
- how many

mediator ($Y$)

- dark matter ($X$)
  - mass
  - spin
  - how many

- which one(s)

- SM
Guiding questions

mediator \((Y)\)

dark matter \((X)\)

SM

mass
spin
total width
how many

size
Lorentz structure

which one(s)

mass
spin
how many
Guiding questions

- fundamental/composite
- mass
- spin
- total width
- how many
- size
- Lorentz structure
- mediator (Y)
- dark matter (X)
- SM
- which one(s)
- mass spin how many
Depending on the possibilities:

- Can we observe a signal? And how?
- How does cosmology constrain the parameters?
- How do we reinterpret results?
- Can we define benchmarks for LHC to cover the widest range of possibilities?
Temporary structure

To be reorganized once all contributions are in advanced state.
The models

Simplified models suitable for performing MC simulations at NLO in QCD and testing against cosmological observables

Coloured mediators

<table>
<thead>
<tr>
<th>Mediator</th>
<th>Spin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dark matter</td>
<td>0, 1/2</td>
</tr>
</tbody>
</table>

- DM real or complex
- Couplings with any SM quark
- Restrictions to select representations or coupling hierarchies (only one generation, universal couplings...)

Other models will be used for specific problems (leptophilic DM, multi-component DM...)

Mapping results from simplified models to theoretical scenarios
Cosmology
contribution by C. Arina
Cosmology of t-channel DM models

Goals of the section

- Provide a general overview of the cosmology of t-channel models and point to the relevant literature
- Give overview of production mechanisms
- Give overview of main searches for:
  - Direct detection
  - Indirect detection
- Illustrate cosmological bounds for the models selected in the t-channel paper (minimal model, universal couplings, flavored, leptophilic, …)
- From parameter space available define viable benchmarks for collider searches


If you are interested in joining please contact Chiara Arina (Chiara.arina@uclouvain.be)
**Dark Matter production in the early universe**

Rebirth abundance via freeze-out

**Planck experiment sets** \( \Omega h^2 = 0.12 \)

[arXiv:1807.06209]

Relic abundance via freeze-out

**Standard mechanism**

**LO processes**

- DM annihilation: \( \propto \lambda^4 \phi \)
- Coannihilation (compressed spectrum): \( \propto \alpha_s^2 \)
- \( \propto \lambda^2 \phi \alpha_s \)

**LO processes + non perturbative corrections (Sommerfeld enhancement + bound states)**

Freeze-in, SuperWIMPs achieve relic density via decay of heavy species and provide LLPs signatures also detailed

*T-channel white paper - Cosmology section*
Dark Matter direct and indirect searches

Direct detection

Indirect detection

- In many models LO annihilation is p-wave suppressed
- NLO processes uplift the suppression and produce a sharp feature in the gamma-ray energy spectrum

T-channel white paper - Cosmology section
Cosmology: current status

The section is divided mainly into two parts

1. general overview of t-channel models concerning

✓ production mechanisms in the early universe (freeze-out, freeze-in, conversion driven freeze-out, super wimp) $\rightarrow$ basically all done
✓ addition of non-perturbative corrections such as bound states to the relic density computation (freeze-out, conversion driven cases) $\rightarrow$ done
✓ direct, indirect searches (gamma-rays lines especially) $\rightarrow$ yet to be written but literature widely available

2. benchmark models

✓ coupling to third generation ($b_R$, $t_R$) for Majorana dark matter for all production mechanisms $\rightarrow$ basically all done
✓ $u_R$ case for all DM spin and mediators $\rightarrow$ to be written but data already available
✓ non perturbative corrections for universal case (freeze-out and conversion driven) $\rightarrow$ writing almost complete
✓ frustrated DM (see A. Cornell’s contribution later) $\rightarrow$ will be written by the authors, first contact made some time ago
Collider signatures
Which signatures

Not all processes might be possible at tree-level depending on coupling or mass splitting.

**Long-lived mediators**
- Bound states
- Displaced vertices
- Delayed jets/photons

**Mediators with prompt decay**
- MET+SM

depending on which SM particle

- quark-philic
  - 1st generation
  - 2nd generation
  - 3rd generation
  - Universal
- lepto-philic

Interacting with SM gauge bosons ($Z/W$) or the Higgs boson
**Prompt mediator decays**

interaction with the up quark

**Goals**

- Go beyond existing results

---

**Combination of all channels, relevance of NLO corrections and interference effects**


Prompt mediator decays
interaction with the up quark

Goals
- Go beyond existing results
- Identify benchmarks allowed by LHC and cosmology observables

<table>
<thead>
<tr>
<th></th>
<th>$M_Y$</th>
<th>$M_X$</th>
<th>$\lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>S3M_uR</td>
<td>3300</td>
<td>2700</td>
<td>4.79563</td>
</tr>
<tr>
<td>F3S_uR</td>
<td>3400</td>
<td>2500</td>
<td>4.88088</td>
</tr>
<tr>
<td>F3V_uR</td>
<td>3500</td>
<td>1500</td>
<td>1.0066</td>
</tr>
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Prompt mediator decays interaction with the up quark

Goals

- Go beyond existing results
- Identify benchmarks allowed by LHC and cosmology observables

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Store event samples and kinematical distributions for subsequent analyses
Collider: current status

This section requires long simulations but writing will be fast at the end

1. Simulation status (only authors with access to clusters)

✓ $u_R, d_R, c_R, t_R$ recast done for all simplified scenarios
✓ $s_R, b_R$ in progress
✓ MC samples not ready

2. Development of a common simulation framework on condor

O. Iorio and A. Cagnotta (CMS)

3. Analysis code for interpretation in general scenarios

A. Desai
Flavoured dark matter
contribution by R. Costa Batalha Pedro
Top-philic Dark Matter

- Models of flavoured DM beyond Minimal Flavour Violation
  - 1702.08457 1702.08457
  - Flavour carried by the DM candidate and not by the mediator
  - DM is either a Dirac or Majorana fermion
  - Quark-flavoured DM coupling to the SM quarks
    - Lepton-flavoured models may link to the \((g - 2)\_\mu\) anomaly 2212.08142

- Constrains from LHC for top-philic scenario
  - Mainly on mediator pair production
  - \(t j + E_T\) and \(t\bar{t} + E_T\) final states (common to searches for SUSY squarks)

- Majorana-specific phenomenology
  - t-channel \(\phi\)-pair-production leading to same-sign \(tt + E_T\)
  - Enhanced cross-section at the LHC due to the \(up\)-quark PDF in the protons

\[ \lambda^{ij}\bar{q}_i \chi_j \phi \]

- \(q_i\) SM quarks
- \(\chi_j\) DM fermion, flavoured
- \(\phi\) coloured scalar mediator
- \(\lambda\) flavour-violating coupling matrix

\( (b) \) \(\phi\phi\) production

Majorana-specific
**Single top signatures**

- **Simplified models of top-flavoured Dark Matter**
  - 2010.10530
  - Within the framework of Minimal Flavour Violation
  - $\phi$ coloured mediator
    - Right-handed model: couplings to up-type quarks only
    - Left-handed model: couplings to up/down-type quarks
      (more constrained by flavour physics)

- **Single top signatures**
  - $t + E_T$
  - $tq + E_T$, where $q = \{u, d, s, c\}$
  - $tb + E_T$
Charm/strange-philic DM

- **Review/draw constrains on charm-flavoured DM**
  - Limits for the charm-philic model using four jets+MET searches
  - Phenomenology investigations of charm tagging

- **Similar content for a strange-philic model?**
Leptophilic models
contribution by M. Baker
Leptophilic Models: Classification

Leptophilic $t$-channel models:

DM **only** couples to SM leptons via a $t$-channel diagram

- DM can couple to RH and/or LH $e, \mu$ and/or $\tau$
- DM is gauge singlet $\rightarrow$ charged mediator
- Fermionic DM $\rightarrow$ bosonic mediator and vice versa
- DM could be a real or complex scalar, a Majorana or Dirac fermion or a real or complex vector
- The mediator must be complex/Dirac

E.g.,

\[
\mathcal{L} \supset y_{Ri}^j \phi^j \chi R^i + y_{Li}^k \varphi^k \chi L^i_L + h.c.
\]

**RH Model Parameters:**
- $m_\chi$
- $\Delta = (m_\phi - m_\chi)/m_\chi$
- $y_R^i$

<table>
<thead>
<tr>
<th>Field</th>
<th>$(SU(3)_C, SU(2)_L, U(1)_Y)$</th>
<th>Spin</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\ell_R$</td>
<td>$(1, 1, -1)$</td>
<td>1/2</td>
</tr>
<tr>
<td>$L_L$</td>
<td>$(1, 2, -1/2)$</td>
<td>1/2</td>
</tr>
<tr>
<td>$\chi$</td>
<td>$(1, 1, 0)$</td>
<td>0, 1/2, 1</td>
</tr>
<tr>
<td>$\phi$</td>
<td>$(1, 1, 1)$</td>
<td>1/2, ${0, 1}$, 1/2</td>
</tr>
<tr>
<td>$\varphi$</td>
<td>$(1, 2, 1/2)$</td>
<td>1/2, ${0, 1}$, 1/2</td>
</tr>
</tbody>
</table>
Leptophilic Models: Phenomenology

Phenomenology depends on

**Mass Regime**
- Decoupled: $0.3 \lesssim \Delta$
- Coannihilation: $0.02 \lesssim \Delta \lesssim 0.3$
- Quasi-degenerate: $\Delta \lesssim 0.02$

**DM Production Mechanism (3 $\rightarrow$ 2 parameters)**
- Freeze-out
- Freeze-in
- Other
- Undefined (3 parameters)

**DM Particle Identity**
- Real scalar and Majorana fermion has velocity suppressed freeze-out, direct detection and indirect detection processes
- Not directly relevant at LHC, but important when comparing with other searches or using production as constraint

Main LHC channel:

Two (SF) OS leptons + MET

(Also one lepton + MET in LH models from $W^\pm \rightarrow \phi^0 \phi^{\pm}$)

**Mass Regimes:**
- Decoupled: $\rightarrow$ hard leptons
- Coannihilation: $\rightarrow$ soft leptons (ISR boost?)
- Quasi-degenerate and small couplings: $\rightarrow$ long-lived mediator
Status

- Classification complete
- Benchmark models defined
- Completing work on combining existing limits and relic surfaces
Long-lived mediators
contribution by J. Heisig
Why long-lived particles (LLPs)?

⇒ MET signature

⇒ LLPs if:

- λ small or/and
- Small mass splitting, in particular:
  \[ \Delta m = m_Y - m_X < m(q) \]
Range of dark matter couplings

\[ \Omega h^2 \]

schematic plot

- superWIMPs
- Freeze-in
- Conversion FO
- Co-annihilation
- WIMP Freeze-out

relic density constraint

- \( 10^{-15} \sim 10^{-6} \)
- \( 10^{-7} \sim 10^{-3} \)
- \( 10^{-1} \sim 1 \)
Range of dark matter couplings

\[ \Omega h^2 \]

schematic plot

superWIMPs
Freeze-in
Conversion FO
Co-annihilation
WIMP Freeze-out

\[ 10^{-15} \sim 10^{-6} \]
\[ 10^{-7} \sim 10^{-3} \]
\[ 10^{-1} \sim 1 \]

WIMP searches
Range of dark matter couplings

- superWIMPs
- Freeze-in
- Conversion FO
- Co-annihilation
- WIMP Freeze-out

schematic plot

Long-lived particles!
LLP Signatures: light dark matter
(superWIMPs, Freeze-in)
LLP Signatures: small mass splitting
(Conversion FO, Co-annihilation)
LLP Signatures: small mass splitting

Closing experimental gaps:

- How far do MET searches cover LLP regime? (transition prompt-LLP)
- How to tackle small mass splittings, i.e. softish displaced objects?

(highly ionising, disappearing) track

invisble

soft jet/lepton

developing
Going beyond the minimal setup
contribution by A. Cornell
Subsection 8.1
Top-philic composite dark matter

- Top-philic scalar DM models represent very simple, testable and viable models of WIMP DM:
  [S.W. Baek, P. Ko, P. Wu (2016)], [Colucci, Fuks, Giacchino et al. (2018)]
  - very few new particles and parameters
    (one DM scalar $S$ and a vector-like fermion mediator $T$),
  - renormalizable,
  - simple cosmology (thermal relic, standard evolution),
  - testable in DM direct detection, indirect detection (photons), and at colliders.

- VLQs which primarily couple to the SM top quark are common in many SM extensions (extra dimensions, little Higgs, twin Higgs, VLQ extensions of SUSY, Composite Higgs Models ....)

- If $S$ and $T$ are part of a UV completion with additional states/dynamics at typical scale $\Lambda$ (of a few TeV), integrating out the additional states induces higher-dimensional operators in the top-philic scalar DM Lagrangian.
Sub-section 8.2
Frustrated dark matter models

• All mediator fields couple both to $\chi$ and to SM fields carry SM gauge charges that preclude renormalizable gauge-invariant interactions between the DM and any SM fermion.

• Interactions of the DM are \textit{frustrated} in the sense that the specific mediator assignments preclude its tree level interaction with the SM

$$\text{SM} \longleftrightarrow \text{mediators} \left\{ \varphi \ (\text{scalar}) \atop \psi \ (\text{Dirac}) \right\} \longleftrightarrow \text{DM} \ \chi.$$ 

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{med}} + \mathcal{L}_\chi,$$

$$\mathcal{L}_{\text{med}} = (D_\mu \phi)^s(D^\mu \phi)_s - m^2_\phi \phi^s \phi_s + \bar{\psi}^s (i\gamma^\mu - m_\psi) \psi_s + \mathcal{L}_{\text{decay}}$$

$$\mathcal{L}_\chi = \bar{\chi}(i\gamma^\mu - m_\chi)\chi + y_\chi (\varphi^s \bar{\chi} \psi_s + \text{H.c.})$$
**Sub-section 8.3**

**B-mesogenesis models**

- Mesogenesis is a recent experimentally testable mechanism of baryogenesis and dark matter production which utilizes CP violation in Standard Model mesons.

- In the Mesogenesis mechanism, a scalar field $\Phi$ with a mass of $10$ to $O(100 \text{ GeV})$ decays at a low temperature $T_R \sim O(\text{MeV})$ to equal numbers quarks and anti-quarks pairs.

- Critical to the setup of these mechanisms is a t-channel coloured scalar mediator which mediates the decays of mesons in to dark sector baryons.

- In neutral B mesogenesis, the CP violation of $B^{0, s,d}_s - \bar{B}^{0, s,d}_s$ is leveraged

$$\mathcal{L}_Y = \sum_{i,j} Y^* \bar{u}_{i,R} d^c_{j,R} - \sum_k y_{\psi_B} k Y d^c_{k R} \psi_B + \text{h.c.}$$
Conclusion

Work is proceeding on multiple fronts

**Tentative timescales of the white paper**

- **End of the year** → complete production of numerical data (mostly collider side)
- **End of the year / Early January** → Advanced draft
- **Early 2024** → General meeting to finalise writeup

- **Spring 2024** → Full white paper 🙌